Category Framework

Release 10.3

The Sage Development Team

Mar 20, 2024
## CONTENTS

1 Introduction 1
2 The Sage Category Framework 3
3 Maps and Morphisms 105
4 Individual Categories 159
5 Functorial constructions 817
6 Examples of parents using categories 847
7 Internals 907
8 Indices and Tables 917
Python Module Index 919
Index 923
CHAPTER
ONE

INTRODUCTION

1.1 Sage categories quickref

- `sage.categories.primer?` a primer on Elements, Parents, and Categories
- `sage.categories.tutorial?` a tutorial on Elements, Parents, and Categories
- `Category?` technical background on categories
- `Sets(),Semigroups(),Algebras(QQ)` some categories
- `SemiGroups().example()?` sample implementation of a semigroup
- `Hom(A, B),End(A, Algebras())` homomorphisms sets
- `tensor/cartesian_product` functorial constructions

Module layout:

- `sage.categories.basic` the basic categories
- `sage.categories.all` all categories
- `sage.categories.semigroups` the Semigroups() category
- `sage.categories.examples.semigroups` the example of Semigroups()
- `sage.categories.homset` morphisms, ...
- `sage.categories.map`
- `sage.categories.morphism`
- `sage.categories.functors`
- `sage.categories.cartesian_product` functorial constructions
- `sage.categories.tensor`
- `sage.categories.dual`
2.1 Elements, parents, and categories in Sage: a primer

2.1.1 Abstract

The purpose of categories in Sage is to translate the mathematical concept of categories (category of groups, of vector spaces, …) into a concrete software engineering design pattern for:

• organizing and promoting generic code
• fostering consistency across the Sage library (naming conventions, doc, tests)
• embedding more mathematical knowledge into the system

This design pattern is largely inspired from Axiom and its followers (Aldor, Fricas, MuPAD, …). It differs from those by:

• blending in the Magma inspired concept of Parent/Element
• being built on top of (and not into) the standard Python object oriented and class hierarchy mechanism. This did not require changing the language, and could in principle be implemented in any language supporting the creation of new classes dynamically.
The general philosophy is that Building mathematical information into the system yields more expressive, more conceptual and, at the end, easier to maintain and faster code (within a programming realm; this would not necessarily apply to specialized libraries like gmp!).

One line pitch for mathematicians

Categories in Sage provide a library of interrelated bookshelves, with each bookshelf containing algorithms, tests, documentation, or some mathematical facts about the objects of a given category (e.g. groups).

One line pitch for programmers

Categories in Sage provide a large hierarchy of abstract classes for mathematical objects. To keep it maintainable, the inheritance information between the classes is not hardcoded but instead reconstructed dynamically from duplication free semantic information.

2.1.2 Introduction: Sage as a library of objects and algorithms

The Sage library, with more than one million lines of code, documentation, and tests, implements:

- Thousands of different kinds of objects (classes):
  Integers, polynomials, matrices, groups, number fields, elliptic curves, permutations, morphisms, languages, … and a few racoons …
- Tens of thousands methods and functions:
  Arithmetic, integer and polynomial factorization, pattern matching on words, …

Some challenges

- How to organize this library?
  One needs some bookshelves to group together related objects and algorithms.
- How to ensure consistency?
  Similar objects should behave similarly:

```sage
sage: Permutations(5).cardinality()
sage: GL(2,2).cardinality()
sage: A = random_matrix(ZZ, 6, 3, x=7)
sage: L = LatticePolytope(A.rows())
sage: L.npoints()  # oops!  # random
```

- How to ensure robustness?
• How to reduce duplication?

Example: binary powering:

```
sage: m = 3
sage: m^8 == m*m*m*m*m*m*m*m == ((m^2)^2)^2
True
```

```
sage: # needs sage.modules
sage: m = random_matrix(QQ, 4, algorithm='echelonizable', ....: rank=3, upper_bound=60)
sage: m^8 == m*m*m*m*m*m*m*m == ((m^2)^2)^2
True
```

We want to implement binary powering only once, as generic code that will apply in all cases.

### 2.1.3 A bit of help from abstract algebra

#### The hierarchy of categories

What makes binary powering work in the above examples? In both cases, we have a set endowed with a multiplicative binary operation which is associative and which has a unit element. Such a set is called a monoid, and binary powering (to a non-negative power) works generally for any monoid.

Sage knows about monoids:

```
sage: Monoids()
Category of monoids
```

and sure enough, binary powering is defined there:

```
sage: m._pow_int.__module__
˓→ needs sage.modules
'sage.categories.monoids'
```

That’s our bookshelf! And it’s used in many places:

```
sage: GL(2, ZZ) in Monoids()
˓→ needs sage.modules
True
sage: NN in Monoids()
True
```

For a less trivial bookshelf we can consider euclidean rings: once we know how to do euclidean division in some set $R$, we can compute gcd’s in $R$ generically using the Euclidean algorithm.

We are in fact very lucky: abstract algebra provides us right away with a large and robust set of bookshelves which is the result of centuries of work of mathematicians to identify the important concepts. This includes for example:

```
sage: Sets()
Category of sets
sage: Groups()
Category of groups
sage: Rings()
```

(continues on next page)
Each of the above is called a category. It typically specifies what are the operations on the elements, as well as the axioms satisfied by those operations. For example the category of groups specifies that a group is a set endowed with a binary operation (the multiplication) which is associative and admits a unit and inverses.

Each set in Sage knows which bookshelf of generic algorithms it can use, that is to which category it belongs:

```
sage: G = GL(2, ZZ)  # needs sage.modules
sage: G.category()   # needs sage.modules
Category of infinite groups
```

In fact a group is a semigroup, and Sage knows about this:

```
sage: Groups().is_subcategory(Semigroups())
True
sage: G in Semigroups()  # needs sage.modules
True
```

Altogether, our group gets algorithms from a bunch of bookshelves:

```
sage: G.categories()  # needs sage.modules
[Category of infinite groups, Category of groups, Category of monoids, ...
, Category of magmas, Category of infinite sets, ...]
```

Those can be viewed graphically:

```
sage: g = Groups().category_graph()  # needs sage.graphs
sage: g.set_latex_options(format="dot2tex")  # needs sage.graphs sage.modules
sage: view(g)  # not tested
```

In case `dot2tex` is not available, you can use instead:

```
sage: g.show(vertex_shape=\textcolor{red}{None}, figsize=20)  # needs sage.graphs sage.modules sage.plot
```

Here is an overview of all categories in Sage:

```
sage: g = sage.categories.category.category_graph()  # needs sage.graphs sage.modules
sage: g.set_latex_options(format="dot2tex")  # needs sage.graphs sage.modules
```
Wrap-up: generic algorithms in Sage are organized in a hierarchy of bookshelves modelled upon the usual hierarchy of categories provided by abstract algebra.

**Elements, Parents, Categories**

**Parent**

A *parent* is a Python instance modelling a set of mathematical elements together with its additional (algebraic) structure. Examples include the ring of integers, the group $S_3$, the set of prime numbers, the set of linear maps between two given vector spaces, and a given finite semigroup.

These sets are often equipped with additional structure: the set of all integers forms a ring. The main way of encoding this information is specifying which categories a parent belongs to.

It is completely possible to have different Python instances modelling the same set of elements. For example, one might want to consider the ring of integers, or the poset of integers under their standard order, or the poset of integers under divisibility, or the semiring of integers under the operations of maximum and addition. Each of these would be a different instance, belonging to different categories.

For a given model, there should be a unique instance in Sage representing that parent:

```
sage: IntegerRing() is IntegerRing()
True
```

**Element**

An *element* is a Python instance modelling a mathematical element of a set.

Examples of element include $5$ in the integer ring, $x^3 - x$ in the polynomial ring in $x$ over the rationals, $4 + O(3^3)$ in the 3-adics, the transposition $(12)$ in $S_3$, and the identity morphism in the set of linear maps from $Q^3$ to $Q^3$.

Every element in Sage has a parent. The standard idiom in Sage for creating elements is to create their parent, and then provide enough data to define the element:

```
sage: R = PolynomialRing(ZZ, name='x')
sage: R([1,2,3])
3*x^2 + 2*x + 1
```

One can also create elements using various methods on the parent and arithmetic of elements:

```
sage: x = R.gen()
sage: 1 + 2*x + 3*x^2
3*x^2 + 2*x + 1
```

Unlike parents, elements in Sage are not necessarily unique:

```
sage: ZZ(5040) is ZZ(5040)
False
```

Many parents model algebraic structures, and their elements support arithmetic operations. One often further wants to do arithmetic by combining elements from different parents: adding together integers and rationals for example. Sage supports this feature using coercion (see `sage.structure.coerce` for more details).

**2.1. Elements, parents, and categories in Sage: a primer**
It is possible for a parent to also have simultaneously the structure of an element. Consider for example the monoid of all finite groups, endowed with the Cartesian product operation. Then, every finite group (which is a parent) is also an element of this monoid. This is not yet implemented, and the design details are not yet fixed but experiments are underway in this direction.

**Todo:** Give a concrete example, typically using `ElementWrapper`.

---

**Category**

A *category* is a Python instance modelling a mathematical category.

Examples of categories include the category of finite semigroups, the category of all (Python) objects, the category of \(\mathbb{Z}\)-algebras, and the category of Cartesian products of \(\mathbb{Z}\)-algebras:

```sage
sage: FiniteSemigroups()
Category of finite semigroups
sage: Objects()
Category of objects
sage: Algebras(ZZ)
Category of algebras over Integer Ring
sage: Algebras(ZZ).CartesianProducts()
Category of Cartesian products of algebras over Integer Ring
```

Mind the 's' in the names of the categories above; `GroupAlgebra` and `GroupAlgebras` are distinct things.

Every parent belongs to a collection of categories. Moreover, categories are interrelated by the *super categories* relation. For example, the category of rings is a super category of the category of fields, because every field is also a ring.

A category serves two roles:

- to provide a model for the mathematical concept of a category and the associated structures: homsets, morphisms, functorial constructions, axioms.
- to organize and promote generic code, naming conventions, documentation, and tests across similar mathematical structures.

**CategoryObject**

Objects of a mathematical category are not necessarily parents. Parent has a superclass that provides a means of modeling such.

For example, the category of schemes does not have a faithful forgetful functor to the category of sets, so it does not make sense to talk about schemes as parents.

**Morphisms, Homsets**

As category theorists will expect, *Morphisms* and *Homsets* will play an ever more important role, as support for them will improve.

Much of the mathematical information in Sage is encoded as relations between elements and their parents, parents and their categories, and categories and their super categories:
**2.1.4 A bit of help from computer science**

**Hierarchy of classes**

How are the bookshelves implemented in practice?

Sage uses the classical design paradigm of Object Oriented Programming (OOP). Its fundamental principle is that any object that a program is to manipulate should be modelled by an instance of a class. The class implements:

- a *data structure*: which describes how the object is stored,
- *methods*: which describe the operations on the object.

The instance itself contains the data for the given object, according to the specified data structure.

Hence, all the objects mentioned above should be instances of some classes. For example, an integer in Sage is an instance of the class `Integer` (and it knows about it!):
Applying an operation is generally done by calling a method:

```
sage: i.factor()
2^2 * 3

sage: # needs sage.symbolic
sage: x = var('x')
sage: p = 6*x^2 + 12*x + 6
sage: type(p)
<class 'sage.symbolic.expression.Expression'>
sage: p.factor()
6*(x + 1)^2

sage: # needs sage.symbolic
sage: R.<x> = PolynomialRing(QQ, sparse=True)
sage: pQ = R(p)
<class 'sage.rings.polynomial.polynomial_element_generic.PolynomialRing_field_with_category.
˓element_class'>
sage: pQ.factor()
(6) * (x + 1)^2

sage: # needs sage.symbolic
sage: pZ = ZZ['x'](p)
<class 'sage.rings.polynomial.polynomial_integer_dense_flint.Polynomial_integer_dense_flint'>
sage: pZ.factor()
2 * 3 * (x + 1)^2
```

Factoring integers, expressions, or polynomials are distinct tasks, with completely different algorithms. Yet, from a user (or caller) point of view, all those objects can be manipulated alike. This illustrates the OOP concepts of polymorphism, data abstraction, and encapsulation.

Let us be curious, and see where some methods are defined. This can be done by introspection:

```
sage: i._mul_  # not tested
'sage.categories.semisigroups'

sage: pQ._mul_  # not tested (Issue #24275)
'needs sage.symbolic'
'sage.rings.polynomial.polynomial_element_generic'

sage: pZ._mul_  # not tested (Issue #24275)
'needs sage.symbolic'
'sage.categories.semisigroups'
```

We see that integers and polynomials have each their own multiplication method: the multiplication algorithms are indeed unrelated and deeply tied to their respective datastructures. On the other hand, as we have seen above, they share the same powering method because the set \( \mathbb{Z} \) of integers, and the set \( \mathbb{Q}[x] \) of polynomials are both semigroups. Namely, the class for integers and the class for polynomials both derive from an abstract class for semigroup elements, which factors out
the generic methods like \texttt{\_\_pow\_.} This illustrates the use of hierarchy of classes to share common code between classes having common behavior.

OOP design is all about isolating the objects that one wants to model together with their operations, and designing an appropriate hierarchy of classes for organizing the code. As we have seen above, the design of the class hierarchy is easy since it can be modelled upon the hierarchy of categories (bookshelves). Here is for example a piece of the hierarchy of classes for an element of a group of permutations:

```python
sage: P = Permutations(4)
sage: m = P.an_element()
sage: for cls in m.__class__.mro(): print(cls)
<class 'sage.combinat.permutation.StandardPermutations_n_with_category.element_class'>
<class 'sage.combinat.permutation.StandardPermutations_n.Element'>
<class 'sage.combinat.permutation.Permutation'>
...
```

On the top, we see concrete classes that describe the data structure for matrices and provide the operations that are tied to this data structure. Then follow abstract classes that are attached to the hierarchy of categories and provide generic algorithms.

The full hierarchy is best viewed graphically:

```python
sage: g = class_graph(m.__class__) # needs sage.combinat sage.graphs
sage: g.set_latex_options(format="dot2tex") # needs sage.combinat sage.graphs
sage: view(g) # not tested # needs sage.combinat sage.graphs sage.plot
```

### Parallel hierarchy of classes for parents

Let us recall that we do not just want to compute with elements of mathematical sets, but with the sets themselves:

```python
sage: ZZ.one()
1
sage: R = QQ[\mediate]-x,y|]
sage: R.krull_dimension()
2
sage: A = R.quotient( R.ideal(x^2 - 2) )
sage: A.krull_dimension() # todo: not implemented
```

Here are some typical operations that one may want to carry on various kinds of sets:

- The set of permutations of 5, the set of rational points of an elliptic curve: counting, listing, random generation
- A language (set of words): rationality testing, counting elements, generating series
- A finite semigroup: left/right ideals, center, representation theory
- A vector space, an algebra: Cartesian product, tensor product, quotient

Hence, following the OOP fundamental principle, parents should also be modelled by instances of some (hierarchy of) classes. For example, our group \( G \) is an instance of the following class:

### 2.1. Elements, parents, and categories in Sage: a primer
Here is a piece of the hierarchy of classes above it:

```sage
sage: for cls in G.__class__.mro(): print(cls) #...
needs sage.libs.gap sage.modules
<class 'sage.groups.matrix_gps.linear_gap.LinearMatrixGroup_gap_with_category'>
...
<class 'sage.categories.groups.Groups.parent_class'>
<class 'sage.categories.monoids.Monoids.parent_class'>
<class 'sage.categories.semigroups.Semigroups.parent_class'>
...
```

Note that the hierarchy of abstract classes is again attached to categories and parallel to that we had seen for the elements. This is best viewed graphically:

```sage
sage: # needs sage.graphs sage.modules
sage: g = class_graph(m.__class__)
```

```sage
sage: g.relabel(lambda x: x.replace("_",r"\_"))
```

```sage
sage: g.set_latex_options(format="dot2tex")
```

```sage
sage: view(g) # not tested #...
needs sage.plot
```

Note: This is a progress upon systems like Axiom or MuPAD where a parent is modelled by the class of its elements; this oversimplification leads to confusion between methods on parents and elements, and makes parents special; in particular it prevents potentially interesting constructions like “groups of groups”.

### 2.1.5 Sage categories

Why this business of categories? And to start with, why don’t we just have a good old hierarchy of classes `Group`, `Semigroup`, `Magma`, …?

**Dynamic hierarchy of classes**

As we have just seen, when we manipulate groups, we actually manipulate several kinds of objects:

- groups
- group elements
- morphisms between groups
- and even the category of groups itself!

Thus, on the group bookshelf, we want to put generic code for each of the above. We therefore need three, parallel hierarchies of abstract classes:

- `Group`, `Monoid`, `Semigroup`, `Magma`, …
- `GroupElement`, `MonoidElement`, `SemigroupElement`, `MagmaElement`, …
- `GroupMorphism`, `MonoidMorphism`, `SemigroupMorphism`, `MagmaMorphism`, …
(and in fact many more as we will see).

We could implement the above hierarchies as usual:

```python
class Group(Monoid):
    # generic methods that apply to all groups

class GroupElement(MonoidElement):
    # generic methods that apply to all group elements

class GroupMorphism(MonoidMorphism):
    # generic methods that apply to all group morphisms
```

And indeed that's how it was done in Sage before 2009, and there are still many traces of this. The drawback of this approach is duplication: the fact that a group is a monoid is repeated three times above!

Instead, Sage now uses the following syntax, where the Groups bookshelf is structured into units with nested classes:

```python
class Groups(Category):
    def super_categories(self):
        return [Monoids(), ...]

class ParentMethods:
    # generic methods that apply to all groups

class ElementMethods:
    # generic methods that apply to all group elements

class MorphismMethods:
    # generic methods that apply to all group morphisms (not yet implemented)

class SubcategoryMethods:
    # generic methods that apply to all subcategories of Groups()
```

With this syntax, the information that a group is a monoid is specified only once, in the `Category.super_categories()` method. And indeed, when the category of inverse unital magmas was introduced, there was a single point of truth to update in order to reflect the fact that a group is an inverse unital magma:

```python
sage: Groups().super_categories()
[Category of monoids, Category of inverse unital magmas]
```

The price to pay (there is no free lunch) is that some magic is required to construct the actual hierarchy of classes for parents, elements, and morphisms. Namely, `Groups.ElementMethods` should be seen as just a bag of methods, and the actual class `Groups().element_class` is constructed from it by adding the appropriate super classes according to `Groups().super_categories()`:

```python
sage: Groups().element_class
class 'sage.categories.groups.Groups.element_class'
sage: Groups().element_class.__bases__
(<class 'sage.categories.monoids.Monoids.element_class'>,
 <class 'sage.categories.magas.Magmas.Unital.Inverse.element_class'>)
```

We now see that the hierarchy of classes for parents and elements is parallel to the hierarchy of categories:

```python
sage: Groups().all_super_categories()
[Category of groups,
  Category of monoids, ...]
```

(continues on next page)
Another advantage of building the hierarchy of classes dynamically is that, for parametrized categories, the hierarchy may depend on the parameters. For example an algebra over $\mathbb{Q}$ is a $\mathbb{Q}$-vector space, but an algebra over $\mathbb{Z}$ is not (it is just a $\mathbb{Z}$-module)!

\begin{verbatim}
 sage: for cls in Groups().element_class.mro(): print(cls)
<class 'sage.categories.groups.Groups.element_class'>
<class 'sage.categories.monoids.Monoids.element_class'>
<class 'sage.categories.semigroups.Semigroups.element_class'>
...
<class 'sage.categories.magmas.Magmas.element_class'>
...
 sage: for cls in Groups().parent_class.mro(): print(cls)
<class 'sage.categories.groups.Groups.parent_class'>
<class 'sage.categories.monoids.Monoids.parent_class'>
<class 'sage.categories.semigroups.Semigroups.parent_class'>
...
<class 'sage.categories.magmas.Magmas.parent_class'>
...
\end{verbatim}

Note: At this point this whole infrastructure may feel like overdesigning, right? We felt like this too! But we will see later that, once one gets used to it, this approach scales very naturally.

From a computer science point of view, this infrastructure implements, on top of standard multiple inheritance, a dynamic composition mechanism of mixin classes (Wikipedia article Mixin), governed by mathematical properties.

For implementation details on how the hierarchy of classes for parents and elements is constructed, see Category.

On the category hierarchy: subcategories and super categories

We have seen above that, for example, the category of sets is a super category of the category of groups. This models the fact that a group can be unambiguously considered as a set by forgetting its group operation. In object-oriented parlance, we want the relation "a group is a set", so that groups can directly inherit code implemented on sets.

Formally, a category $\mathcal{C}$ is a super category of a category $\mathcal{D}$ if Sage considers any object of $\mathcal{D}$ to be an object of $\mathcal{C}$, up to an implicit application of a canonical functor from $\mathcal{D}$ to $\mathcal{C}$. This functor is normally an inclusion of categories or a forgetful functor. Reciprocally, $\mathcal{D}$ is said to be a subcategory of $\mathcal{C}$.

Warning: This terminology deviates from the usual mathematical definition of subcategory and is subject to change. Indeed, the forgetful functor from the category of groups to the category of sets is not an inclusion of categories, as it is not injective: a given set may admit more than one group structure. See github issue #16183 for more details. The name supercategory is also used with a different meaning in certain areas of mathematics.
Categories are instances and have operations

Note that categories themselves are naturally modelled by instances because they can have operations of their own. An important one is:

```sage
sage: Groups().example()
# needs sage.modules
General Linear Group of degree 4 over Rational Field
```

which gives an example of object of the category. Besides illustrating the category, the example provides a minimal template for implementing a new object in the category:

```sage
sage: S = Semigroups().example(); S
An example of a semigroup: the left zero semigroup
```

Its source code can be obtained by introspection:

```sage
sage: S
# not tested
```

This example is also typically used for testing generic methods. See `Category.example()` for more.

Other operations on categories include querying the super categories or the axioms satisfied by the operations of a category:

```sage
sage: Groups().super_categories()
[Category of monoids, Category of inverse unital magmas]
sage: Groups().axioms()
frozenset({'Associative', 'Inverse', 'Unital'})
```

or constructing the intersection of two categories, or the smallest category containing them:

```sage
sage: Groups() & FiniteSets()
Category of finite groups
sage: Algebras(QQ) | Groups()
Category of monoids
```

Specifications and generic documentation

Categories do not only contain code but also the specifications of the operations. In particular a list of mandatory and optional methods to be implemented can be found by introspection with:

```sage
sage: Groups().required_methods()
{'element': {"optional": ['_mul_'], 'required': []},
 'parent': {"optional": [], 'required': ['__contains__']}}
```

Documentation about those methods can be obtained with:

```sage
sage: G = Groups()
sage: G.element_class._mul_
# not tested
sage: G.parent_class.one
# not tested
```

See also the `abstract_method()` decorator.

**Warning:** Well, more precisely, that’s how things should be, but there is still some work to do in this direction. For example, the inverse operation is not specified above. Also, we are still missing a good programmatic syntax to specify the input and output types of the methods. Finally, in many cases the implementer must provide at least one of two
methods, each having a default implementation using the other one (e.g. listing or iterating for a finite enumerated set); there is currently no good programmatic way to specify this.

**Generic tests**

Another feature that parents and elements receive from categories is generic tests; their purpose is to check (at least to some extent) that the parent satisfies the required mathematical properties (is my semigroup indeed associative?) and is implemented according to the specifications (does the method \texttt{an_element} indeed return an element of the parent?):

```
sage: S = FiniteSemigroups().example(alphabet=('a', 'b'))
sage: TestSuite(S).run(verbos = True)
running ._test_an_element() . . . pass
running ._test_associativity() . . . pass
running ._test_cardinality() . . . pass
running ._test_category() . . . pass
running ._test_construction() . . . pass
running ._test_elements() . . .
   Running the test suite of self.an_element()
   running ._test_category() . . . pass
   running ._test_eq() . . . pass
   running ._test_new() . . . pass
   running ._test_not_implemented_methods() . . . pass
   running ._test_pickling() . . . pass
   pass
   running ._test_elements_eq_reflexive() . . . pass
   running ._test_elements_eq_symmetric() . . . pass
   running ._test_elements_eq_transitive() . . . pass
   running ._test_elements_neq() . . . pass
running ._test_enumerated_set_contains() . . . pass
running ._test_enumerated_set_iter_cardinality() . . . pass
running ._test_enumerated_set_iter_list() . . . pass
running ._test_eq() . . . pass
running ._test_new() . . . pass
running ._test_not_implemented_methods() . . . pass
running ._test_pickling() . . . pass
running ._test_some_elements() . . . pass
```

Tests can be run individually:

```
sage: S._test_associativity()
```

Here is how to access the code of this test:

```
sage: S._test_associativity
```

Here is how to run the test on all elements:

```
sage: L = S.list()
sage: S._test_associativity(elements=L)
```

See \texttt{TestSuite} for more information.

Let us see what happens when a test fails. Here we redefine the product of $S$ to something definitely not associative:

```
sage: S.product = lambda x, y: S("("+x.value +y.value+")")
```
And rerun the test:

```
sage: S._test_associativity(elements=L)
Traceback (most recent call last):
...
File ".../sage/categories/semigroups.py", line ..., in _test_associativity
tester.assertTrue((x * y) * z == x * (y * z))
...
AssertionError: '((aa)a)' != '(a(aa))'
```

We can recover instantly the actual values of \(x, y, z\), that is, a counterexample to the associativity of our broken semigroup, using post mortem introspection with the Python debugger \texttt{pdb} (this does not work yet in the notebook):

```
sage: import pdb
sage: pdb.pm() # not tested
> /opt/sage-5.11.rc1/local/lib/python/unittest/case.py(424)assertTrue()
-> raise self.failureException(msg)
(Pdb) u
> /opt/sage-5.11.rc1/local/lib/python2.7/site-packages/sage/categories/semigroups.
˓→py(145)_test_associativity()
-> tester.assertTrue((x * y) * z == x * (y * z))
(Pdb) p x, y, z
('a', 'a', 'a')
(Pdb) p (x * y) * z
'((aa)a)'
(Pdb) p x * (y * z)
'(a(aa))'
```

Wrap-up

- Categories provide a natural hierarchy of bookshelves to organize not only code, but also specifications and testing tools.
- Everything about, say, algebras with a distinguished basis is gathered in \texttt{AlgebrasWithBasis} or its super categories. This includes properties and algorithms for elements, parents, morphisms, but also, as we will see, for constructions like Cartesian products or quotients.
- The mathematical relations between elements, parents, and categories translate dynamically into a traditional hierarchy of classes.
- This design enforces robustness and consistency, which is particularly welcome given that Python is an interpreted language without static type checking.

### 2.1.6 Case study

In this section, we study an existing parent in detail; a good followup is to go through the \texttt{sage.categories.tutorial} or the thematic tutorial on coercion and categories (“How to implement new algebraic structures in Sage”) to learn how to implement a new one!

We consider the example of finite semigroup provided by the category:

```
sage: S = FiniteSemigroups().example(); S
An example of a finite semigroup: the left regular band generated by {'a', 'b', 'c', ...
˓→'d'}
sage: S
```

### 2.1. Elements, parents, and categories in Sage: a primer
Where do all the operations on $S$ and its elements come from?

```sage
sage: x = S('a')
```

`_repr_` is a technical method which comes with the data structure (ElementWrapper); since it's implemented in Cython, we need to use Sage's introspection tools to recover where it's implemented:

```sage
sage: x._repr_.__module__
sage: sage.misc.sageinspect.sage_getfile(x._repr_)
'../sage/structure/element_wrapper.pyx'
```

`_pow_int` is a generic method for all finite semigroups:

```sage
sage: x._pow_int.__module__
'sage.categories.semigroups'
```

`__mul__` is a generic method provided by the Magmas category (a magma is a set with an inner law $\ast$, not necessarily associative). If the two arguments are in the same parent, it will call the method `__mul__`, and otherwise let the coercion model try to discover how to do the multiplication:

```sage
sage: x.__mul__
# not tested
```

Since it is a speed critical method, it is implemented in Cython in a separate file:

```sage
sage: x.__mul__.__module__
'sage.categories.coercion_methods'
```

`__mul__` is a default implementation, also provided by the Magmas category, that delegates the work to the method `product` of the parent (following the advice: if you do not know what to do, ask your parent); it's also a speed critical method:

```sage
sage: x.__mul__
# not tested
sage: x.__mul__.__module__
'sage.categories.coercion_methods'
sage: x.__mul__.__func__ is Magmas.ElementMethods._mul_parent
True
```

`product` is a mathematical method implemented by the parent:

```sage
sage: S.product.__module__
'sage.categories.examples.finite_semigroups'
```

cayley_graph is a generic method on the parent, provided by the FiniteSemigroups category:

```sage
sage: S.cayley_graph.__module__
'sage.categories.semigroups'
```

multiplication_table is a generic method on the parent, provided by the Magmas category (it does not require associativity):

```sage
sage: S.multiplication_table.__module__
'sage.categories.magas'
```

Consider now the implementation of the semigroup:

```sage
sage: S
# not tested
```
This implementation specifies a data structure for the parents and the elements, and makes a promise: the implemented parent is a finite semigroup. Then it fulfills the promise by implementing the basic operation product. It also implements the optional method semigroup_generators. In exchange, $S$ and its elements receive generic implementations of all the other operations. $S$ may override any of those by more efficient ones. It may typically implement the element method is_idempotent to always return True.

A (not yet complete) list of mandatory and optional methods to be implemented can be found by introspection with:

```
sage: FiniteSemigroups().required_methods()
{'element': {'optional': ['_mul_'], 'required': []},
 'parent': {'optional': ['semigroup_generators'],
 'required': ['__contains__']})
```

product does not appear in the list because a default implementation is provided in term of the method _mul_ on elements. Of course, at least one of them should be implemented. On the other hand, a default implementation for __contains__ is provided by Parent.

Documentation about those methods can be obtained with:

```
sage: C = FiniteSemigroups().element_class
sage: C._mul_  # not tested
```

See also the abstract_method() decorator.

Here is the code for the finite semigroups category:

```
sage: FiniteSemigroups  # not tested
```

### 2.1.7 Specifying the category of a parent

Some parent constructors (not enough!) allow to specify the desired category for the parent. This can typically be used to specify additional properties of the parent that we know to hold a priori. For example, permutation groups are by default in the category of finite permutation groups (no surprise):

```
sage: P = PermutationGroup([[(1,2,3)]]); P
Permutation Group with generators [(1,2,3)]
sage: P.category()
Category of finite enumerated permutation groups
```

In this case, the group is commutative, so we can specify this:

```
sage: P = PermutationGroup([[(1,2,3)]]);
....:     category=PermutationGroups().Finite().Commutative()); P
Permutation Group with generators [(1,2,3)]
sage: P.category()
Category of finite enumerated commutative permutation groups
```

This feature can even be used, typically in experimental code, to add more structure to existing parents, and in particular to add methods for the parents or the elements, without touching the code base:

```
sage: class Foos(Category):
    ....:     def super_categories(self):
```

(continues on next page)
In the long run, it would be thinkable to use this idiom to implement forgetful functors; for example the above group could be constructed as a plain set with:

```python
sage: P = PermutationGroup([[1,2,3]], category=Sets())  # not implemented, needs...
```

At this stage though, this is still to be explored for robustness and practicality. For now, most parents that accept a category argument only accept a subcategory of the default one.

### 2.1.8 Scaling further: functorial constructions, axioms, ...

In this section, we explore more advanced features of categories. Along the way, we illustrate that a large hierarchy of categories is desirable to model complicated mathematics, and that scaling to support such a large hierarchy is the driving motivation for the design of the category infrastructure.

#### Functorial constructions

Sage has support for a certain number of so-called covariant functorial constructions which can be used to construct new parents from existing ones while carrying over as much as possible of their algebraic structure. This includes:

- Cartesian products: See `cartesian_product`
- Tensor products: See `tensor`
- Subquotients / quotients / subobjects / isomorphic objects: See:
  - `Sets().Subquotients`
  - `Sets().Quotients`
  - `Sets().Subobjects`
  - `Sets().IsomorphicObjects`
- Dual objects: See `Modules().DualObjects`
- Algebras, as in group algebras, monoid algebras, ...: See `Sets.ParentMethods.algebra()`

Let for example $A$ and $B$ be two parents, and let us construct the Cartesian product $A \times B \times B$:
In which category should this new parent be? Since $A$ and $B$ are vector spaces, the result is, as a vector space, the direct sum $A \oplus B \oplus B$, hence the notation. Also, since both $A$ and $B$ are monoids, $A \times B \times B$ is naturally endowed with a monoid structure for pointwise multiplication:

```
sage: C in Monoids()  # needs sage.combinat sage.modules
True
```

the unit being the Cartesian product of the units of the operands:

```
sage: C.one()  # needs sage.combinat sage.modules
B[(0, word: )] + B[(1, ())] + B[(2, ())]
sage: cartesian_product([A.one(), B.one(), B.one()])  # needs sage.combinat sage.modules
B[(0, word: )] + B[(1, ())] + B[(2, ())]
```

The pointwise product can be implemented generically for all magmas (i.e. sets endowed with a multiplicative operation) that are constructed as Cartesian products. It’s thus implemented in the `Magmas` category:

```
sage: C.product.__module__  # needs sage.combinat sage.modules
'sage.categories.magmas'
```

More specifically, keeping on using nested classes to structure the code, the product method is put in the nested class `Magmas.CartesianProducts.ParentMethods`:

```
class Magmas(Category):
    class ParentMethods:
        # methods for magmas
    class ElementMethods:
        # methods for elements of magmas
    class CartesianProduct(CartesianProductCategory):
        class ParentMethods:
            # methods for magmas that are constructed as Cartesian products
            def product(self, x, y):
                # ...
        class ElementMethods:
            # ...
```

**Note:** The support for nested classes in Python is relatively recent. Their intensive use for the category infrastructure did reveal some glitches in their implementation, in particular around class naming and introspection. Sage currently works around the more annoying ones but some remain visible. See e.g. `sage.misc.test_nested_class`.

Let us now look at the categories of $C$:
This reveals the parallel hierarchy of categories for Cartesian products of semigroups magmas, ... We are thus glad that Sage uses its knowledge that a monoid is a semigroup to automatically deduce that a Cartesian product of monoids is a Cartesian product of semigroups, and build the hierarchy of classes for parents and elements accordingly.

In general, the Cartesian product of $A$ and $B$ can potentially be an algebra, a coalgebra, a differential module, and be finite dimensional, or graded, or …. This can only be decided at runtime, by introspection into the properties of $A$ and $B$; furthermore, the number of possible combinations (e.g. finite dimensional differential algebra) grows exponentially with the number of properties.

**Axioms**

**First examples**

We have seen that Sage is aware of the axioms satisfied by, for example, groups:

```python
sage: Groups().axioms()
frozenset({'Associative', 'Inverse', 'Unital'})
```

In fact, the category of groups can be defined by stating that a group is a magma, that is a set endowed with an internal binary multiplication, which satisfies the above axioms. Accordingly, we can construct the category of groups from the category of magmas:

```python
sage: Magmas().Associative().Unital().Inverse()
Category of groups
```

In general, we can construct new categories in Sage by specifying the axioms that are satisfied by the operations of the super categories. For example, starting from the category of magmas, we can construct all the following categories just by specifying the axioms satisfied by the multiplication:

```python
sage: Magmas()
Category of magmas
sage: Magmas().Unital()
Category of unital magmas
```

```python
sage: Magmas().Commutative().Unital()
Category of commutative unital magmas
sage: Magmas().Unital().Commutative()
Category of commutative unital magmas
```

```python
sage: Magmas().Associative()
Category of semigroups
```

```python
sage: Magmas().Associative().Unital()
Category of monoids
```
Axioms and categories with axioms

Here, Associative, Unital, Commutative are axioms. In general, any category Cs in Sage can declare a new axiom A. Then, the category with axiom Cs.A() models the subcategory of the objects of Cs satisfying the axiom A. Similarly, for any subcategory Ds of Cs, Ds.A() models the subcategory of the objects of Ds satisfying the axiom A. In most cases, it's a full subcategory (see Wikipedia article Subcategory).

For example, the category of sets defines the Finite axiom, and this axiom is available in the subcategory of groups:

```
sage: Sets().Finite()
Category of finite sets
sage: Groups().Finite()
Category of finite groups
```

The meaning of each axiom is described in the documentation of the corresponding method, which can be obtained as usual by introspection:

```
sage: C = Groups()
sage: C.Finite # not tested
```

The purpose of categories with axioms is no different from other categories: to provide bookshelves of code, documentation, mathematical knowledge, tests, for their objects. The extra feature is that, when intersecting categories, axioms are automatically combined together:

```
sage: C = Magmas().Associative() & Magmas().Unital().Inverse() & Sets().Finite(); C
Category of finite groups
sage: sorted(C.axioms())
['Associative', 'Finite', 'Inverse', 'Unital']
```

For a more advanced example, Sage knows that a ring is a set C endowed with a multiplication which distributes over addition, such that (C, +) is a commutative additive group and (C, *) is a monoid:

```
sage: C = (CommutativeAdditiveGroups() & Monoids()).Distributive(); C
Category of rings
sage: sorted(C.axioms())
['AdditiveAssociative', 'AdditiveCommutative', 'AdditiveInverse', 'AdditiveUnital', 'Associative', 'Distributive', 'Unital']
```

The infrastructure allows for specifying further deduction rules, in order to encode mathematical facts like Wedderburn’s theorem:

```
sage: DivisionRings() & Sets().Finite()
Category of finite enumerated fields
```

Note: When an axiom specifies the properties of some operations in Sage, the notations for those operations are tied to this axiom. For example, as we have seen above, we need two distinct axioms for associativity: the axiom “Additive-
Associative” is about the properties of the addition +, whereas the axiom “Associative” is about the properties of the multiplication *.

We are touching here an inherent limitation of the current infrastructure. There is indeed no support for providing generic code that is independent of the notations. In particular, the category hierarchy about additive structures (additive monoids, additive groups, …) is completely duplicated by that for multiplicative structures (monoids, groups, …).

As far as we know, none of the existing computer algebra systems has a good solution for this problem. The difficulty is that this is not only about a single notation but a bunch of operators and methods: +, -, zero, summation, sum, … in one case, *, /, one, product, prod, factor, … in the other. Sharing something between the two hierarchies of categories would only be useful if one could write generic code that applies in both cases; for that one needs to somehow automatically substitute the right operations in the right spots in the code. That’s kind of what we are doing manually between e.g. AdditiveMagmas.ParentMethods.addition_table() and Magmas.ParentMethods.multiplication_table(), but doing this systematically is a different beast from what we have been doing so far with just usual inheritance.

Single entry point and name space usage

A nice feature of the notation Cs.A() is that, from a single entry point (say the category Magmas as above), one can explore a whole range of related categories, typically with the help of introspection to discover which axioms are available, and without having to import new Python modules. This feature will be used in github issue #15741 to unclutter the global name space from, for example, the many variants of the category of algebras like:

```
sage: FiniteDimensionalAlgebrasWithBasis(QQ)
Category of finite dimensional algebras with basis over Rational Field
```

There will of course be a deprecation step, but it’s recommended to prefer right away the more flexible notation:

```
sage: Algebras(QQ).WithBasis().FiniteDimensional()
Category of finite dimensional algebras with basis over Rational Field
```

Design discussion

How far should this be pushed? Fields should definitely stay, but should FiniteGroups or DivisionRings be removed from the global namespace? Do we want to further completely deprecate the notation FiniteGroups() in favor of ``Groups().Finite()? On the potential combinatorial explosion of categories with axioms

Even for a very simple category like Magmas, there are about $2^5$ potential combinations of the axioms! Think about what this becomes for a category with two operations + and *:

```
sage: C = (Magmas() & AdditiveMagmas()).Distributive(); C
Category of distributive magmas and additive magmas
```
```
sage: CAA = C.Associative().AdditiveAssociative()
sage: CAA.AdditiveCommutative().AdditiveUnital().AdditiveInverse()
Category of rngs
```
```
sage: CAA.AdditiveCommutative().AdditiveUnital().Unital()
Category of semirings
```
(continues on next page)


sage: CA.AdditiveCommutative().AdditiveUnital().AdditiveInverse().Unital()
Category of rings

sage: Rings().Division()
Category of division rings

sage: Rings().Division().Commutative()
Category of fields

sage: Rings().Division().Finite()
Category of finite enumerated fields

or for more advanced categories:

sage: g = HopfAlgebras(QQ).WithBasis().Graded().Connected().category_graph()  # needs sage.graphs
sage: g.set_latex_options(format="dot2tex")  # needs sage.graphs
sage: view(g)  # not tested  # needs sage.graphs sage.plot

Difference between axioms and regressive covariant functorial constructions

Our running examples here will be the axiom 

FiniteDimensional

and the regressive covariant functorial construction 

Graded.

Let 

Cs

be some subcategory of 

Modules,

say the category of modules itself:

sage: Cs = Modules(QQ)

Then, 

Cs.FiniteDimensional()

(respectively 

Cs.Graded())

is the subcategory of the objects of 

Cs

which are finite dimensional (respectively graded).

Let also 

Ds

be a subcategory of 

Cs,

say:

sage: Ds = Algebras(QQ)

A finite dimensional algebra is also a finite dimensional module:

sage: Algebras(QQ).FiniteDimensional().is_subcategory(Modules(QQ).FiniteDimensional())
True

Similarly a graded algebra is also a graded module:

sage: Algebras(QQ).Graded().is_subcategory(Modules(QQ).Graded())
True

This is the covariance property: for 

A

an axiom or a covariant functorial construction, if 

Ds

is a subcategory of 

Cs,

then 

Ds.A()

is a subcategory of 

Cs.A().

What happens if we consider reciprocally an object of 

Cs.A()

which is also in 

Ds? A finite dimensional module which is also an algebra is a finite dimensional algebra:

sage: Modules(QQ).FiniteDimensional() & Algebras(QQ)
Category of finite dimensional algebras over Rational Field

2.1. Elements, parents, and categories in Sage: a primer
On the other hand, a graded module $O$ which is also an algebra is not necessarily a graded algebra! Indeed, the grading on $O$ may not be compatible with the product on $O$:

```
sage: Modules(QQ).Graded() & Algebras(QQ)
Join of Category of algebras over Rational Field and Category of graded vector spaces over Rational Field
```

The relevant difference between *FiniteDimensional* and *Graded* is that *FiniteDimensional* is a statement about the properties of $O$ seen as a module (and thus does not depend on the given category), whereas *Graded* is a statement about the properties of $O$ and all its operations in the given category.

In general, if a category satisfies a given axiom, any subcategory also satisfies that axiom. Another formulation is that, for an axiom $A$ defined in a super category $Cs$ of $Ds$, $Ds.A()$ is the intersection of the categories $Ds$ and $Cs.A()$:

```
sage: As = Algebras(QQ).FiniteDimensional(); As
Category of finite dimensional algebras over Rational Field
sage: Bs = Algebras(QQ).WithBasis().FiniteDimensional(); Bs
Category of finite dimensional algebras with basis over Rational Field
sage: As is Bs
True
```

An immediate consequence is that, as we have already noticed, axioms commute:

```
sage: As = Algebras(QQ).FiniteDimensional().WithBasis(); As
Category of finite dimensional algebras with basis over Rational Field
sage: Bs = Algebras(QQ).WithBasis().FiniteDimensional(); Bs
Category of finite dimensional algebras with basis over Rational Field
sage: As is Bs
True
```

On the other hand, axioms do not necessarily commute with functorial constructions, even if the current printout may missuggest so:

```
sage: As = Algebras(QQ).Graded().WithBasis(); As
Category of graded algebras with basis over Rational Field
sage: Bs = Algebras(QQ).WithBasis().Graded(); Bs
Category of graded algebras with basis over Rational Field
sage: As is Bs
False
```

This is because $Bs$ is the category of algebras endowed with basis, which are further graded; in particular the basis must respect the grading (i.e. be made of homogeneous elements). On the other hand, $As$ is the category of graded algebras, which are further endowed with some basis; that basis need not respect the grading. In fact $As$ is really a join category:

```
sage: type(As)
<class 'sage.categories.category.JoinCategory_with_category'>
sage: As._repr_(as_join=True)
'Join of Category of algebras with basis over Rational Field and Category of graded..._algebras over Rational Field'
```

**Todo:** Improve the printing of functorial constructions and joins to raise this potentially dangerous ambiguity.
Further reading on axioms

We refer to `sage.categories.category_with_axiom` for how to implement axioms.

Wrap-up

As we have seen, there is a combinatorial explosion of possible classes. Constructing by hand the full class hierarchy would not scale unless one would restrict to a very rigid subset. Even if it was possible to construct automatically the full hierarchy, this would not scale with respect to system resources.

When designing software systems with large hierarchies of abstract classes for business objects, the difficulty is usually to identify a proper set of key concepts. Here we are lucky, as the key concepts have been long identified and are relatively few:

- Operations (+, *, …)
- Axioms on those operations (associativity, …)
- Constructions (Cartesian products, …)

Better, those concepts are sufficiently well known so that a user can reasonably be expected to be familiar with the concepts that are involved for his own needs.

Instead, the difficulty is concentrated in the huge number of possible combinations, an unpredictable large subset of which being potentially of interest; at the same time, only a small – but moving – subset has code naturally attached to it.

This has led to the current design, where one focuses on writing the relatively few classes for which there is actual code or mathematical information, and lets Sage compose dynamically and lazily those building blocks to construct the minimal hierarchy of classes needed for the computation at hand. This allows for the infrastructure to scale smoothly as bookshelves are added, extended, or reorganized.

2.1.9 Writing a new category

Each category `C` must be provided with a method `C.super_categories()` and can be provided with a method `C._subcategory_hook_(D)`. Also, it may be needed to insert `C` into the output of the `super_categories()` method of some other category. This determines the position of `C` in the category graph.

A category may provide methods that can be used by all its objects, respectively by all elements of its objects.

Each category should come with a good example, in `sage.categories.examples`.

Inserting the new category into the category graph

`C.super_categories()` must return a list of categories, namely the immediate super categories of `C`. Of course, if you know that your new category `C` is an immediate super category of some existing category `D`, then you should also update the method `D.super_categories` to include `C`.

The immediate super categories of `C` should not be `join categories`. Furthermore, one always should have:

```python
Cs().is_subcategory( Category.join(Cs().super_categories()) )
Cs()._cmp_key > other._cmp_key for other in Cs().super_categories()
```

This is checked by `_test_category()`.
In several cases, the category $C$ is directly provided with a generic implementation of `super_categories`; a typical example is when $C$ implements an axiom or a functorial construction; in such a case, $C$ may implement $C$. `extra_super_categories()` to complement the super categories discovered by the generic implementation. This method needs not return immediate super categories; instead it’s usually best to specify the largest super category providing the desired mathematical information. For example, the category `Magmas.Commutative.Algebras` just states that the algebra of a commutative magma is a commutative magma. This is sufficient to let Sage deduce that it’s in fact a commutative algebra.

**Methods for objects and elements**

Different objects of the same category share some algebraic features, and very often these features can be encoded in a method, in a generic way. For example, for every commutative additive monoid, it makes sense to ask for the sum of a list of elements. Sage’s category framework allows to provide a generic implementation for all objects of a category.

If you want to provide your new category with generic methods for objects (or elements of objects), then you simply add a nested class called `ParentMethods` (or `ElementMethods`). The methods of that class will automatically become methods of the objects (or the elements). For instance:

```python
sage: P.<x,y> = ZZ[]
sage: P.prod([x,y,2])
2*x*y
sage: P.prod.__module__
sage.categories.monoids
sage: P.prod.__func__ is raw_getattr(Monoids().ParentMethods, "prod")
True
```

We recommend to study the code of one example:

```python
sage: C = CommutativeAdditiveMonoids()
sage: C ?
# not tested
```

**On the order of super categories**

The generic method $C$.all_super_categories() determines recursively the list of all super categories of $C$.

The order of the categories in this list does influence the inheritance of methods for parents and elements. Namely, if $P$ is an object in the category $C$ and if $C_1$ and $C_2$ are both super categories of $C$ defining some method `foo` in `ParentMethods`, then $P$ will use $C_1$’s version of `foo` if and only if $C_1$ appears in $C$.all_super_categories() before $C_2$.

However this must be considered as an implementation detail: if $C_1$ and $C_2$ are incomparable categories, then the order in which they appear must be mathematically irrelevant: in particular, the methods `foo` in $C_1$ and $C_2$ must have the same semantic. Code should not rely on any specific order, as it is subject to later change. Whenever one of the implementations is preferred in some common subcategory of $C_1$ and $C_2$, for example for efficiency reasons, the ambiguity should be resolved explicitly by defining a method `foo` in this category. See the method `some_elements` in the code of the category `FiniteCoxeterGroups` for an example.

Since github issue #11943, $C$.all_super_categories() is computed by the so-called C3 algorithm used by Python to compute Method Resolution Order of new-style classes. Thus the order in $C$.all_super_categories(), $C$.parent_class.mro() and $C$.element_class.mro() are guaranteed to be consistent.

Since github issue #13589, the C3 algorithm is put under control of some total order on categories. This order is not necessarily meaningful, but it guarantees that C3 always finds a consistent Method Resolution Order. For background, see `sage.misc.c3_controlled`. A visible effect is that the order in which categories are specified in $C$.super_categories(), or in a join category, no longer influences the result of $C$.all_super_categories().
Subcategory hook (advanced optimization feature)

The default implementation of the method `C.is_subcategory(D)` is to look up whether `D` appears in `C.all_super_categories()`. However, building the list of all the super categories of `C` is an expensive operation that is sometimes best avoided. For example, if both `C` and `D` are categories defined over a base, but the bases differ, then one knows right away that they can not be subcategories of each other.

When such a short-path is known, one can implement a method `_subcategory_hook_`. Then, `C.is_subcategory(D)` first calls `D._subcategory_hook_(C)`. If this returns Unknown, then `C.is_subcategory(D)` tries to find `D` in `C.all_super_categories()`. Otherwise, `C.is_subcategory(D)` returns the result of `D._subcategory_hook_(C)`.

By default, `D._subcategory_hook_(C)` tests whether `issubclass(C.parent_class,D.parent_class)`, which is very often giving the right answer:

```python
sage: Rings()._subcategory_hook_(Algebras(QQ))
True
sage: HopfAlgebras(QQ)._subcategory_hook_(Algebras(QQ))
False
sage: Algebras(QQ)._subcategory_hook_(HopfAlgebras(QQ))
True
```

2.2 Categories

AUTHORS:

• David Kohel, William Stein and Nicolas M. Thiery

Every Sage object lies in a category. Categories in Sage are modeled on the mathematical idea of category, and are distinct from Python classes, which are a programming construct.

In most cases, typing `x.category()` returns the category to which `x` belongs. If `C` is a category and `x` is any object, `C(x)` tries to make an object in `C` from `x`. Checking if `x` belongs to `C` is done as usually by `x in C`.

See `Category` and `sage.categories.primer` for more details.

EXAMPLES:

We create a couple of categories:

```python
sage: Sets()
Category of sets
sage: GSets(AbelianGroup([2, 4, 9]))
Category of G-sets for Multiplicative Abelian group isomorphic to C2 x C4 x C9
sage: Semigroups()
Category of semigroups
sage: VectorSpaces(FiniteField(11))
Category of vector spaces over Finite Field of size 11
sage: Ideals(IntegerRing())
Category of ring ideals in Integer Ring
```

Let’s request the category of some objects:

```python
sage: V = VectorSpace(RationalField(), 3)
```

(continues on next page)
needs sage.modules
Category of finite dimensional vector spaces with basis
over (number fields and quotient fields and metric spaces)

sage: G = SymmetricGroup(9)  #...
needs sage.groups
sage: G.category()  #...
needs sage.groups
Join of
Category of finite enumerated permutation groups and
Category of finite Weyl groups and
Category of well generated finite irreducible complex reflection groups

sage: P = PerfectMatchings(3)  #...
needs sage.combinat
sage: P.category()  #...
needs sage.combinat
Category of finite enumerated sets

Let's check some memberships:

sage: V in VectorSpaces(QQ)  #...
needs sage.modules
True
sage: V in VectorSpaces(FiniteField(11))  #...
needs sage.modules
False
sage: G in Monoids()  #...
needs sage.groups
True
sage: P in Rings()  #...
needs sage.combinat
False

For parametrized categories one can use the following shorthand:

sage: V in VectorSpaces  #...
needs sage.modules
True
sage: G in VectorSpaces  #...
needs sage.groups
False

A parent \( P \) is in a category \( C \) if \( P \).category() is a subcategory of \( C \).

Note: Any object of a category should be an instance of \code{CategoryObject}.

For backward compatibility this is not yet enforced:

sage: class A:
    ....:    def category(self):
    ....:        return Fields()
sage: A() in Rings()
True

By default, the category of an element \( x \) of a parent \( P \) is the category of all objects of \( P \) (this is dubious and may be deprecated):
**2.2. Categories**

```python
sage: V = VectorSpace(RationalField(), 3)  #-- needs sage.modules
sage: v = V.gen(1)  #-- needs sage.modules
sage: v.category()  #-- needs sage.modules
Category of elements of Vector space of dimension 3 over Rational Field
```

```python
class sage.categories.category.Category
    Bases: UniqueRepresentation, SageObject

    The base class for modeling mathematical categories, like for example:

    • Groups(): the category of groups
    • EuclideanDomains(): the category of euclidean rings
    • VectorSpaces(QQ): the category of vector spaces over the field of rationals

    See `sage.categories.primer` for an introduction to categories in Sage, their relevance, purpose, and usage. The documentation below will focus on their implementation.

    Technically, a category is an instance of the class `Category` or some of its subclasses. Some categories, like `VectorSpaces`, are parametrized: `VectorSpaces(QQ)` is one of many instances of the class `VectorSpaces`. On the other hand, `EuclideanDomains()` is the single instance of the class `EuclideanDomains`.

    Recall that an algebraic structure (say, the ring `QQ[x]`) is modelled in Sage by an object which is called a parent. This object belongs to certain categories (here `EuclideanDomains()` and `Algebras()`). The elements of the ring are themselves objects.

    The class of a category (say `EuclideanDomains`) can define simultaneously:

    • Operations on the category itself (what is its super categories? its category of morphisms? its dual category?).
    • Generic operations on parents in this category, like the ring `QQ[x]`.
    • Generic operations on elements of such parents (e. g., the Euclidean algorithm for computing gcds).
    • Generic operations on morphisms of this category.

    This is achieved as follows:

```python
sage: from sage.categories.category import Category
sage: class EuclideanDomains(Category):
    #-- super_categories(self):
    #-- [Rings()]
    def super_categories(self):
        return [Rings()]
    def dummy(self):
        # TODO: find some good examples
        pass

class ParentMethods:
    # holds the generic operations on parents
    # TODO: find a good example of an operation
    pass

class ElementMethods:
    # holds the generic operations on elements
    def gcd(x,y):
        # Euclid algorithms
        pass
```

(continues on next page)
....:   class MorphismMethods:  # holds the generic operations on morphisms
....:       # TODO: find a good example of an operation
....:       pass
....:

Note that the nested class `ParentMethods` is merely a container of operations, and does not inherit from anything. Instead, the hierarchy relation is defined once at the level of the categories, and the actual hierarchy of classes is built in parallel from all the `ParentMethods` nested classes, and stored in the attributes `parent_class`. Then, a parent in a category $C$ receives the appropriate operations from all the super categories by usual class inheritance from `C.parent_class`.

Similarly, two other hierarchies of classes, for elements and morphisms respectively, are built from all the `ElementMethods` and `MorphismMethods` nested classes.

**EXAMPLES:**

We define a hierarchy of four categories $A()$, $B()$, $C()$, $D()$ with a diamond inheritance. Think for example:

- $A()$: the category of sets
- $B()$: the category of additive groups
- $C()$: the category of multiplicative monoids
- $D()$: the category of rings

```python
sage: from sage.categories.category import Category
sage: from sage.misc.lazy_attribute import lazy_attribute
sage: class As (Category):
....:   def super_categories(self):
....:       return []
....:
....:   class ParentMethods:
....:       def fA(self):
....:           return "A"
....:       f = fA
sage: class Bs (Category):
....:   def super_categories(self):
....:       return [As()]
....:
....:   class ParentMethods:
....:       def fB(self):
....:           return "B"
sage: class Cs (Category):
....:   def super_categories(self):
....:       return [As()]
....:
....:   class ParentMethods:
....:       def fC(self):
....:           return "C"
....:       f = fC
sage: class Ds (Category):
....:   def super_categories(self):
....:       return [Bs(), Cs()]
```

...
Categories should always have unique representation; by github issue #12215, this means that it will be kept in cache, but only if there is still some strong reference to it.

We check this before proceeding:

```
sage: import gc
sage: idAs = id(As())
sage: _ = gc.collect()
sage: n == id(As())
False
sage: a = As()
sage: id(As()) == id(As())
True
sage: As().parent_class == As().parent_class
True
```

We construct a parent in the category `Ds()` (that is an instance of `Ds().parent_class`), and check that it has access to all the methods provided by all the categories, with the appropriate inheritance order:

```
sage: D = Ds().parent_class()
sage: [ D.fA(), D.fB(), D.fC(), D.fD() ]
['A', 'B', 'C', 'D']
sage: D.f()
'C'
```

```
sage: C = Cs().parent_class()
sage: [ C.fA(), C.fc() ]
['A', 'C']
sage: C.f()
'C'
```

Here is the parallel hierarchy of classes which has been built automatically, together with the method resolution order (:mro:):

```
sage: As().parent_class
<class '__main__.As.parent_class'>
sage: As().parent_class.__bases__
(... 'object',)
sage: As().parent_class.mro()
[<class '__main__.As.parent_class'>, <... 'object'>]
```

```
sage: Bs().parent_class
<class '__main__.Bs.parent_class'>
sage: Bs().parent_class.__bases__
[<class '__main__.As.parent_class'>,]
sage: Bs().parent_class.mro()
[<class '__main__.Bs.parent_class'>, <class '__main__.As.parent_class'>, <... 'object'>]
```

```
sage: Cs().parent_class
<class '__main__.Cs.parent_class'>
```

(continues on next page)
Note that two categories in the same class need not have the same super_categories. For example, \texttt{Algebras(QQ)} has \texttt{VectorSpaces(QQ)} as super category, whereas \texttt{Algebras(ZZ)} only has \texttt{Modules(ZZ)} as super category. In particular, the constructed parent class and element class will differ (inheriting, or not, methods specific for vector spaces):

\begin{verbatim}
\end{verbatim}

On the other hand, identical hierarchies of classes are, preferably, built only once (e.g. for categories over a base ring):

\begin{verbatim}
sage: Algebras(GF(5)).parent_class is Algebras(GF(7)).parent_class True sage: F = FractionField(ZZ['t']) sage: Coalgebras(F).parent_class is Coalgebras(FractionField(F['x'])).parent_class True
\end{verbatim}

We now construct a parent in the usual way:

\begin{verbatim}
sage: class myparent(Parent):
....:     def __init__(self):
....:         Parent.__init__(self, category=Ds())
....:     def g(self):
....:         return "myparent"
....:     class Element():
....:         pass
sage: D = myparent()
sage: D.__class__
<class '__main__.myparent_with_category'>
sage: D.__class__.__bases__
(<class '__main__.myparent_with_category'>, <class '__main__.Ds.parent_class'>)
sage: D.__class__.mro()
[<class '__main__.myparent_with_category'>, <class '__main__.myparent'>, <class 'sage.structure.parent.Parent'>, <class 'sage.structure.category_object.CategoryObject'>, <class 'sage.structure.sage_object.SageObject'>, <class '__main__.Ds.parent_class'>, <class '__main__.Cs.parent_class'>, ...
\end{verbatim}
<class '__main__.Bs.parent_class'>,
<class '__main__.As.parent_class'>,
<... 'object'>]
sage: D.fA()
'A'
sage: D.fB()
'B'
sage: D.fC()
'C'
sage: D.fD()
'D'
sage: D.f()
'C'
sage: D.g()
'myparent'
sage: D.element_class
<class '__main__.myparent_with_category.element_class'>
sage: D.element_class.mro()
[<class '__main__.myparent_with_category.element_class'>,
<class ...__main__....Element...>,
<class '__main__.Ds.element_class'>,
<class '__main__.Cs.element_class'>,
<class '__main__.Bs.element_class'>,
<class '__main__.As.element_class'>,
<... 'object'>]

__super_categories()  

The immediate super categories of this category.

This lazy attribute caches the result of the mandatory method super_categories() for speed. It also does some mangling (flattening join categories, sorting,...).

Whenever speed matters, developers are advised to use this lazy attribute rather than calling super_categories().

Note:  This attribute is likely to eventually become a tuple.  When this happens, we might as well use Category._sort(), if not Category._sort_uniq().

EXAMPLES:

sage: Rings()._super_categories
[Category of rngs, Category of semirings]

__super_categories_for_classes()  

The super categories of this category used for building classes.

This is a close variant of __super_categories() used for constructing the list of the bases for parent_class(), element_class(), and friends. The purpose is ensure that Python will find a proper Method Resolution Order for those classes. For background, see sage.misc.c3_controlled.

See also:  
_cmp_key().

2.2. Categories 35
Note: This attribute is calculated as a by-product of computing \texttt{\_all\_super\_categories()}.  

\textbf{EXAMPLES:}

\begin{verbatim}
sage: Rings()._super_categories_for_classes
[Category of rngs, Category of semirings]
\end{verbatim}

\texttt{\_all\_super\_categories()}

All the super categories of this category, including this category.

Since \texttt{github issue \#11943}, the order of super categories is determined by Python's method resolution order C3 algorithm.

See also:

\texttt{all\_super\_categories()}

Note: this attribute is likely to eventually become a tuple.

Note: this sets \texttt{\_super\_categories\_for\_classes()} as a side effect.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: C = Rings(); C
Category of rings
sage: C._all_super_categories
[Category of rings, Category of rngs, Category of semirings, ...
    Category of monoids, ...
    Category of commutative additive groups, ...
    Category of sets, Category of sets with partial maps,
    Category of objects]
\end{verbatim}

\texttt{\_all\_super\_categories\_proper()}

All the proper super categories of this category.

Since \texttt{github issue \#11943}, the order of super categories is determined by Python's method resolution order C3 algorithm.

See also:

\texttt{all\_super\_categories()}

Note: this attribute is likely to eventually become a tuple.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: C = Rings(); C
Category of rings
sage: C._all_super_categories_proper
[Category of rngs, Category of semirings, ...
    Category of monoids, ...
    Category of commutative additive groups, ...
\end{verbatim}

(continues on next page)
_set_of_super_categories()

The frozen set of all proper super categories of this category.

**Note:** this is used for speeding up category containment tests.

**See also:**

*a ll_super_categories()

**EXAMPLES:**

```sage
sorted(Groups()._set_of_super_categories, key=str)

[Category of inverse unital magmas,
 Category of magmas,
 Category of monoids,
 Category of objects,
 Category of semigroups,
 Category of sets,
 Category of sets with partial maps,
 Category of unital magmas]
```

```sage
sorted(Groups()._set_of_super_categories, key=str)

[Category of inverse unital magmas, Category of magmas, Category of monoids, Category of objects, Category of semigroups, Category of sets, Category of sets with partial maps, Category of unital magmas]
```

_make_named_class*(name, method_provider, cache=False, picklable=True)

Construction of the parent/element/... class of *self*.

**INPUT:**

- *name* – a string; the name of the class as an attribute of *self*. E.g. “parent_class”
- *method_provider* – a string; the name of an attribute of *self* that provides methods for the new class (in addition to those coming from the super categories). E.g. “ParentMethods”
- *cache* – a boolean or *ignore_reduction* (default: False) (passed down to dynamic_class; for internal use only)
- *picklable* – a boolean (default: True)

**ASSUMPTION:**

It is assumed that this method is only called from a lazy attribute whose name coincides with the given *name*.

**OUTPUT:**

A dynamic class with bases given by the corresponding named classes of *self*’s super_categories, and methods taken from the class `getattr(self, method_provider)`.

**Note:**

- In this default implementation, the reduction data of the named class makes it depend on *self*. Since the result is going to be stored in a lazy attribute of *self* anyway, we may as well disable the caching in `dynamic_class` (hence the default value *cache=False*).
• \texttt{CategoryWithParameters} overrides this method so that the same parent/element/\ldots classes can be shared between closely related categories.

• The bases of the named class may also contain the named classes of some indirect super categories, according to \_\texttt{super\_categories\_for\_classes()}. This is to guarantee that Python will build consistent method resolution orders. For background, see \texttt{sage.misc.c3\_controlled}.

See also:

\texttt{CategoryWithParameters\_\_make\_named\_class()}

EXAMPLES:

\begin{verbatim}
sage: PC = Rings().\_make\_named\_class("parent\_class", "ParentMethods"); PC
<class 'sage.categories.rings.Rings.parent\_class'>
sage: type(PC)
<class 'sage.structure.dynamic\_class.DynamicMeta\_class'>
sage: PC.\_\_bases\_
([<class 'sage.categories.rngs.Rngs.parent\_class'>],
 <class 'sage.categories.semirings.Semirings.parent\_class'>)
\end{verbatim}

Note that, by default, the result is not cached:

\begin{verbatim}
sage: PC is Rings().\_make\_named\_class("parent\_class", "ParentMethods")
False
\end{verbatim}

Indeed this method is only meant to construct lazy attributes like \texttt{parent\_class} which already handle this caching:

\begin{verbatim}
sage: Rings().parent\_class
<class 'sage.categories.rings.Rings.parent\_class'>
\end{verbatim}

Reduction for pickling also assumes the existence of this lazy attribute:

\begin{verbatim}
sage: PC.\_\_reduction
(<built-in function get\_attr>, (Category of rings, 'parent\_class'))
sage: loads(dumps(PC)) is Rings().parent\_class
True
\end{verbatim}

\texttt{\_\_repr\_()}  
Return the print representation of this category.

EXAMPLES:

\begin{verbatim}
sage: Sets() # indirect doctest
Category of sets
\end{verbatim}

\texttt{\_\_repr\_object\_names()}  
Return the name of the objects of this category.

EXAMPLES:

\begin{verbatim}
sage: FiniteGroups().\_\_\_repr\_object\_names()
'finite groups'
sage: AlgebrasWithBasis(QQ).\_\_\_repr\_object\_names()
'algebras with basis over Rational Field'
\end{verbatim}
_test_category (**options)

Run generic tests on this category

See also:

TestSuite.

EXAMPLES:

```sage```
Sets()._test_category()
```

Let us now write a couple broken categories:

```sage```
class MyObjects(Category):
    ....:     pass
sage: MyObjects()._test_category()
Traceback (most recent call last):
  ...,
NotImplementedError: <abstract method super_categories at ...>
```

```sage```
class MyObjects(Category):
    ....:     def super_categories(self):
    ....:         return tuple()
sage: MyObjects()._test_category()
Traceback (most recent call last):
  ...,
AssertionError: Category of my objects.super_categories() should return a list
```

```sage```
class MyObjects(Category):
    ....:     def super_categories(self):
    ....:         return []
sage: MyObjects()._test_category()
Traceback (most recent call last):
  ...,
AssertionError: Category of my objects is not a subcategory of Objects()
```

_with_axiom (**axiom**)

Return the subcategory of the objects of self satisfying the given axiom.

INPUT:

- axiom -- a string, the name of an axiom

EXAMPLES:

```sage```
Sets()._with_axiom("Finite")
Category of finite sets
```

```sage```
type(Magmas().Finite().Commutative())
<class 'sage.categories.category.JoinCategory_with_category'>
sage: Magmas().Finite().Commutative().super_categories()
[Category of commutative magmas, Category of finite sets]
sage: C = Algebras(QQ).WithBasis().Commutative()
sage: C is Algebras(QQ).Commutative().WithBasis()
True
```

When axiom is not defined for self, self is returned:

```sage```
Sets()._with_axiom("Associative")
Category of sets
```
**Warning:** This may be changed in the future to raising an error.

**_with_axiom_as_tuple**(axiom)

Return a tuple of categories whose join is `self._with_axiom()`.

**INPUT:**

- axiom — a string, the name of an axiom

This is a lazy version of `_with_axiom()` which is used to avoid recursion loops during join calculations.

**Note:** The order in the result is irrelevant.

**EXAMPLES:**

```
sage: Sets()._with_axiom_as_tuple('Finite')
(Category of finite sets,)
sage: Magmas()._with_axiom_as_tuple('Finite')
(Category of magmas, Category of finite sets)
sage: Rings().Division()._with_axiom_as_tuple('Finite')
(Category of division rings,
Category of finite monoids,
Category of commutative magmas,
Category of finite additive groups)
sage: HopfAlgebras(QQ)._with_axiom_as_tuple('FiniteDimensional')
(Category of Hopf algebras over Rational Field,
Category of finite dimensional vector spaces over Rational Field)
```

**_without_axioms**(named=False)

Return the category without the axioms that have been added to create it.

**INPUT:**

- named — a boolean (default: False)

**Todo:** Improve this explanation.

If named is True, then this stops at the first category that has an explicit name of its own. See `category_with_axiom.CategoryWithAxiom._without_axioms()`.

**EXAMPLES:**

```
sage: Sets()._without_axioms()
Category of sets
sage: Semigroups()._without_axioms()
Category of magmas
sage: Algebras(QQ).Commutative().WithBasis()._without_axioms()
Category of magmatic algebras over Rational Field
sage: Algebras(QQ).Commutative().WithBasis()._without_axioms(named=True)
Category of algebras over Rational Field
```

**static _sort**(categories)

Return the categories after sorting them decreasingly according to their comparison key.
See also: 

_cmp_key()

INPUT:

• categories – a list (or iterable) of non-join categories

OUTPUT:

A sorted tuple of categories, possibly with repeats.

Note: The auxiliary function _flatten_categories used in the test below expects a second argument, which is a type such that instances of that type will be replaced by its super categories. Usually, this type is JoinCategory.

EXAMPLES:

```
sage: Category._sort([Sets(), Objects(), Coalgebras(QQ), Monoids(), Sets().Finite()])
(Category of monoids,
Category of coalgebras over Rational Field,
Category of finite sets,
Category of sets,
Category of objects)
sage: Category._sort([Sets().Finite(), Semigroups().Finite(), Sets().Facade(),
                    Magmas().Commutative()])
(Category of finite semigroups,
Category of commutative magmas,
Category of finite sets,
Category of facade sets)
sage: Category._sort(Category._flatten_categories([Sets().Finite(),
                                                      Algebras(QQ).WithBasis(),
                                                      Semigroups().Finite(),
                                                      Sets().Facade(),
                                                      Algebras(QQ).Commutative(),
                                                      Algebras(QQ).Graded().WithBasis()])
(Category of algebras with basis over Rational Field,
Category of algebras with basis over Rational Field,
Category of graded algebras over Rational Field,
Category of commutative algebras over Rational Field,
Category of finite semigroups,
Category of finite sets,
Category of facade sets)
```

static _sort_uniq(categories)

Return the categories after sorting them and removing redundant categories.

Redundant categories include duplicates and categories which are super categories of other categories in the input.

INPUT:

• categories – a list (or iterable) of categories

OUTPUT: a sorted tuple of mutually incomparable categories

EXAMPLES:
Note that, in the above example, `Monoids()` does not appear in the result because it is a super category of `Rings()`.

```
sage: Category._sort_uniq([Rings(), Monoids(), Coalgebras(QQ)])
(Category of rings, Category of coalgebras over Rational Field)
```

`static __classcall__(^args, **options)`

Input mangling for unique representation.

Let \( C = Cs(...), \) be a category. Since GitHub issue \#12895, the class of \( C \) is a dynamic subclass \( Cs\_with\_category \) of \( Cs \) in order for \( C \) to inherit code from the SubcategoryMethods nested classes of its super categories.

The purpose of this \( \_\_\_\_classcall\_\_\_ \) method is to ensure that reconstructing \( C \) from its class with \( Cs\_with\_category(...) \) actually calls properly \( Cs(...) \) and gives back \( C \).

See also:

```
subcategory_class()
```

EXAMPLES:

```
sage: A = Algebras(QQ)
sage: A.\_\_\_\_class\_\_
<class 'sage.categories.algebras.Algebras\_with\_category'>
sage: A is Algebras(QQ)
True
sage: A is A.\_\_\_\_class\_\_\_(QQ)
True
```

\( __init__() \)

Initialize this category.

EXAMPLES:

```
sage: class SemiprimitiveRings(Category):
....:     def super_categories(self):
....:         return [Rings()]
....:     class ParentMethods:
....:         def jacobson_radical(self):
....:             return self.ideal(0)
sage: C = SemiprimitiveRings()
sage: C
Category of semiprimitive rings
sage: C.\_\_\_\_class\_\_
<class 'main.SemiprimitiveRings\_with\_category'>
```

Note: If the default name of the category (built from the name of the class) is not adequate, please implement \( \_\_\_\_repr\_object\_names() \) to customize it.

Realizations()

Return the category of realizations of the parent \( self \) or of objects of the category \( self \).

INPUT:

- \( self \) – a parent or a concrete category
Note: this function is actually inserted as a method in the class Category (see Realizations()). It is defined here for code locality reasons.

EXAMPLES:

The category of realizations of some algebra:

```sage```
Algebras(QQ).Realizations()
Join of Category of algebras over Rational Field
and Category of realizations of unital magmas
```

The category of realizations of a given algebra:

```sage```
A = Sets().WithRealizations().example(); A
˓→ # needs sage.modules
The subset algebra of {1, 2, 3} over Rational Field
A.Realizations()
˓→ # needs sage.modules
Category of realizations of
The subset algebra of {1, 2, 3} over Rational Field
C = GradedHopfAlgebrasWithBasis(QQ).Realizations(); C
Join of Category of graded Hopf algebras with basis over Rational Field
and Category of realizations of Hopf algebras over Rational Field
C.super_categories()
[Category of graded Hopf algebras with basis over Rational Field,
Category of realizations of Hopf algebras over Rational Field]
TestSuite(C).run()
```

See also:

- `Sets().WithRealizations`
- `ClasscallMetaClass`

Todo: Add an optional argument to allow for:

```sage```
Realizations(A, category=Blahs()) # todo: not implemented
```

**WithRealizations()**

Return the category of parents in self endowed with multiple realizations.

INPUT:

- `self` – a category

See also:

- The documentation and code (`sage.categories.examples.with_realizations`) of `Sets().WithRealizations().example()` for more on how to use and implement a parent with several realizations.
- Various use cases:
  - `SymmetricFunctions`
- QuasiSymmetricFunctions
- NonCommutativeSymmetricFunctions
- SymmetricFunctionsNonCommutingVariables
- DescentAlgebra
- algebras.Moebius
- IwahoriHeckeAlgebra
- ExtendedAffineWeylGroup

- The Implementing Algebraic Structures thematic tutorial.
- sage.categories.realizations

Note: this function is actually inserted as a method in the class Category (see WithRealizations()). It is defined here for code locality reasons.

EXAMPLES:

```python
sage: Sets().WithRealizations()
Category of sets with realizations
```

**Parent with realizations**

Let us now explain the concept of realizations. A parent with realizations is a facade parent (see Sets. Facade) admitting multiple concrete realizations where its elements are represented. Consider for example an algebra $A$ which admits several natural bases:

```python
sage: A = Sets().WithRealizations().example(); A
The subset algebra of {1, 2, 3} over Rational Field
```

For each such basis $B$ one implements a parent $P_B$ which realizes $A$ with its elements represented by expanding them on the basis $B$:

```python
sage: # needs sage.modules
sage: A.F()
The subset algebra of {1, 2, 3} over Rational Field in the Fundamental basis
```

If $B$ and $B'$ are two bases, then the change of basis from $B$ to $B'$ is implemented by a canonical coercion between $P_B$ and $P_{B'}$:

```python
sage: # needs sage.combinat sage.modules
sage: F = A.F(); In = A.In(); Out = A.Out()
sage: i = In.an_element(); i
In[{}] + 2*In[{1}] + 3*In[{2}] + In[{1, 2}]
sage: F(i)
(continues on next page)
allowing for mixed arithmetic:

```
sage: (1 + Out.from_set(1)) * In.from_set(2,3)
```

In our example, there are three realizations:

```
sage: A.realizations()
```

Instead of manually defining the shorthands $F$, $I\!n$, and $O\!ut$, as above one can just do:

```
sage: A.inject_shorthands()
```

### Rationale

Besides some goodies described below, the role of $A$ is threefold:

- To provide, as illustrated above, a single entry point for the algebra as a whole: documentation, access to its properties and different realizations, etc.
- To provide a natural location for the initialization of the bases and the coercions between, and other methods that are common to all bases.
- To let other objects refer to $A$ while allowing elements to be represented in any of the realizations.

We now illustrate this second point by defining the polynomial ring with coefficients in $A$:

```
sage: P = A['x']; P
```

In the following examples, the coefficients turn out to be all represented in the $F$ basis:
sage: P.one()
    # needs sage.modules
F[{}]
sage: (P.an_element() + 1)^2
    # needs sage.modules
F[{}]*x^2 + 2*F[{}]*x + F[{}]

However we can create a polynomial with mixed coefficients, and compute with it:

\[
\text{sage: } p = P([1, In[{}], Out[{}]]); p
    # needs sage.combinat sage.modules
Out[2]*x^2 + In[1]*x + F[{}]
\]
\[
\text{sage: } p^2
    # needs sage.combinat sage.modules
Out[2]*x^4
+ (-8*In[{}] + 4*In[{}]) + 8*In[{}]*x + 4*In[{}]*x^3
+ (F[{}] + 3*F[{}]*x^2 + 2*F[{}]*x + 2*F[{}]*x^2 + 2*F[{}]*x + F[{}])
\]

Note how each coefficient involves a single basis which need not be that of the other coefficients. Which basis is used depends on how coercion happened during mixed arithmetic and needs not be deterministic.

One can easily coerce all coefficient to a given basis with:

\[
\text{sage: } p.map_coefficients(In)
    # needs sage.combinat sage.modules
(-4*In[{}] + 2*In[{}]) + 4*In[{}]*x + 2*In[{}]*x^2 + In[{}]*x + F[{}]
\]

Alas, the natural notation for constructing such polynomials does not yet work:

\[
\text{sage: } In[{}]*x
    # needs sage.combinat sage.modules
Traceback (most recent call last):
...
TypeError: unsupported operand parent(s) for *:
The subset algebra of \{1, 2, 3\} over Rational Field in the In basis
and Univariate Polynomial Ring in x over
The subset algebra of \{1, 2, 3\} over Rational Field
\]

The category of realizations of \(\mathcal{A}\)

The set of all realizations of \(\mathcal{A}\), together with the coercion morphisms is a category (whose class inherits from \texttt{Category_realization_of_parent}):
A itself is in the category of algebras with realizations:

```
sage: A in A.Realizations()
      → # needs sage.modules
      True
```

The (mostly technical) `WithRealizations` categories are the analogs of the *WithSeveralBases* categories in MuPAD-Combinat. They provide support tools for handling the different realizations and the morphisms between them.

Typically, `VectorSpaces(QQ).FiniteDimensional().WithRealizations()` will eventually be in charge, whenever a coercion $\phi: A \rightarrow B$ is registered, to register $\phi^{-1}$ as coercion $B \rightarrow A$ if there is no defined yet. To achieve this, `FiniteDimensionalVectorSpaces` would provide a nested class `WithRealizations` implementing the appropriate logic.

`WithRealizations` is a regressive covariant functorial construction. On our example, this simply means that $A$ is automatically in the category of rings with realizations (covariance):

```
sage: A in Rings().WithRealizations()
      → # needs sage.modules
      True
```

and in the category of algebras (regressiveness):

```
sage: A in Algebras(QQ)
      → # needs sage.modules
      True
```

Note: For $C$ a category, $C.WithRealizations()$ in fact calls `sage.categories.with_realizations.WithRealizations(C)`. The later is responsible for building the hierarchy of the categories with realizations in parallel to that of their base categories, optimizing away those categories that do not provide a `WithRealizations` nested class. See `sage.categories.covariant_functorial_construction` for the technical details.

Note: Design question: currently `WithRealizations` is a regressive construction. That is `self. WithRealizations()` is a subcategory of `self` by default:

```
sage: Algebras(QQ).WithRealizations().super_categories()
[Category of algebras over Rational Field,
 Category of monoids with realizations,
 Category of additive unital additive magmas with realizations]
```

Is this always desirable? For example, `AlgebrasWithBasis(QQ).WithRealizations()` should certainly be a subcategory of `Algebras(QQ)`, but not of `AlgebrasWithBasis(QQ)`. This is because `AlgebrasWithBasis(QQ)` is specifying something about the concrete realization.

```
def additional_structure()
    Return whether `self` defines additional structure.
```

OUTPUT:
• self if self defines additional structure and None otherwise. This default implementation returns self.

A category \( C \) defines additional structure if \( C \)-morphisms shall preserve more structure (e.g. operations) than that specified by the super categories of \( C \). For example, the category of magmas defines additional structure, namely the operation \( * \) that shall be preserved by magma morphisms. On the other hand the category of rings does not define additional structure: a function between two rings that is both a unital magma morphism and a unital additive magma morphism is automatically a ring morphism.

Formally speaking \( C \) defines additional structure, if \( C \) is not a full subcategory of the join of its super categories: the morphisms need to preserve more structure, and thus the homsets are smaller.

By default, a category is considered as defining additional structure, unless it is a category with axiom.

EXAMPLES:

Here are some typical structure categories, with the additional structure they define:

```python
sage: Sets().additional_structure()
Category of sets
sage: Magmas().additional_structure()  # '*'
Category of magmas
sage: AdditiveMagmas().additional_structure()  # '+'
Category of additive magmas
sage: LeftModules(ZZ).additional_structure()  # left multiplication by scalar
Category of left modules over Integer Ring
sage: Coalgebras(QQ).additional_structure()  # coproduct
Category of coalgebras over Rational Field
sage: Crystals().additional_structure()  # crystal operators
Category of crystals
```

On the other hand, the category of semigroups is not a structure category, since its operation \( + \) is already defined by the category of magmas:

```python
sage: Semigroups().additional_structure()
```

Most categories with axiom don’t define additional structure:

```python
sage: Sets().Finite().additional_structure()
sage: Rings().Commutative().additional_structure()
sage: Modules(QQ).FiniteDimensional().additional_structure()
sage: from sage.categories.magmatic_algebras import MagmaticAlgebras
sage: MagmaticAlgebras(QQ).Unital().additional_structure()
```

As of Sage 6.4, the only exceptions are the category of unital magmas or the category of unital additive magmas (both define a unit which shall be preserved by morphisms):

```python
sage: Magmas().Unital().additional_structure()
Category of unital magmas
sage: AdditiveMagmas().AdditiveUnital().additional_structure()
Category of additive unital additive magmas
```

Similarly, functorial construction categories don’t define additional structure, unless the construction is actually defined by their base category. For example, the category of graded modules defines a grading which shall be preserved by morphisms:

```python
sage: Modules(ZZ).Graded().additional_structure()
Category of graded modules over Integer Ring
```
On the other hand, the category of graded algebras does not define additional structure; indeed an algebra morphism which is also a module morphism is a graded algebra morphism:

```
sage: Algebras(ZZ).Graded().additional_structure()
```

Similarly, morphisms are requested to preserve the structure given by the following constructions:

```
sage: Sets().Quotients().additional_structure()
Category of quotients of sets
sage: Sets().CartesianProducts().additional_structure()
Category of Cartesian products of sets
sage: Modules(QQ).TensorProducts().additional_structure()
```

This might change, as we are lacking enough data points to guarantee that this was the correct design decision.

**Note:** In some cases a category defines additional structure, where the structure can be useful to manipulate morphisms but where, in most use cases, we don’t want the morphisms to necessarily preserve it. For example, in the context of finite dimensional vector spaces, having a distinguished basis allows for representing morphisms by matrices; yet considering only morphisms that preserve that distinguished basis would be boring.

In such cases, we might want to eventually have two categories, one where the additional structure is preserved, and one where it’s not necessarily preserved (we would need to find an idiom for this).

At this point, a choice is to be made each time, according to the main use cases. Some of those choices are yet to be settled. For example, should by default:

- an euclidean domain morphism preserve euclidean division?

```
sage: EuclideanDomains().additional_structure()
Category of euclidean domains
```

- an enumerated set morphism preserve the distinguished enumeration?

```
sage: EnumeratedSets().additional_structure()
```

- a module with basis morphism preserve the distinguished basis?

```
sage: Modules(QQ).WithBasis().additional_structure()
```

**See also:**

This method together with the methods overloading it provide the basic data to determine, for a given category, the super categories that define some structure (see `structure()`), and to test whether a category is a full subcategory of some other category (see `is_full_subcategory()`). For example, the category of Coxeter groups is not full subcategory of the category of groups since morphisms need to preserve the distinguished generators:

```
sage: CoxeterGroups().is_full_subcategory(Groups())
False
```

The support for modeling full subcategories has been introduced in github issue #16340.

**all_super_categories** *(proper=False)*

Returns the list of all super categories of this category.

**INPUT:**
• **proper** – a boolean (default: `False`); whether to exclude this category.

Since `github issue #11943`, the order of super categories is determined by Python’s method resolution order C3 algorithm.

**Note:** Whenever speed matters, the developers are advised to use instead the lazy attributes `__all_super_categories()`, `__all_super_categories_proper()`, or `__set_of_super_categories()`, as appropriate. Simply because lazy attributes are much faster than any method.

### EXAMPLES:

```python
sage: C = Rings(); C
Category of rings
sage: C.all_super_categories()
[Category of rings, Category of rngs, Category of semirings, ...
Category of monoids, ...
Category of commutative additive groups, ...
Category of sets, Category of sets with partial maps,
Category of objects]
```

```python
sage: C.all_super_categories(proper = True)
[Category of rngs, Category of semirings, ...
Category of monoids, ...
Category of commutative additive groups, ...
Category of sets, Category of sets with partial maps,
Category of objects]
```

```python
sage: Sets().all_super_categories()
[Category of sets, Category of sets with partial maps, Category of objects]
```

```python
sage: Sets().all_super_categories(proper=True)
[Category of sets with partial maps, Category of objects]
```

```python
sage: Sets().all_super_categories() is Sets()._all_super_categories
True
```

```python
sage: Sets().all_super_categories(proper=True) is Sets()._all_super_categories_proper
True
```

### classmethod `an_instance()`

Return an instance of this class.

### EXAMPLES:

```python
sage: Rings.an_instance()
Category of rings
```

Parametrized categories should overload this default implementation to provide appropriate arguments:

```python
sage: Algebras.an_instance()
Category of algebras over Rational Field
```

```python
sage: Bimodules.an_instance()  
# needs sage.rings.real_mpfr
```

```python
Category of bimodules over Rational Field on the left
and Real Field with 53 bits of precision on the right
```

```python
sage: AlgebraIdeals.an_instance()
Category of algebra ideals
in Univariate Polynomial Ring in x over Rational Field
```
axioms()

Return the axioms known to be satisfied by all the objects of self.

Technically, this is the set of all the axioms $A$ such that, if $Cs$ is the category defining $A$, then self is a subcategory of $Cs().A()$. Any additional axiom $A$ would yield a strict subcategory of self, at the very least self & $Cs().A()$ where $Cs$ is the category defining $A$.

EXAMPLES:

```
sage: Monoids().axioms()
frozenset({'Associative', 'Unital'})
sage: (EnumeratedSets().Infinite() & Sets().Facade()).axioms()
frozenset({'Enumerated', 'Facade', 'Infinite'})
```

category()

Return the category of this category. So far, all categories are in the category of objects.

EXAMPLES:

```
sage: Sets().category()
Category of objects
sage: VectorSpaces(QQ).category()
Category of objects
```

category_graph()

Returns the graph of all super categories of this category

EXAMPLES:

```
sage: C = Algebras(QQ)
sage: G = C.category_graph()
# needs sage.graphs
sage: G.is_directed_acyclic()
# needs sage.graphs
True
```

The girth of a directed acyclic graph is infinite, however, the girth of the underlying undirected graph is 4 in this case:

```
sage: Graph(G).girth()
# needs sage.graphs
4
```

element_class()

A common superclass for all elements of parents in this category (and its subcategories).

This class contains the methods defined in the nested class self.ElementMethods (if it exists), and has as bases the element classes of the super categories of self.

See also:

- `parent_class()`, `morphism_class()`
- `Category` for details

EXAMPLES:
By github issue #11935, some categories share their element classes. For example, the element class of an algebra only depends on the category of the base. A typical example is the category of algebras over a field versus algebras over a non-field:

```python
sage: Algebras(GF(5)).element_class is Algebras(GF(3)).element_class
True
sage: Algebras(QQ).element_class is Algebras(ZZ).element_class
False
sage: Algebras(ZZ['t']).element_class is Algebras(ZZ['t','x']).element_class
True
```

These classes are constructed with `__slots__ = ()`, so instances may not have a `__dict__`:

```python
sage: E = FiniteEnumeratedSets().element_class
sage: E.__dictoffset__
0
```

See also:

`parent_class()`

```
example(*args, **keywords)
```

Returns an object in this category. Most of the time, this is a parent.

This serves three purposes:

- Give a typical example to better explain what the category is all about. (and by the way prove that the category is non empty :-))
- Provide a minimal template for implementing other objects in this category
- Provide an object on which to test generic code implemented by the category

For all those applications, the implementation of the object shall be kept to a strict minimum. The object is therefore not meant to be used for other applications; most of the time a full featured version is available elsewhere in Sage, and should be used instead.

Technical note: by default FooBar(...).example() is constructed by looking up `sage.categories.examples.foo_bar.Example` and calling it as `Example()`. Extra positional or named parameters are also passed down. For a category over base ring, the base ring is further passed down as an optional argument.

Categories are welcome to override this default implementation.

EXAMPLES:

```python
sage: Semigroups().example()
An example of a semigroup: the left zero semigroup
sage: Monoids().Subquotients().example()
NotImplemented
```

`full_super_categories()`

Return the immediate full super categories of `self`.

See also:
• super_categories()
• is_full_subcategory()

**Warning:** The current implementation selects the full subcategories among the immediate super categories of `self`. This assumes that, if \( C \subset B \subset A \) is a chain of categories and \( C \) is a full subcategory of \( A \), then \( C \) is a full subcategory of \( B \) and \( B \) is a full subcategory of \( A \).

This assumption is guaranteed to hold with the current model and implementation of full subcategories in Sage. However, mathematically speaking, this is too restrictive. This indeed prevents the complete modelling of situations where any \( A \) morphism between elements of \( C \) automatically preserves the \( B \) structure. See below for an example.

**EXAMPLES:**

A semigroup morphism between two finite semigroups is a finite semigroup morphism:

```sage
sage: Semigroups().Finite().full_super_categories()
[Category of semigroups]
```

On the other hand, a semigroup morphism between two monoids is not necessarily a monoid morphism (which must map the unit to the unit):

```sage
sage: Monoids().super_categories()
[Category of semigroups, Category of unital magmas]
sage: Monoids().full_super_categories()
[Category of unital magmas]
```

Any semigroup morphism between two groups is automatically a monoid morphism (in a group the unit is the unique idempotent, so it has to be mapped to the unit). Yet, due to the limitation of the model advertised above, Sage currently cannot be taught that the category of groups is a full subcategory of the category of semigroups:

```sage
sage: Groups().full_super_categories()  # todo: not implemented
[Category of monoids, Category of semigroups, Category of inverse unital magmas]
sage: Groups().full_super_categories()
[Category of monoids, Category of inverse unital magmas]
```

**is_abelian()**

Return whether this category is abelian.

An abelian category is a category satisfying:
- It has a zero object;
- It has all pullbacks and pushouts;
- All monomorphisms and epimorphisms are normal.

Equivalently, one can define an increasing sequence of conditions:
- A category is pre-additive if it is enriched over abelian groups (all homsets are abelian groups and composition is bilinear);
- A pre-additive category is additive if every finite set of objects has a biproduct (we can form direct sums and direct products);
- An additive category is pre-abelian if every morphism has both a kernel and a cokernel;
• A pre-abelian category is abelian if every monomorphism is the kernel of some morphism and every epimorphism is the cokernel of some morphism.

EXEMPLARY:

```sage
Modules(ZZ).is_abelian()
True
sage: FreeModules(ZZ).is_abelian()
False
sage: FreeModules(QQ).is_abelian()
True
sage: CommutativeAdditiveGroups().is_abelian()
True
sage: Semigroups().is_abelian()
Traceback (most recent call last):
... NotImplementedError: is_abelian
```

`is_full_subcategory(other)`

Return whether `self` is a full subcategory of `other`.

A subcategory `B` of a category `A` is a full subcategory if any `A`-morphism between two objects of `B` is also a `B`-morphism (the reciprocal always holds: any `B`-morphism between two objects of `B` is an `A`-morphism).

This is computed by testing whether `self` is a subcategory of `other` and whether they have the same structure, as determined by `structure()` from the result of `additional_structure()` on the super categories.

**Warning:** A positive answer is guaranteed to be mathematically correct. A negative answer may mean that Sage has not been taught enough information (or can not yet within the current model) to derive this information. See `full_super_categories()` for a discussion.

**See also:**

• `is_subcategory()`

• `full_super_categories()`

**EXAMPLES:**

```sage
Magmas().Associative().is_full_subcategory(Magmas())
True
sage: Magmas().Unital().is_full_subcategory(Magmas())
False
sage: Rings().is_full_subcategory(Magmas().Unital() & AdditiveMagmas().→AdditiveUnital())
True
```

Here are two typical examples of false negatives:

```sage
Groups().is_full_subcategory(Semigroups())
False
sage: Groups().is_full_subcategory(Semigroups()) # todo: not implemented
True
sage: Fields().is_full_subcategory(Rings())
False
```

(continues on next page)
Todo: The latter is a consequence of `EuclideanDomains` currently being a structure category. Is this what we want?

```sage```
```
EuclideanDomains().is_full_subcategory(Rings())
False
```
```

`is_subcategory(c)`

Returns True if self is naturally embedded as a subcategory of c.

**EXAMPLES:**

```sage```
```
AbGrps = CommutativeAdditiveGroups()
Rings().is_subcategory(AbGrps)
True
AbGrps.is_subcategory(Rings())
False
```
```

The `is_subcategory` function takes into account the base.

```sage```
```
M3 = VectorSpaces(FiniteField(3))
M9 = VectorSpaces(FiniteField(9, 'a'))
# needs sage.rings.finite_rings
M3.is_subcategory(M9)
False
```
```

Join categories are properly handled:

```sage```
```
M3 = VectorSpaces(FiniteField(3))
M9 = VectorSpaces(FiniteField(9, 'a'))
# needs sage.rings.finite_rings
M3.is_subcategory(M9)
False
```
```

**static join:** `static join(categories, as_list=False, ignore_axioms=(), axioms=())`  
Return the join of the input categories in the lattice of categories.

At the level of objects and morphisms, this operation corresponds to intersection: the objects and morphisms of a join category are those that belong to all its super categories.

**INPUT:**
• **categories** – a list (or iterable) of categories
• **as_list** – a boolean (default: False); whether the result should be returned as a list
• **axioms** – a tuple of strings; the names of some supplementary axioms

See also:
`__and__()` for a shortcut

**EXAMPLES:**

```
sage: J = Category.join((Groups(), CommutativeAdditiveMonoids())); J
Join of Category of groups and Category of commutative additive monoids
sage: J.super_categories()
[Category of groups, Category of commutative additive monoids]
sage: J.all_super_categories(proper=True)
[Category of groups, ..., Category of magmas,
 Category of commutative additive monoids, ..., Category of additive magmas,
 Category of sets, ...]
```

As a short hand, one can use:

```
sage: Groups() & CommutativeAdditiveMonoids()
Join of Category of groups and Category of commutative additive monoids
```

This is a commutative and associative operation:

```
sage: Groups() & Posets()
Join of Category of groups and Category of posets
sage: Posets() & Groups()
Join of Category of groups and Category of posets
sage: Groups() & (CommutativeAdditiveMonoids() & Posets())
Join of Category of groups
    and Category of commutative additive monoids
    and Category of posets
sage: (Groups() & CommutativeAdditiveMonoids()) & Posets()
Join of Category of groups
    and Category of commutative additive monoids
    and Category of posets
```

The join of a single category is the category itself:

```
sage: Category.join([Monoids()])
Category of monoids
```

Similarly, the join of several mutually comparable categories is the smallest one:

```
sage: Category.join((Sets(), Rings(), Monoids()))
Category of rings
```

In particular, the unit is the top category `Objects`:

```
sage: Groups() & Objects()
Category of groups
```

If the optional parameter `as_list` is `True`, this returns the super categories of the join as a list, without constructing the join category itself:
sage: Category.join((Groups(), CommutativeAdditiveMonoids()), as_list=True)
[Category of groups, Category of commutative additive monoids]
sage: Category.join((Sets(), Rings(), Monoids()), as_list=True)
[Category of rings]
sage: Category.join((Modules(ZZ), FiniteFields()), as_list=True)
[Category of finite enumerated fields, Category of modules over Integer Ring]
sage: Category.join([], as_list=True)
[]
sage: Category.join([Groups()], as_list=True)
[Category of groups]
sage: Category.join([Groups() & Posets()], as_list=True)
[Category of groups, Category of posets]

Support for axiom categories (TODO: put here meaningful examples):

sage: Sets().Facade() & Sets().Infinite()
Category of facade infinite sets
sage: Magmas().Infinite() & Sets().Facade()
Category of facade infinite magmas
sage: FiniteSets() & Monoids()
Category of finite monoids
sage: Rings().Commutative() & Sets().Finite()
Category of finite commutative rings

Note that several of the above examples are actually join categories; they are just nicely displayed:

sage: AlgebrasWithBasis(QQ) & FiniteSets().Algebras(QQ)
Join of Category of finite dimensional algebras with basis over Rational Field
and Category of finite set algebras over Rational Field
sage: UniqueFactorizationDomains() & Algebras(QQ)
Join of Category of unique factorization domains
and Category of commutative algebras over Rational Field

static meet(categories)

Returns the meet of a list of categories

INPUT:

• categories - a non empty list (or iterable) of categories

See also:

__or__() for a shortcut

EXAMPLES:

sage: Category.meet([Algebras(ZZ), Algebras(QQ), Groups()])
Category of monoids

That meet of an empty list should be a category which is a subcategory of all categories, which does not make practical sense:

sage: Category.meet([])
Traceback (most recent call last):
...
ValueError: The meet of an empty list of categories is not implemented

2.2. Categories
morphism_class()

A common super class for all morphisms between parents in this category (and its subcategories).

This class contains the methods defined in the nested class self.MorphismMethods (if it exists), and has as bases the morphism classes of the super categories of self.

See also:

• parent_class(), element_class()
• Category for details

EXAMPLES:

```
sage: C = Algebras(QQ).morphism_class; C
<class 'sage.categories.algebras.Algebras.morphism_class'>
sage: type(C)
<class 'sage.structure.dynamic_class.DynamicMetaClass'>
```

or_subcategory(category=None, join=False)

Return category or self if category is None.

INPUT:

• category – a sub category of self, tuple/list thereof, or None
• join – a boolean (default: False)

OUTPUT:

• a category

EXAMPLES:

```
sage: Monoids().or_subcategory(Groups())
Category of groups
sage: Monoids().or_subcategory(None)
Category of monoids
```

If category is a list/tuple, then a join category is returned:

```
sage: Monoids().or_subcategory((CommutativeAdditiveMonoids(), Groups()))
Join of Category of groups and Category of commutative additive monoids
```

If join is False, an error if raised if category is not a subcategory of self:

```
sage: Monoids().or_subcategory(EnumeratedSets())
Traceback (most recent call last):
  ...
ValueError: Subcategory of `Category of monoids` required; got `Category of enumerated sets`
```

Otherwise, the two categories are joined together:

```
sage: Monoids().or_subcategory(EnumeratedSets(), join=True)
Category of enumerated monoids
```

parent_class()

A common super class for all parents in this category (and its subcategories).
This class contains the methods defined in the nested class `self.ParentMethods` (if it exists), and has as bases the parent classes of the super categories of `self`.

See also:

- `element_class()`, `morphism_class()`
- `Category` for details

EXAMPLES:

```
sage: C = Algebras(QQ).parent_class; C
<class 'sage.categories.algebras.Algebras.parent_class'>
sage: type(C)
<class 'sage.structure.dynamic_class.DynamicMetaclass'>
```

By github issue #11935, some categories share their parent classes. For example, the parent class of an algebra only depends on the category of the base ring. A typical example is the category of algebras over a finite field versus algebras over a non-field:

```
sage: Algebras(GF(7)).parent_class is Algebras(GF(5)).parent_class
True
sage: Algebras(QQ).parent_class is Algebras(ZZ).parent_class
False
sage: Algebras(ZZ['t']).parent_class is Algebras(ZZ['t','x']).parent_class
True
```

See `CategoryWithParameters` for an abstract base class for categories that depend on parameters, even though the parent and element classes only depend on the parent or element classes of its super categories. It is used in `Bimodules`, `Category_over_base` and `sage.categories.category.JoinCategory`.

**required_methods()**

Returns the methods that are required and optional for parents in this category and their elements.

EXAMPLES:

```
sage: Algebras(QQ).required_methods()
{'element': {'optional': ['_add_'], 'required': ['__bool__']},
 'parent': {'optional': ['algebra_generators'], 'required': ['__contains__']}}
```

**structure()**

Return the structure `self` is endowed with.

This method returns the structure that morphisms in this category shall be preserving. For example, it tells that a ring is a set endowed with a structure of both a unital magma and an additive unital magma which satisfies some further axioms. In other words, a ring morphism is a function that preserves the unital magma and additive unital magma structure.

In practice, this returns the collection of all the super categories of `self` that define some additional structure, as a frozen set.

EXAMPLES:

```
sage: Objects().structure()
frozenset()
sage: def structure(C):
    (continues on next page)
```
In the following example, we only list the smallest structure categories to get a more readable output:

```python
sage: def structure(C):
    ....:     return Category._sort_uniq(C.structure())

sage: structure(Magmas())
(Category of magmas,)

sage: structure(Rings())
(Category of unital magmas, Category of additive unital additive magmas)

sage: structure(Fields())
(Category of euclidean domains,)

sage: structure(Algebras(QQ))
(Category of unital magmas, Category of right modules over Rational Field, Category of left modules over Rational Field)

sage: structure(HopfAlgebras(QQ).Graded().WithBasis().Connected())
(Category of Hopf algebras over Rational Field, Category of graded modules over Rational Field)
```

This method is used in `is_full_subcategory()` for deciding whether a category is a full subcategory of some other category, and for documentation purposes. It is computed recursively from the result of `additional_structure()` on the super categories of `self`. 

**subcategory_class()**

A common superclass for all subcategories of this category (including this one).

This class derives from `Dsubcategory_class` for each super category `D` of `self`, and includes all the methods from the nested class `self.SubcategoryMethods`, if it exists.

See also:

- github issue #12895
- `parent_class()`
- `element_class()`
- `__make_named_class()`

**EXAMPLES:**

```python
sage: cls = Rings().subcategory_class; cls
<class 'sage.categories.rings.Ringssubcategory_class'>
sage: type(cls)
<class 'sage.structure.dynamic_class.DynamicMetaClass'>
```

Rings() is an instance of this class, as well as all its subcategories:

```python
sage: isinstance(Rings(), cls)
True
```
sage: isinstance(AlgebrasWithBasis(QQ), cls)
True

super_categories()

Return the immediate super categories of self.

OUTPUT:

• a duplicate-free list of categories.

Every category should implement this method.

EXAMPLES:

sage: Groups().super_categories()
[Category of monoids, Category of inverse unital magmas]
sage: Objects().super_categories()
[]

Note: Since github issue #10963, the order of the categories in the result is irrelevant. For details, see On the order of super categories.

Note: Whenever speed matters, developers are advised to use the lazy attribute _super_categories() instead of calling this method.

class sage.categories.category.CategoryWithParameters
Bases: Category

A parametrized category whose parent/element classes depend only on its super categories.

Many categories in Sage are parametrized, like C = Algebras(K) which takes a base ring as parameter. In many cases, however, the operations provided by C in the parent class and element class depend only on the super categories of C. For example, the vector space operations are provided if and only if K is a field, since VectorSpaces(K) is a super category of C only in that case. In such cases, and as an optimization (see github issue #11935), we want to use the same parent and element class for all fields. This is the purpose of this abstract class.

Currently, JoinCategory, Category_over_base and Bimodules inherit from this class.

EXAMPLES:

sage: C1 = Algebras(GF(5))
sage: C2 = Algebras(GF(3))
sage: C3 = Algebras(ZZ)
sage: from sage.categories.category import CategoryWithParameters
sage: isinstance(C1, CategoryWithParameters)
True
sage: C1.parent_class is C2.parent_class
True
sage: C1.parent_class is C3.parent_class
False

Category._make_named_class (name, method_provider, cache=False, picklable=True)

Construction of the parent/element/… class of self.
INPUT:

- **name** – a string; the name of the class as an attribute of `self`. E.g. “parent_class”
- **method_provider** – a string; the name of an attribute of `self` that provides methods for the new class (in addition to those coming from the super categories). E.g. “ParentMethods”
- **cache** – a boolean or `ignore_reduction` (default: `False`) (passed down to `dynamic_class`; for internal use only)
- **picklable** – a boolean (default: `True`)

ASSUMPTION:

It is assumed that this method is only called from a lazy attribute whose name coincides with the given `name`.

OUTPUT:

A dynamic class with bases given by the corresponding named classes of `self`’s super categories, and methods taken from the class `getattr(self, method_provider)`.

Note:

- In this default implementation, the reduction data of the named class makes it depend on `self`. Since the result is going to be stored in a lazy attribute of `self` anyway, we may as well disable the caching in `dynamic_class` (hence the default value `cache=False`).
- `CategoryWithParameters` overrides this method so that the same parent/element/… classes can be shared between closely related categories.
- The bases of the named class may also contain the named classes of some indirect super categories, according to `_super_categories_for_classes()`.

See also:

`CategoryWithParameters._make_named_class()`

EXAMPLES:

```python
sage: PC = Rings()._make_named_class("parent_class", "ParentMethods"); PC
<class 'sage.categories.rings.Rings.parent_class'>
sage: type(PC)
<class 'sage.structure.dynamic_class.DynamicMetaClass'>
sage: PC.__bases__
(<class 'sage.categories.rings.Rings.parent_class'>,
 <class 'sage.categories.semirings.Semirings.parent_class'>)
```

Indeed this method is only meant to construct lazy attributes like `parent_class` which already handle this caching:

```python
sage: Rings().parent_class
<class 'sage.categories.rings.Rings.parent_class'>
```

Reduction for pickling also assumes the existence of this lazy attribute:
class sage.categories.category.JoinCategory(super_categories, **kwds)

Bases: CategoryWithParameters

A class for joins of several categories. Do not use directly; see Category.join instead.

EXAMPLES:

sage: from sage.categories.category import JoinCategory
sage: J = JoinCategory((Groups(), CommutativeAdditiveMonoids())); J
Join of Category of groups and Category of commutative additive monoids
sage: J.super_categories()
[Category of groups, Category of commutative additive monoids]

By github issue #11935, join categories and categories over base rings inherit from CategoryWithParameters. This allows for sharing parent and element classes between similar categories. For example, since group algebras belong to a join category and since the underlying implementation is the same for all finite fields, we have:

sage: # needs sage.groups sage.rings.finite_rings
sage: G = SymmetricGroup(10)
sage: A3 = G.algebra(GF(3))
sage: A5 = G.algebra(GF(5))
sage: type(A3.category())
<class 'sage.categories.category.JoinCategory_with_category'>
sage: type(A3) == type(A5)
True

Category._repr_object_names()

Return the name of the objects of this category.

EXAMPLES:

sage: FiniteGroups()._repr_object_names()
'finite groups'
sage: AlgebrasWithBasis(QQ)._repr_object_names()
'algebras with basis over Rational Field'

Category._repr_()

Return the print representation of this category.

EXAMPLES:

sage: Sets() # indirect doctest
Category of sets

Category._without_axioms(named=False)

Return the category without the axioms that have been added to create it.

INPUT:

- named -- a boolean (default: False)
Todo: Improve this explanation.

If named is True, then this stops at the first category that has an explicit name of its own. See `category_with_axiom.CategoryWithAxiom._without_axioms()`

**EXAMPLES:**

```
sage: Sets()._without_axioms()
Category of sets
sage: Semigroups()._without_axioms()
Category of magmas
sage: Algebras(QQ).Commutative().WithBasis()._without_axioms()
Category of magmatic algebras over Rational Field
sage: Algebras(QQ).Commutative().WithBasis()._without_axioms(named=True)
Category of algebras over Rational Field
```

**additional_structure()**

Return None.

Indeed, a join category defines no additional structure.

See also: `Category.additional_structure()`

**EXAMPLES:**

```
sage: Modules(ZZ).additional_structure()
```

**is_subcategory(C)**

Check whether this join category is subcategory of another category C.

**EXAMPLES:**

```
sage: Category.join([Rings(),Modules(QQ)]).is_subcategory(Category.join([Rngs(),Bimodules(QQ,QQ)]))
True
```

**super_categories()**

Returns the immediate super categories, as per `Category.super_categories()`.

**EXAMPLES:**

```
sage: from sage.categories.category import JoinCategory
sage: JoinCategory((Semigroups(), FiniteEnumeratedSets())).super_categories()

[Category of semigroups, Category of finite enumerated sets]
```

**sage.categories.category.category_graph(categories=None)**

Return the graph of the categories in Sage.

**INPUT:**

- categories – a list (or iterable) of categories

If categories is specified, then the graph contains the mentioned categories together with all their super categories. Otherwise the graph contains (an instance of) each category in `sage.categories.all` (e.g. `Algebras(QQ)` for algebras).

For readability, the names of the category are shortened.
Todo: Further remove the base ring (see also github issue #15801).

EXAMPLES:

```python
sage: G = sage.categories.category.category_graph(categories=[Groups()])  # needs sage.graphs
sage: G.vertices(sort=True)  # needs sage.graphs
['groups', 'inverse unital magmas', 'magnas', 'monoids', 'objects', 'semigroups', 'sets', 'sets with partial maps', 'unital magmas']
sage: G.plot()  # needs sage.graphs sage.plot
Graphics object consisting of 20 graphics primitives
sage: sage.categories.category.category_graph().plot()  # needs sage.graphs sage.plot
Graphics object consisting of ... graphics primitives
```

`sage.categories.category.category_sample()`

Return a sample of categories.

It is constructed by looking for all concrete category classes declared in `sage.categories.all`, calling `Category.an_instance()` on those and taking all their super categories.

EXAMPLES:

```python
sage: from sage.categories.category import category_sample
sage: sorted(category_sample(), key=str)  # needs sage.groups
[Category of Coxeter groups, Category of Dedekind domains, Category of G-sets for Symmetric group of order 8! as a permutation group, Category of Hecke modules over Rational Field, Category of Hopf algebras over Rational Field, Category of Hopf algebras with basis over Rational Field, Category of Lie algebras over Rational Field, Category of Weyl groups, Category of abelian varieties over Rational Field, Category of additive magmas, ..., Category of fields, ..., Category of graded Hopf algebras with basis over Rational Field, ..., Category of modular abelian varieties over Rational Field, ..., Category of simplicial complexes, ..., Category of vector spaces over Rational Field, ...]
```

`sage.categories.category.is_Category(x)`

Returns True if x is a category.

EXAMPLES:

```python
sage: sage.categories.category.is_Category(CommutativeAdditiveSemigroups())
True
sage: sage.categories.category.is_Category(ZZ)
False
```
2.3 Axioms

This documentation covers how to implement axioms and proceeds with an overview of the implementation of the axiom infrastructure. It assumes that the reader is familiar with the category primer, and in particular its section about axioms.

2.3.1 Implementing axioms

Simple case involving a single predefined axiom

Suppose that one wants to provide code (and documentation, tests, ...) for the objects of some existing category \( \text{Cs}() \) that satisfy some predefined axiom \( A \).

The first step is to open the hood and check whether there already exists a class implementing the category \( \text{Cs}() \cdot A() \).

For example, taking \( \text{Cs} = \text{Semigroups} \) and the \text{Finite} axiom, there already exists a class for the category of finite semigroups:

```
sage: Semigroups().Finite()
Category of finite semigroups
sage: type(Semigroups().Finite())
<class 'sage.categories.finite_semigroups.FiniteSemigroups_with_category'>
```

In this case, we say that the category of semigroups implements the axiom \text{Finite}, and code about finite semigroups should go in the class \text{FiniteSemigroups} (or, as usual, in its nested classes \text{ParentMethods}, \text{ElementMethods}, and so on).

On the other hand, there is no class for the category of infinite semigroups:

```
sage: Semigroups().Infinite()
Category of infinite semigroups
sage: type(Semigroups().Infinite())
<class 'sage.categories.category.JoinCategory_with_category'>
```

This category is indeed just constructed as the intersection of the categories of semigroups and of infinite sets respectively:

```
sage: Semigroups().Infinite().super_categories()
[Category of semigroups, Category of infinite sets]
```

In this case, one needs to create a new class to implement the axiom \text{Infinite} for this category. This boils down to adding a nested class \text{Semigroups.Infinite} inheriting from \text{CategoryWithAxiom}.

In the following example, we implement a category \text{Cs}, with a subcategory for the objects satisfying the \text{Finite} axiom defined in the super category \text{Sets} (we will see later on how to define new axioms):

```
sage: from sage.categories.category_with_axiom import CategoryWithAxiom
class Cs(Category):
    ....:    def super_categories(self):
    ....:        return [Sets()]
    ....:    class Finite(CategoryWithAxiom):
    ....:        class ParentMethods:
    ....:            def foo(self):
    ....:                print("I am a method on finite C's")
```

```
sage: Cs().Finite()
Category of finite cs
sage: Cs().Finite().super_categories()
(continues on next page)
```
Now a parent declared in the category \texttt{Cs().Finite()} inherits from all the methods of finite sets and of finite \(C\)'s, as desired:

\begin{verbatim}
sage: P = Parent(category=Cs().Finite())
sage: P.is_finite() # Provided by Sets.Finite.ParentMethods
True
sage: P.foo() # Provided by Cs.Finite.ParentMethods
I am a method on finite C's
\end{verbatim}

\textbf{Note:}

- This follows the same idiom as for \textit{Covariant Functorial Constructions}.

- From an object oriented point of view, any subcategory \texttt{Cs()} of \texttt{Sets} inherits a \texttt{Finite} method. Usually \texttt{Cs} could complement this method by overriding it with a method \texttt{Cs.Finite} which would make a super call to \texttt{Sets.Finite} and then do extra stuff.

In the above example, \texttt{Cs} also wants to complement \texttt{Sets.Finite}, though not by doing more stuff, but by providing it with an additional mixin class containing the code for finite \texttt{Cs}. To keep the analogy, this mixin class is to be put in \texttt{Cs.Finite}.

- By defining the axiom \texttt{Finite}, \texttt{Sets} fixes the semantic of \texttt{Cs.Finite()} for all its subcategories \texttt{Cs}: namely “the category of \texttt{Cs} which are finite as sets”. Hence, for example, \texttt{Modules.Free.Finite} cannot be used to model the category of free modules of finite rank, even though their traditional name “finite free modules” might suggest it.

- It may come as a surprise that we can actually use the same name \texttt{Finite} for the mixin class and for the method defining the axiom; indeed, by default a class does not have a binding behavior and would completely override the method. See the section \textit{Defining a new axiom} for details and the rationale behind it.

An alternative would have been to give another name to the mixin class, like \texttt{FiniteCategory}. However this would have resulted in more namespace pollution, whereas using \texttt{Finite} is already clear, explicit, and easier to remember.

- Under the hood, the category \texttt{Cs().Finite()} is aware that it has been constructed from the category \texttt{Cs()} by adding the axiom \texttt{Finite}:

\begin{verbatim}
sage: Cs().Finite().base_category()
Category of cs
sage: Cs().Finite()._axiom
'Finite'
\end{verbatim}

Over time, the nested class \texttt{Cs.Finite} may become large and too cumbersome to keep as a nested subclass of \texttt{Cs}. Or the category with axiom may have a name of its own in the literature, like \textit{semigroups} rather than \textit{associative magmas}, or \textit{fields} rather than \textit{commutative division rings}. In this case, the category with axiom can be put elsewhere, typically in a separate file, with just a link from \texttt{Cs}:

\section*{2.3. Axioms}
sage: class Cs(Category):
    ....:     def super_categories(self):
    ....:         return [Sets()]

sage: class FiniteCs(CategoryWithAxiom):
    ....:     class ParentMethods:
    ....:         def foo(self):
    ....:             print("I am a method on finite C's")

sage: Cs().Finite()  # Category of finite cs

For a real example, see the code of the class FiniteGroups and the link to it in Groups. Note that the link is implemented using LazyImport; this is highly recommended: it makes sure that FiniteGroups is imported after Groups it depends upon, and makes it explicit that the class Groups can be imported and is fully functional without importing FiniteGroups.

Note: Some categories with axioms are created upon Sage’s startup. In such a case, one needs to pass the at_startup=True option to LazyImport, in order to quiet the warning about that lazy import being resolved upon startup. See for example Sets.Finite.

This is undoubtedly a code smell. Nevertheless, it is preferable to stick to lazy imports, first to resolve the import order properly, and more importantly as a reminder that the category would be best not constructed upon Sage’s startup. This is to spur developers to reduce the number of parents (and therefore categories) that are constructed upon startup. Each at_startup=True that will be removed will be a measure of progress in this direction.

Note: In principle, due to a limitation of LazyImport with nested classes (see github issue #15648), one should pass the option as_name to LazyImport:

```python
Finite = LazyImport('sage.categories.finite_groups', 'FiniteGroups', as_name='Finite')
```

in order to prevent Groups.Finite to keep on reimporting FiniteGroups.

Given that passing this option introduces some redundancy and is error prone, the axiom infrastructure includes a little workaround which makes the as_name unnecessary in this case.

Making the category with axiom directly callable

If desired, a category with axiom can be constructed directly through its class rather than through its base category:

```python
sage: Semigroups()
Category of semigroups
sage: Semigroups() is Magmas().Associative()
True

sage: FiniteGroups()
Category of finite groups
sage: FiniteGroups() is Groups().Finite()
True
```

For this notation to work, the class Semigroups needs to be aware of the base category class (here, Magmas) and of the axiom (here, Associative):
In our example, the attribute `_base_category_class_and_axiom` was set upon calling `Cs().Finite()`, which makes the notation seemingly work:

```python
sage: FiniteCs()
Category of finite cs
sage: FiniteCs._base_category_class_and_axiom
(<class '__main__.Cs'>, 'Finite')
```

But calling `FiniteCs()` right after defining the class would have failed (try it!). In general, one needs to set the attribute explicitly:

```python
sage: class FiniteCs(CategoryWithAxiom):
    _base_category_class_and_axiom = (Cs, 'Finite')

sage: def foo(self):
    print("I am a method on finite C's")
```

Having to set explicitly this link back from `FiniteCs` to `Cs` introduces redundancy in the code. It would therefore be desirable to have the infrastructure set the link automatically instead (a difficulty is to achieve this while supporting lazy imported categories with axiom).

As a first step, the link is set automatically upon accessing the class from the base category class:

```python
sage: Algebras.WithBasis._base_category_class_and_axiom
(<class 'sage.categories.algebras.Algebras'>, 'WithBasis')
```

Hence, for whatever this notation is worth, one can currently do:

```python
sage: Algebras.WithBasis(QQ)
Category of algebras with basis over Rational Field
```

We don't recommend using syntax like `Algebras.WithBasis(QQ)`, as it may eventually be deprecated.

As a second step, Sage tries some obvious heuristics to deduce the link from the name of the category with axiom (see `base_category_class_and_axiom()` for the details). This typically covers the following examples:

```python
sage: FiniteCoxeterGroups()
Category of finite Coxeter groups
sage: FiniteCoxeterGroups() is CoxeterGroups().Finite()
True
sage: FiniteCoxeterGroups._base_category_class_and_axiom_origin
'deduced by base_category_class_and_axiom'
```

(continues on next page)
Category of finite dimensional algebras with basis over Rational Field

```
sage: FiniteDimensionalAlgebrasWithBasis(QQ) is Algebras(QQ).FiniteDimensional().WithBasis()
True
```

If the heuristic succeeds, the result is guaranteed to be correct. If it fails, typically because the category has a name of its own like `Fields`, the attribute `_base_category_class_and_axiom` should be set explicitly. For more examples, see the code of the classes `Semigroups` or `Fields`.

**Note:** When printing out a category with axiom, the heuristic determines whether a category has a name of its own by checking out how `_base_category_class_and_axiom` was set:

```
sage: Fields._base_category_class_and_axiom_origin 'hardcoded'
```

See `CategoryWithAxiom._without_axioms()`, `CategoryWithAxiom._repr_object_names_static()`.

In our running example `FiniteCs`, Sage failed to deduce automatically the base category class and axiom because the class `Cs` is not in the standard location `sage.categories.cs`.

**Design discussion**

The above deduction, based on names, is undoubtedly inelegant. But it's safe (either the result is guaranteed to be correct, or an error is raised), it saves on some redundant information, and it is only used for the simple shorthands like `FiniteGroups()` for `Groups().Finite()`. Finally, most if not all of these shorthands are likely to eventually disappear (see github issue #15741 and the related discussion in the primer).

**Defining a new axiom**

We describe now how to define a new axiom. The first step is to figure out the largest category where the axiom makes sense. For example `Sets` for `Finite`, `Magmas` for `Associative`, or `Modules` for `FiniteDimensional`. Here we define the axiom `Green` for the category `Cs` and its subcategories:

```
sage: from sage.categories.category_with_axiom import CategoryWithAxiom
sage: class Cs(Category):
    ....:     def super_categories(self):
    ....:         return [Sets()]
    ....:     class SubcategoryMethods:
    ....:         def Green(self):
    ....:             '<documentation of the axiom Green>'
    ....:             return self._with_axiom("Green")
    ....:     class Green(CategoryWithAxiom):
    ....:         class ParentMethods:
    ....:             def foo(self):
    ....:                 print("I am a method on green C's")
```

With the current implementation, the name of the axiom must also be added to a global container:

```
sage: all_axioms = sage.categories.category_with_axiom.all_axioms
sage: all_axioms += ("Green",)
```
We can now use the axiom as usual:

```
sage: Cs().Green()
Category of green cs
```

```
sage: P = Parent(category=Cs().Green())
sage: P.foo()
I am a method on green C's
```

Compared with our first example, the only newcomer is the method `.Green()` that can be used by any subcategory `Ds()` of `Cs()` to add the axiom `Green`. Note that the expression `Ds().Green` always evaluates to this method, regardless of whether `Ds` has a nested class `Ds.Green` or not (an implementation detail):

```
sage: Cs().Green
<bound method Cs.SubcategoryMethods.Green of Category of cs>
```

Thanks to this feature (implemented in `CategoryWithAxiom.__classget__()`), the user is systematically referred to the documentation of this method when doing introspection on `Ds().Green`:

```
sage: C = Cs()
sage: C.Green?
# not tested
sage: Cs().Green.__doc__
'documentation of the axiom Green'
```

It is therefore the natural spot for the documentation of the axiom.

**Note:** The presence of the nested class `Green` in `Cs` is currently mandatory even if it is empty.

**Todo:** Specify whether or not one should systematically use `@cached_method` in the definition of the axiom. And make sure all the definition of axioms in Sage are consistent in this respect!

**Todo:** We could possibly define an `@axiom` decorator? This could hide two little implementation details: whether or not to make the method a cached method, and the call to `__with_axiom(...)` under the hood. It could do possibly do some more magic. The gain is not obvious though.

**Note:** `all_axioms` is only used marginally, for sanity checks and when trying to derive automatically the base category class. The order of the axioms in this tuple also controls the order in which they appear when printing out categories with axioms (see `CategoryWithAxiom._repr_object_names_static()`).

During a Sage session, new axioms should only be added at the *end* of `all_axioms`, as above, so as to not break the cache of `axioms_rank()`. Otherwise, they can be inserted statically anywhere in the tuple. For axioms defined within the Sage library, the name is best inserted by editing directly the definition of `all_axioms` in `sage.categories.category_with_axiom`.

**Design note**

Let us state again that, unlike what the existence of `all_axioms` might suggest, the definition of an axiom is local to a category and its subcategories. In particular, two independent categories `Cs()` and `Ds()` can very well define axioms with the same name and different semantics. As long as the two hierarchies of subcategories don’t intersect,
this is not a problem. And if they do intersect naturally (that is if one is likely to create a parent belonging to both categories), this probably means that the categories $C_s$ and $D_s$ are about related enough areas of mathematics that one should clear the ambiguity by having either the same semantic or different names.

This caveat is no different from that of name clashes in hierarchy of classes involving multiple inheritance.

**Todo:** Explore ways to get rid of this global `all_axioms` tuple, and/or have automatic registration there, and/or having a `register_axiom(...)` method.

### Special case: defining an axiom depending on several categories

In some cases, the largest category where the axiom makes sense is the intersection of two categories. This is typically the case for axioms specifying compatibility conditions between two otherwise unrelated operations, like `Distributive` which specifies a compatibility between $*$ and $+$. Ideally, we would want the `Distributive` axiom to be defined by:

```sage
Magmas() & AdditiveMagmas()
```

The current infrastructure does not support this perfectly: indeed, defining an axiom for a category $C$ requires $C$ to have a class of its own; hence a `JoinCategory` as above won’t do; we need to implement a new class like `MagmasAndAdditiveMagmas`; furthermore, we cannot yet model the fact that `MagmasAndAdditiveMagmas()` is the intersection of `Magmas()` and `AdditiveMagmas()` rather than a mere subcategory:

```sage
from sage.categories.magmas_and_additive_magmas import MagmasAndAdditiveMagmas
Magmas() & AdditiveMagmas() is MagmasAndAdditiveMagmas()
False

# todo: not implemented

```

Still, there is a workaround to get the natural notations:

```sage
(Magmas() & AdditiveMagmas()).Distributive()
```

The trick is to define `Distributive` as usual in `MagmasAndAdditiveMagmas`, and to add a method `Magmas. SubcategoryMethods.Distributive()` which checks that `self` is a subcategory of both `Magmas()` and `AdditiveMagmas()`, complains if not, and otherwise takes the intersection of `self` with `MagmasAndAdditiveMagmas()` before calling `Distributive`.

The downsides of this workaround are:

- Creation of an otherwise empty class `MagmasAndAdditiveMagmas`.
- Pollution of the namespace of `Magmas()` (and subcategories like `Groups()`) with a method that is irrelevant (but safely complains if called).
- `$C._with_axiom('Distributive')` is not strictly equivalent to `$C.Distributive()`, which can be unpleasantly surprising:

```sage
(Monoids() & CommutativeAdditiveGroups()).Distributive()
```

(continues on next page)
Todo: Other categories that would be better implemented via an axiom depending on a join category include:

- **Algebras**: defining an associative unital algebra as a ring and a module satisfying the suitable compatibility axiom between inner multiplication and multiplication by scalars (bilinearity). Of course this should be implemented at the level of `MagmaticAlgebras`, if not higher.
- **Bialgebras**: defining a bialgebra as an algebra and coalgebra where the coproduct is a morphism for the product.
- **Bimodules**: defining a bimodule as a left and right module where the two actions commute.

Todo:

- Design and implement an idiom for the definition of an axiom by a join category.
- Or support more advanced joins, through some hook or registration process to specify that a given category is the intersection of two (or more) categories.
- Or at least improve the above workaround to avoid the last issue; this possibly could be achieved using a class `Magmas.Distributive` with a bit of `_classcall__magic`.

### Handling multiple axioms, arborescence structure of the code

#### Prelude

Let us consider the category of magmas, together with two of its axioms, namely `Associative` and `Unital`. An associative magma is a *semigroup* and a unital semigroup is a *monoid*. We have also seen that axioms commute:

```
sage: Magmas().Unital()
Category of unital magmas
sage: Magmas().Associative()
Category of semigroups
sage: Magmas().Associative().Unital()
Category of monoids
sage: Magmas().Unital().Associative()
Category of monoids
```

At the level of the classes implementing these categories, the following comes as a general naturalization of the previous section:

```
sage: Magmas.Unital
<class 'sage.categories.magmas.Magmas.Unital'>
sage: Magmas.Associative
<class 'sage.categories.semigroups.Semigroups'>
sage: Magmas.Associative.Unital
<class 'sage.categories.monoids.Monoids'>
```

However, the following may look suspicious at first:
The purpose of this section is to explain the design of the code layout and the rationale for this mismatch.

**Abstract model**

As we have seen in the *Primer*, the objects of a category $\mathsf{Cs}()$ can usually satisfy, or not, many different axioms. Out of all combinations of axioms, only a small number are relevant in practice, in the sense that we actually want to provide features for the objects satisfying these axioms.

Therefore, in the context of the category class $\mathsf{Cs}$, we want to provide the system with a collection $(D_S)_{S \in \mathcal{S}}$ where each $S$ is a subset of the axioms and the corresponding $D_S$ is a class for the subcategory of the objects of $\mathsf{Cs}()$ satisfying the axioms in $S$. For example, if $\mathsf{Cs}()$ is the category of magmas, the pairs $(S, D_S)$ would include:

\[
\begin{align*}
\{\text{Associative}\} & : \text{Semigroups} \\
\{\text{Associative, Unital}\} & : \text{Monoids} \\
\{\text{Associative, Unital, Inverse}\} & : \text{Groups} \\
\{\text{Associative, Commutative}\} & : \text{Commutative Semigroups} \\
\{\text{Unital, Inverse}\} & : \text{Loops}
\end{align*}
\]

Then, given a subset $T$ of axioms, we want the system to be able to select automatically the relevant classes $(D_S)_{S \in \mathcal{S}, S \subseteq T}$ and build from them a category for the objects of $\mathsf{Cs}$ satisfying the axioms in $T$, together with its hierarchy of super categories. If $T$ is in the indexing set $\mathcal{S}$, then the class of the resulting category is directly $D_T$:

```python
sage: C = Magmas().Unital().Inverse().Associative(); C
Category of groups
sage: type(C)
<class 'sage.categories.groups.Groups_with_category'>
```

Otherwise, we get a join category:

```python
sage: C = Magmas().Infinite().Unital().Associative(); C
Category of infinite monoids
sage: type(C)
<class 'sage.categories.category.JoinCategory_with_category'>
```

```python
sage: C.super_categories()
[Category of monoids, Category of infinite sets]
```

**Concrete model as an arborescence of nested classes**

We further want the construction to be efficient and amenable to laziness. This led us to the following design decision: the collection $(D_S)_{S \in \mathcal{S}}$ of classes should be structured as an arborescence (or equivalently a *rooted forest*). The root is $\mathsf{Cs}$, corresponding to $S = \emptyset$. Any other class $D_S$ should be the child of a single class $D_{S'}$ where $S'$ is obtained from $S$ by removing a single axiom $A$. Of course, $D_{S'}$ and $A$ are respectively the base category class and axiom of the category with axiom $D_S$ that we have met in the first section.

At this point, we urge the reader to explore the code of $\mathsf{Magmas}$ and $\mathsf{DistributiveMagmasAndAdditiveMagmas}$ and see how the arborescence structure on the categories with axioms is reflected by the nesting of category classes.
Discussion of the design

Performance

Thanks to the arborescence structure on subsets of axioms, constructing the hierarchy of categories and computing intersections can be made efficient with, roughly speaking, a linear/quadratic complexity in the size of the involved category hierarchy multiplied by the number of axioms (see Section Algorithms). This is to be put in perspective with the manipulation of arbitrary collections of subsets (aka boolean functions) which can easily raise NP-hard problems.

Furthermore, thanks to its locality, the algorithms can be made suitably lazy: in particular, only the involved category classes need to be imported.

Flexibility

This design also brings in quite some flexibility, with the possibility to support features such as defining new axioms depending on other axioms and deduction rules. See below.

Asymmetry

As we have seen at the beginning of this section, this design introduces an asymmetry. It’s not so bad in practice, since in most practical cases, we want to work incrementally. It’s for example more natural to describe \texttt{FiniteFields} as \texttt{Fields} with the axiom \texttt{Finite} rather than \texttt{Magmas} and \texttt{AdditiveMagmas} with all (or at least sufficiently many) of the following axioms:

\begin{verbatim}
sage: sorted(Fields().axioms())
['AdditiveAssociative', 'AdditiveCommutative', 'AdditiveInverse',
 'AdditiveUnital', 'Associative', 'Commutative', 'Distributive',
 'Division', 'NoZeroDivisors', 'Unital']
\end{verbatim}

The main limitation is that the infrastructure currently imposes to be incremental by steps of a single axiom.

In practice, among the roughly 60 categories with axioms that are currently implemented in Sage, most admitted a (rather) natural choice of a base category and single axiom to add. For example, one usually thinks more naturally of a monoid as a semigroup which is unital rather than as a unital magma which is associative. Modeling this asymmetry in the code actually brings a bonus: it is used for printing out categories in a (heuristically) mathematician-friendly way:

\begin{verbatim}
sage: Magmas().Commutative().Associative()
Category of commutative semigroups
\end{verbatim}

Only in a few cases is a choice made that feels mathematically arbitrary. This is essentially in the chain of nested classes \texttt{distributive_magmas_and_additive_magmas.DistributiveMagmasAndAdditiveMagmas.AdditiveAssociative.AdditiveCommutative.AdditiveUnital.Associative}. 

2.3. Axioms
Placeholder classes

Given that we can only add a single axiom at a time when implementing a `CategoryWithAxiom`, we need to create a few category classes that are just placeholders. For the worst example, see the chain of nested classes `distributive_magmas_and_additive_magmas.DistributiveMagmasAndAdditiveMagmas.AdditiveAssociative.AdditiveCommutative.AdditiveUnital.Associative`.

This is suboptimal, but fits within the scope of the axiom infrastructure which is to reduce a potentially exponential number of placeholder category classes to just a couple.

Note also that, in the above example, it's likely that some of the intermediate classes will grow to non-placeholder ones, as people will explore more weaker variants of rings.

Mismatch between the arborescence of nested classes and the hierarchy of categories

The fact that the hierarchy relation between categories is not reflected directly as a relation between the classes may sound suspicious at first! However, as mentioned in the primer, this is actually a big selling point of the axioms infrastructure: by calculating automatically the hierarchy relation between categories with axioms one avoids the nightmare of maintaining it by hand. Instead, only a rather minimal number of links needs to be maintained in the code (one per category with axiom).

Besides, with the flexibility introduced by runtime deduction rules (see below), the hierarchy of categories may depend on the parameters of the categories and not just their class. So it's fine to make it clear from the onset that the two relations do not match.

Evolutivity

At this point, the arborescence structure has to be hardcoded by hand with the annoyances we have seen. This does not preclude, in a future iteration, to design and implement some idiom for categories with axioms that adds several axioms at once to a base category; maybe some variation around:

```python
class DistributiveMagmasAndAdditiveMagmas:
    ...
    @category_with_axiom(
        AdditiveAssociative,
        AdditiveCommutative,
        AdditiveUnital,
        AdditiveInverse,
        Associative)
    def _(): return LazyImport('sage.categories.rngs', 'Rngs', at_startup=True)
```

or:

```python
register_axiom_category(DistributiveMagmasAndAdditiveMagmas,
    {AdditiveAssociative,
    AdditiveCommutative,
    AdditiveUnital,
    AdditiveInverse,
    Associative},
    'sage.categories.rngs', 'Rngs', at_startup=True)
```

The infrastructure would then be in charge of building the appropriate arborescence under the hood. Or rely on some database (see discussion on github issue #10963, in particular at the end of comment 332).
Axioms defined upon other axioms

Sometimes an axiom can only be defined when some other axiom holds. For example, the axiom `NoZeroDivisors` only makes sense if there is a zero, that is if the axiom `AdditiveUnital` holds. Hence, for the category `MagmasAndAdditiveMagmas`, we consider in the abstract model only those subsets of axioms where the presence of `NoZeroDivisors` implies that of `AdditiveUnital`. We also want the axiom to be only available if meaningful:

```python
sage: Rings().NoZeroDivisors()
Category of domains
sage: Rings().Commutative().NoZeroDivisors()
Category of integral domains
sage: Semirings().NoZeroDivisors()
Traceback (most recent call last):
... AttributeError: 'Semirings_with_category' object has no attribute 'NoZeroDivisors'
```

Concretely, this is to be implemented by defining the new axiom in the (SubcategoryMethods nested class of the) appropriate category with axiom. For example the axiom `NoZeroDivisors` would be naturally defined in `magmas_and_additive_magmas.MagmasAndAdditiveMagmas.Distributive.AdditiveUnital`.

**Note:** The axiom `NoZeroDivisors` is currently defined in `Rings`, by simple lack of need for the feature; it should be lifted up as soon as relevant, that is when some code will be available for parents with no zero divisors that are not necessarily rings.

Deduction rules

A similar situation is when an axiom $A$ of a category $Cs$ implies some other axiom $B$, with the same consequence as above on the subsets of axioms appearing in the abstract model. For example, a division ring necessarily has no zero divisors:

```python
sage: 'NoZeroDivisors' in Rings().Division().axioms()
True
sage: 'NoZeroDivisors' in Rings().axioms()
False
```

This deduction rule is implemented by the method `Rings.Division.extra_super_categories()`:

```python
sage: Rings().Division().extra_super_categories()
(Category of domains,)
```

In general, this is to be implemented by a method `Cs.A.extra_super_categories` returning a tuple `(Cs().B(),)`, or preferably `(Ds().B(),)` where $Ds$ is the category defining the axiom $B$.

This follows the same idiom as for deduction rules about functorial constructions (see `covariant Functorial construction.CovariantConstructionCategory.extra_super_categories()`). For example, the fact that a Cartesian product of associative magmas (i.e. semigroups) is an associative magma is implemented in `Semigroups.CartesianProducts.extra_super_categories()`:

```python
sage: Magmas().Associative()
Category of semigroups
sage: Magmas().Associative().CartesianProducts().extra_super_categories()
[Category of semigroups]
```
Similarly, the fact that the algebra of a commutative magma is commutative is implemented in `Magmas.Commutative.Algebras.extra_super_categories()`:

```python
sage: Magmas().Commutative().Algebras(QQ).extra_super_categories()
[Category of commutative magmas]
```

**Warning:** In some situations this idiom is inapplicable as it would require to implement two classes for the same category. This is the purpose of the next section.

## Special case

In the previous examples, the deduction rule only had an influence on the super categories of the category with axiom being constructed. For example, when constructing `Rings().Division().extra_super_categories()` simply adds `Rings().NoZeroDivisors()` as a super category thereof.

In some situations this idiom is inapplicable because a class for the category with axiom under construction already exists elsewhere. Take for example Wedderburn’s theorem: any finite division ring is commutative, i.e. is a finite field. In other words, `DivisionRings().Finite()` coincides with `Fields().Finite()`:

```python
sage: DivisionRings().Finite()
Category of finite enumerated fields
sage: DivisionRings().Finite() is Fields().Finite()
True
```

Therefore we cannot create a class `DivisionRings.Finite` to hold the desired `extra_super_categories` method, because there is already a class for this category with axiom, namely `Fields.Finite`.

A natural idiom would be to have `DivisionRings.Finite` be a link to `Fields.Finite` (locally introducing an undirected cycle in the arborescence of nested classes). It would be a bit tricky to implement though, since one would need to detect, upon constructing `DivisionRings().Finite()`, that `DivisionRings.Finite` is actually `Fields.Finite`, in order to construct appropriately `Fields().Finite()`; and reciprocally, upon computing the super categories of `Fields().Finite()`, to not try to add `DivisionRings().Finite()` as a super category.

Instead the current idiom is to have a method `DivisionRings.Finite_extra_super_categories` which mimics the behavior of the would-be `DivisionRings.Finite.extra_super_categories`:

```python
sage: DivisionRings().Finite_extra_super_categories()
(Category of commutative magmas,)
```

This idiom is admittedly rudimentary, but consistent with how mathematical facts specifying non trivial inclusion relations between categories are implemented elsewhere in the various `extra_super_categories` methods of axiom categories and covariant functorial constructions. Besides, it gives a natural spot (the docstring of the method) to document and test the modeling of the mathematical fact. Finally, Wedderburn’s theorem is arguably a theorem about division rings (in the context of division rings, finiteness implies commutativity) and therefore lives naturally in `DivisionRings`.

An alternative would be to implement the category of finite division rings (i.e. finite fields) in a class `DivisionRings.Finite` rather than `Fields.Finite`:

```python
sage: from sage.categories.category_with_axiom import CategoryWithAxiom
sage: class MyDivisionRings(Category):
....:     def super_categories(self):
....:         return [Rings()]
```

(continues on next page)
In general, if several categories $C_1(s)$, $C_2(s)$, ... are mapped to the same category when applying some axiom $A$ (that is $C_1(s).A() == C_2(s).A() == ...$), then one should be careful to implement this category in a single class $C.A$, and set up methods `extra_super_categories` or `A_extra_super_categories` methods as appropriate. Each such method should return something like `[C2s()]` and not `[C2s().A()]` for the latter would likely lead to an infinite recursion.

**Design discussion**

Supporting similar deduction rules will be an important feature in the future, with quite a few occurrences already implemented in upcoming issues. For the time being though there is a single occurrence of this idiom outside of the tests. So this would be an easy thing to refactor after [github issue #10963](https://github.com) if a better idiom is found.

**Larger synthetic examples**

We now consider some larger synthetic examples to check that the machinery works as expected. Let us start with a category defining a bunch of axioms, using `axiom()` for conciseness (don’t do it for real axioms; they deserve a full documentation):

```python
sage: from sage.categories.category_singleton import Category_singleton
sage: from sage.categories.category_with_axiom import axiom
sage: import sage.categories.category_with_axiom

sage: all_axioms = sage.categories.category_with_axiom.all_axioms

sage: class As(Category_singleton):
....:     def super_categories(self):
....:         return [Objects()]
....:
....:     class SubcategoryMethods:
....:         B = axiom(“B”)
....:         C = axiom(“C”)
....:         D = axiom(“D”)
....:         E = axiom(“E”)
....:         F = axiom(“F”)
....:
....:         class B(CategoryWithAxiom):
```

(continues on next page)
Now we construct a subcategory where, by some theorem of William, axioms $B$ and $C$ together are equivalent to $E$ and $F$ together:

```python
sage: class A1s(Category_singleton):
    ....:     def super_categories(self):
    ....:         return [As()]
    ....:     class B(CategoryWithAxiom):
    ....:         def C_extra_super_categories(self):
    ....:             return [As().E(), As().F()]
    ....:     class E(CategoryWithAxiom):
    ....:         def F_extra_super_categories(self):
    ....:             return [As().B(), As().C()]

sage: A1s().B().C()
Category of e f a1s
```

The axioms $B$ and $C$ do not show up in the name of the obtained category because, for concision, the printing uses some heuristics to not show axioms that are implied by others. But they are satisfied:

```python
sage: sorted(A1s().B().C().axioms())
['B', 'C', 'E', 'F']
```

Note also that this is a join category:

```python
sage: type(A1s().B().C())
<class 'sage.categories.category.JoinCategory_with_category'>
sage: A1s().B().C().super_categories()
[Category of e a1s,
 Category of f as,
 Category of b a1s,
 Category of c as]
```

As desired, William's theorem holds:

```python
sage: A1s().B().C() is A1s().E().F()
True
```

and propagates appropriately to subcategories:

```python
sage: C = A1s().E().F().D().B().C()
sage: C is A1s().B().C().E().F().D()  # commutativity
True
sage: C is A1s().E().F().E().F().D()  # William's theorem
True
```
sage: C is A1s().E().E().F().F().D()  # commutativity
True
sage: C is A1s().E().F().D()  # idempotency
True
sage: C is A1s().D().E().F()

In this quick variant, we actually implement the category of \( b c a_2 s \), and choose to do so in \( A_2 s.B.C \):

```python
sage: class A2s(Category_singleton):
   ....: def super_categories(self):
   ....:     return [As()]
   ....:
   ....: class B(CategoryWithAxiom):
   ....:     class C(CategoryWithAxiom):
   ....:         def extra_super_categories(self):
   ....:             return [As().E(), As().F()]
   ....:
   ....: class E(CategoryWithAxiom):
   ....:     def F_extra_super_categories(self):
   ....:         return [As().B(), As().C()]
   ....:

sage: A2s().B().C()
Category of e f a2s
sage: sorted(A2s().B().C().axioms())
['B', 'C', 'E', 'F']
sage: type(A2s().B().C())
<class '__main__.A2s.B.C_with_category'>
```

As desired, William's theorem and its consequences hold:

```python
sage: A2s().B().C() is A2s().E().F()
True
sage: C = A2s().E().F().D().B().C()
sage: C is A2s().B().C().E().F().D()  # commutativity
True
sage: C is A2s().E().F().E().F().D()  # William's theorem
True
sage: C is A2s().E().E().F().F().D()  # commutativity
True
sage: C is A2s().E().F().D()  # idempotency
True
sage: C is A2s().D().E().F()
True
```

Finally, we “accidentally” implement the category of \( b c a_1 s \), both in \( A_3 s.B.C \) and \( A_3 s.E.F \):

```python
sage: class A3s(Category_singleton):
   ....:     def super_categories(self):
   ....:         return [As()]
   ....:
   ....: class B(CategoryWithAxiom):
   ....:     class C(CategoryWithAxiom):
   ....:         def extra_super_categories(self):
   ....:             return [As().E(), As().F()]
   ....:
   ....:
```

(continues on next page)
We can still construct, say:

```
sage: A3s().B()
Category of b a3s
sage: A3s().C()
Category of c a3s
```

However,

```
sage: A3s().B().C()  # not tested
```

runs into an infinite recursion loop, as `A3s().B().C()` wants to have `A3s().E().F()` as super category and reciprocally.

**Todo:** The above example violates the specifications (a category should be modelled by at most one class), so it’s appropriate that it fails. Yet, the error message could be usefully complemented by some hint at what the source of the problem is (a category implemented in two distinct classes). Leaving a large enough piece of the backtrace would be useful though, so that one can explore where the issue comes from (e.g. with post mortem debugging).

### 2.3.2 Specifications

After fixing some vocabulary, we summarize here some specifications about categories and axioms.

#### The lattice of constructible categories

A mathematical category \( C \) is *implemented* if there is a class in Sage modelling it; it is *constructible* if it is either implemented, or is the intersection of implemented categories; in the latter case it is modelled by a `JoinCategory`. The comparison of two constructible categories with the `Category.is_subcategory()` method is supposed to model the comparison of the corresponding mathematical categories for inclusion of the objects (see *On the category hierarchy: subcategories and super categories* for details). For example:

```
sage: Fields().is_subcategory(Rings())
True
```

However this modelling may be incomplete. It can happen that a mathematical fact implying that a category \( A \) is a subcategory of a category \( B \) is not implemented. Still, the comparison should endow the set of constructible categories with a poset structure and in fact a lattice structure.

In this lattice, the join of two categories (`Category.join()`) is supposed to model their intersection. Given that we compare categories for inclusion, it would be more natural to call this operation the *meet*; blame goes to me (Nicolas) for originally comparing categories by *amount of structure* rather than by *inclusion*. In practice, the join of two categories may be a strict super category of their intersection; first because this intersection might not be constructible; second because Sage might miss some mathematical information to recover the smallest constructible super category of the intersection.
Axioms

We say that an axiom $A$ is defined by a category $Cs()$ if $Cs$ defines an appropriate method $Cs$.SubcategoryMethods.A, with the semantic of the axiom specified in the documentation; for any subcategory $Ds()$.Ds().A() models the subcategory of the objects of $Ds()$ satisfying $A$. In this case, we say that the axiom $A$ is defined for the category $Ds()$. Furthermore, $Ds$ implements the axiom $A$ if $Ds$ has a category with axiom as nested class $Ds.A$. The category $Ds()$ satisfies the axiom if $Ds()$ is a subcategory of $Cs().A()$ (meaning that all the objects of $Ds()$ are known to satisfy the axiom $A$).

A digression on the structure of fibers when adding an axiom

Consider the application $\phi_A$ which maps a category to its category of objects satisfying $A$. Equivalently, $\phi_A$ is computing the intersection with the defining category with axiom of $A$. It follows immediately from the latter that $\phi_A$ is a regressive endomorphism of the lattice of categories. It restricts to a regressive endomorphism $Cs() \rightarrow Cs().A()$ on the lattice of constructible categories.

This endomorphism may have non trivial fibers, as in our favorite example: DivisionRings() and Fields() are in the same fiber for the axiom Finite:

```
sage: DivisionRings().Finite() is Fields().Finite()
True
```

Consider the intersection $S$ of such a fiber of $\phi_A$ with the upper set $I_A$ of categories that do not satisfy $A$. The fiber itself is a sublattice. However $I_A$ is not guaranteed to be stable under intersection (though exceptions should be rare). Therefore, there is a priori no guarantee that $S$ would be stable under intersection. Also it’s presumably finite, in fact small, but this is not guaranteed either.

Specifications

- Any constructible category $C$ should admit a finite number of larger constructible categories.
- The methods super_categories, extra_super_categories, and friends should always return strict supercategories.

For example, to specify that a finite division ring is a finite field, DivisionRings.Finite_extra_super_categories should not return Fields().Finite()! It could possibly return Fields(); but it’s preferable to return the largest category that contains the relevant information, in this case Magmas().Commutative(), and to let the infrastructure apply the derivations.

- The base category of a CategoryWithAxiom should be an implemented category (i.e. not a JoinCategory). This is checked by CategoryWithAxiom._test_category_with_axiom().

- Arboreal structure: Let $Cs()$ be a category, and $S$ be some set of axioms defined in some super categories of $Cs()$ but not satisfied by $Cs()$. Suppose we want to provide a category with axiom for the elements of $Cs()$ satisfying the axioms in $S$. Then, there should be a single enumeration $A_1, A_2, \ldots, A_k$ without repetition of axioms in $S$ such that $Cs.A_1.A_2.\ldots.A_k$ is an implemented category. Furthermore, every intermediate step $Cs.A_1.A_2.\ldots.A_i$ with $i \leq k$ should be a category with axiom having $A_i$ as axiom and $Cs.A_1.A_2.\ldots.A_{i-1}$ as base category class; this base category class should not satisfy $A_i$. In particular, when some axioms of $S$ can be deduced from previous ones by deduction rules, they should not appear in the enumeration $A_1, A_2, \ldots, A_k$.

- In particular, if $Cs()$ is a category that satisfies some axiom $A$ (e.g. from one of its super categories), then it should not implement that axiom. For example, a category class $Cs$ can never have a nested class $Cs.A.A$. Similarly, applying the specification recursively, a category satisfying $A$ cannot have a nested class $Cs.A_1.A_2.A_3.A$ where $A_1, A_2, A_3$ are axioms.
• A category can only implement an axiom if this axiom is defined by some super category. The code has not been systematically checked to support having two super categories defining the same axiom (which should of course have the same semantic). You are welcome to try, at your own risk. :-)

• When a category defines an axiom or functorial construction $A$, this fixes the semantic of $A$ for all the subcategories. In particular, if two categories define $A$, then these categories should be independent, and either the semantic of $A$ should be the same, or there should be no natural intersection between the two hierarchies of subcategories.

• Any super category of a CategoryWithParameters should either be a CategoryWithParameters or a Category_singleton.

• A CategoryWithAxiom having a Category_singleton as base category should be a CategoryWithAxiom_singleton. This is handled automatically by CategoryWithAxiom.__init__() and checked in CategoryWithAxiom._test_category_with_axiom().

• A CategoryWithAxiom having a Category_over_base_ring as base category should be a Category_over_base_ring. This currently has to be handled by hand, using CategoryWithAxiom_over_base_ring._test_category_with_axiom().

Todo: The following specifications would be desirable but are not yet implemented:

• A functorial construction category (Graded, CartesianProducts, ...) having a Category_singleton as base category should be a Category_withAxiom_singleton.

Nothing difficult to implement, but this will need to rework the current “no subclass of a concrete class” assertion test of Category_singleton.__call__().

• Similarly, a covariant functorial construction category having a Category_over_base_ring as base category should be a Category_over_base_ring.

The following specification might be desirable, or not:

• A join category involving a Category_over_base_ring should be a Category_over_base_ring. In the mean time, a base_ring method is automatically provided for most of those by Modules.SubcategoryMethods.base_ring().

2.3.3 Design goals

As pointed out in the primer, the main design goal of the axioms infrastructure is to subdue the potential combinatorial explosion of the category hierarchy by letting the developer focus on implementing a few bookshelves for which there is actual code or mathematical information, and let Sage compose dynamically and lazily these building blocks to construct the minimal hierarchy of classes needed for the computation at hand. This allows for the infrastructure to scale smoothly as bookshelves are added, extended, or reorganized.

Other design goals include:

• Flexibility in the code layout: the category of, say, finite sets can be implemented either within the Sets category (in a nested class Sets.Finite), or in a separate file (typically in a class FiniteSets in a lazily imported module sage.categories.finite_sets).

• Single point of truth: a theorem, like Wedderburn’s, should be implemented in a single spot.

• Single entry point: for example, from the entry Rings, one can explore a whole range of related categories just by applying axioms and constructions:
This will allow for progressively getting rid of all the entries like `GradedHopfAlgebrasWithBasis` which are polluting the global name space.

Note that this is not about precluding the existence of multiple natural ways to construct the same category:

- Concise idioms for the users (adding axioms, …)
- Concise idioms and well highlighted hierarchy of bookshelves for the developer (especially with code folding)
- Introspection friendly (listing the axioms, recovering the mixins)

Note: The constructor for instances of this class takes as input the base category. Hence, they should in principle be constructed as:

```
sage: FiniteSets(Sets())
Category of finite sets
sage: Sets().Finite()
Category of finite sets
```

None of these idioms are really practical for the user. So instead, this object is to be constructed using any of the following idioms:

```
sage: Sets()._with_axiom('Finite')
Category of finite sets
sage: FiniteSets()
Category of finite sets
sage: Sets().Finite()
Category of finite sets
```

The later two are implemented using respectively `CategoryWithAxiom.__classcall__()` and `CategoryWithAxiom.__classget__()`.

### 2.3.4 Upcoming features

Todo:

- Implement compatibility axiom / functorial constructions. For example, one would want to have:

```python
A.CartesianProducts() & B.CartesianProducts() = (A&B).CartesianProducts()
```
Once full subcategories are implemented (see github issue #10668), make the relevant categories with axioms be such. This can be done systematically for, e.g., the axioms Associative or Commutative, but not for the axiom Unital: a semigroup morphism between two monoids need not preserve the unit.

Should all full subcategories be implemented in term of axioms?

### 2.3.5 Algorithms

**Computing joins**

The workhorse of the axiom infrastructure is the algorithm for computing the join $J$ of a set $C_1, \ldots, C_k$ of categories (see `Category.join()`). Formally, $J$ is defined as the largest constructible category such that $J \subset C_i$ for all $i$, and $J \subset C.A()$ for every constructible category $C \supset J$ and any axiom $A$ satisfied by $J$.

The join $J$ is naturally computed as a closure in the lattice of constructible categories: it starts with the $C_i$'s, gathers the set $S$ of all the axioms satisfied by them, and repeatedly adds each axiom $A$ to those categories that do not yet satisfy $A$ using `Category._with_axiom()`. Due to deduction rules or (extra) super categories, new categories or new axioms may appear in the process. The process stops when each remaining category has been combined with each axiom. In practice, only the smallest categories are kept along the way; this is correct because adding an axiom is covariant: $C.A()$ is a subcategory of $D.A()$ whenever $C$ is a subcategory of $D$.

As usual in such closure computations, the result does not depend on the order of execution. Furthermore, given that adding an axiom is an idempotent and regressive operation, the process is guaranteed to stop in a number of steps which is bounded by the number of super categories of $J$. In particular, it is a finite process.

**Todo:** Detail this a bit. What could typically go wrong is a situation where, for some category $C_1$, $C_1.A()$ specifies a category $C_2$ as super category such that $C_2.A()$ specifies $C_3$ as super category such that $\ldots$; this would clearly cause an infinite execution. Note that this situation violates the specifications since $C_1.A()$ is supposed to be a subcategory of $C_2.A(), \ldots$ so we would have an infinite increasing chain of constructible categories.

It’s reasonable to assume that there is a finite number of axioms defined in the code. There remains to use this assumption to argue that any infinite execution of the algorithm would give rise to such an infinite sequence.

**Adding an axiom**

Let $C_s$ be a category and $A$ an axiom defined for this category. To compute $C_s().A()$, there are two cases.

**Adding an axiom $A$ to a category $C_s()$ not implementing it**

In this case, $C_s().A()$ returns the join of:

- $C_s()$
- $B_s().A()$ for every direct super category $B_s()$ of $C_s()$
- the categories appearing in $C_s().A\_extra\_super\_categories$

This is a highly recursive process. In fact, as such, it would run right away into an infinite loop! Indeed, the join of $C_s()$ with $B_s().A()$ would trigger the construction of $C_s().A()$ and reciprocally. To avoid this, the `Category.join()` method itself does not use `Category._with_axiom()` to add axioms, but its sister `Category._with_axiom_as_tuple()`: the latter builds a tuple of categories that should be joined together but leaves the computation of the join to its caller, the master join calculation.
Adding an axiom \( A \) to a category \( \text{Cs}() \) implementing it

In this case \( \text{Cs}().A() \) simply constructs an instance \( D \) of \( \text{Cs}.A \) which models the desired category. The non trivial part is the construction of the super categories of \( D \). Very much like above, this includes:

- \( \text{Cs}() \)
- \( \text{Bs}().A() \) for every super category \( \text{Bs}() \) of \( \text{Cs}() \)
- the categories appearing in \( \text{B}.\text{extra_super_categories}() \)

This by itself may not be sufficient, due in particular to deduction rules. One may for example discover a new axiom \( A_1 \) satisfied by \( D \), imposing to add \( A_1 \) to all of the above categories. Therefore the super categories are computed as the join of the above categories. Up to one twist: as is, the computation of this join would trigger recursively a recalculation of \( \text{Cs}().A() \)! To avoid this, \( \text{Category.join}() \) is given an optional argument to specify that the axiom \( A \) should not be applied to \( \text{Cs}() \).

Sketch of proof of correctness and evaluation of complexity

As we have seen, this is a highly recursive process! In particular, one needs to argue that, as long as the specifications are satisfied, the algorithm won’t run in an infinite recursion, in particular in case of deduction rule.

**Theorem**

Consider the construction of a category \( C \) by adding an axiom to a category (or computing of a join). Let \( H \) be the hierarchy of implemented categories above \( C \). Let \( n \) and \( m \) be respectively the number of categories and the number of inheritance edges in \( H \).

Assuming that the specifications are satisfied, the construction of \( C \) involves constructing the categories in \( H \) exactly once (and no other category), and at most \( n \) join calculations. In particular, the time complexity should be, roughly speaking, bounded by \( n^2 \). In particular, it’s finite.

**Remark**

It’s actually to be expected that the complexity is more of the order of magnitude of \( na + m \), where \( a \) is the number of axioms satisfied by \( C \). But this is to be checked in detail, in particular due to the many category inclusion tests involved.

The key argument is that \( \text{Category.join} \) cannot call itself recursively without going through the construction of some implemented category. In turn, the construction of some implemented category \( C \) only involves constructing strictly smaller categories, and possibly a direct join calculation whose result is strictly smaller than \( C \). This statement is obvious if \( C \) implements the \( \text{super_categories} \) method directly, and easy to check for functorial construction categories. It requires a proof for categories with axioms since there is a recursive join involved.

**Lemma**

Let \( C \) be a category implementing an axiom \( A \). Recall that the construction of \( C.A() \) involves a single direct join calculation for computing the super categories. No other direct join calculation occur, and the calculation involves only implemented categories that are strictly smaller than \( C.A() \).
Proof

Let $D$ be a category involved in the join calculation for the super categories of $C.A()$, and assume by induction that $D$ is strictly smaller than $C.A()$. A category $E$ newly constructed from $D$ can come from:

- $D$.extra_super_categories()
  
  In this case, the specifications impose that $E$ should be strictly smaller than $D$ and therefore strictly smaller than $C$.

- $D$.with_axiom_as_tuple('B') or $D$.B_extra_super_categories() for some axiom $B$
  
  In this case, the axiom $B$ is satisfied by some subcategory of $C.A()$, and therefore must be satisfied by $C.A()$ itself. Since adding an axiom is a regressive construction, $E$ must be a subcategory of $C.A()$. If there is equality, then $E$ and $C.A()$ must have the same class, and therefore, $E$ must be directly constructed as $C.A()$. However the join construction explicitly prevents this call.

Note that a call to $D$.with_axiom_as_tuple('B') does not trigger a direct join calculation; but of course, if $D$ implements $B$, the construction of the implemented category $E = D.B()$ will involve a strictly smaller join calculation.

2.3.6 Conclusion

This is the end of the axioms documentation. Congratulations on having read that far!

2.3.7 Tests

Note: Quite a few categories with axioms are constructed early on during Sage's startup. Therefore, when playing around with the implementation of the axiom infrastructure, it is easy to break Sage. The following sequence of tests is designed to test the infrastructure from the ground up even in a partially broken Sage. Please don't remove the imports!

class sage.categories.category_with_axiom.Bars
    Bases: Category_singleton

    A toy singleton category, for testing purposes.

    See also:

    Blahs

    Unital_extra_super_categories()

    Return extraneous super categories for the unital objects of self.

    This method specifies that a unital bar is a test object. Thus, the categories of unital bars and of unital test objects coincide.

    EXAMPLES:

    sage: from sage.categories.category_with_axiom import Bars, TestObjects
    sage: Bars().Unital_extra_super_categories()
    [Category of test objects]
    sage: Bars().Unital()
    Category of unital test objects
    sage: TestObjects().Unital().all_super_categories()
    [Category of unital test objects,
Category of unital blahs,
Category of test objects,
Category of bars,
Category of blahs,
Category of sets,
Category of sets with partial maps,
Category of objects]

super_categories()

class sage.categories.category_with_axiom.Blahs
Bases: Category_singleton

A toy singleton category, for testing purposes.

This is the root of a hierarchy of mathematically meaningless categories, used for testing Sage's category framework:

• Bars
• TestObjects
• TestObjectsOverBaseRing

Blue_extra_super_categories()

Illustrates a current limitation in the way to have an axiom imply another one.

Here, we would want Blue to imply Unital, and to put the class for the category of unital blue blahs in Blahs.Unital.Blue rather than Blahs.Blue.

This currently fails because Blahs is the category where the axiom Blue is defined, and the specifications currently impose that a category defining an axiom should also implement it (here in a category with axiom Blahs.Blue). In practice, due to this violation of the specifications, the axiom is lost during the join calculation.

Todo: Decide whether we care about this feature. In such a situation, we are not really defining a new axiom, but just defining an axiom as an alias for a couple others, which might not be that useful.

Todo: Improve the infrastructure to detect and report this violation of the specifications, if this is easy. Otherwise, it's not so bad: when defining an axiom A in a category Cs the first thing one is supposed to doctest is that Cs().A() works. So the problem should not go unnoticed.

class Commutative(base_category)
Bases: CategoryWithAxiom
class Connected(base_category)
Bases: CategoryWithAxiom
class FiniteDimensional(base_category)
Bases: CategoryWithAxiom
class Flying(base_category)
Bases: CategoryWithAxiom
This illustrates a way to have an axiom imply another one.

Here, we want Flying to imply Unital, and to put the class for the category of unital flying blahs in Blahs.Flying rather than Blahs.Unital.Flying.

class SubcategoryMethods
    Bases: object
    Blue()
    Commutative()
    Connected()
    FiniteDimensional()
    Flying()
    Unital()

class Unital(base_category)
    Bases: CategoryWithAxiom

class Blue(base_category)
    Bases: CategoryWithAxiom

super_categories()

class sage.categories.category_with_axiom.CategoryWithAxiom(base_category)
    Bases: Category

An abstract class for categories obtained by adding an axiom to a base category.

See the category primer, and in particular its section about axioms for an introduction to axioms, and CategoryWithAxiom for how to implement axioms and the documentation of the axiom infrastructure.

static __classcall__(*args, **options)
    Make FoosBar(**) an alias for Foos(**)._with_axiom("Bar").

EXAMPLES:

sage: FiniteGroups()
Category of finite groups
sage: ModulesWithBasis(ZZ)
Category of modules with basis over Integer Ring
sage: AlgebrasWithBasis(QQ)
Category of algebras with basis over Rational Field

This is relevant when e.g. Foos(**) does some non trivial transformations:

sage: Modules(QQ) is VectorSpaces(QQ)
True
sage: type(Modules(QQ))
<class 'sage.categories.modules_with_basis.ModulesWithBasis_with_category'>

sage: ModulesWithBasis(QQ) is VectorSpaces(QQ).WithBasis()
True
sage: type(ModulesWithBasis(QQ))
<class 'sage.categories.modules_with_basis.ModulesWithBasis_with_category'>
static __classget__(base_category, base_category_class)

Implement the binding behavior for categories with axioms.

This method implements a binding behavior on category with axioms so that, when a category Cs implements an axiom A with a nested class Cs.A, the expression Cs().A evaluates to the method defining the axiom A and not the nested class. See those design notes for the rationale behind this behavior.

EXAMPLES:

```
sage: Sets().Infinite()
Category of infinite sets
```
```
sage: Sets().Infinite
Cached version of <function ...Infinite at ...>
```
```
sage: Sets().Infinite.f == Sets.SubcategoryMethods.Infinite.f
True
```

We check that this also works when the class is implemented in a separate file, and lazy imported:

```
sage: Sets().Finite
Cached version of <function ...Finite at ...>
```

There is no binding behavior when accessing Finite or Infinite from the class of the category instead of the category itself:

```
sage: Sets.Finite
<class 'sage.categories.finite_sets.FiniteSets'>
sage: Sets.Infinite
<class 'sage.categories.sets_cat.Sets.Infinite'>
```

This method also initializes the attribute _base_category_class_and_axiom if not already set:

```
sage: Sets.Infinite._base_category_class_and_axiom
(class 'sage.categories.sets_cat.Sets', 'Infinite')
sage: Sets.Infinite._base_category_class_and_axiom_origin
'set by __classget__'
```

__init__(base_category)

__repr_object_names()

The names of the objects of this category, as used by __repr__.

See also:

Category._repr_object_names()

EXAMPLES:

```
sage: FiniteSets()._repr_object_names()
'finite sets'
sage: AlgebrasWithBasis(QQ).FiniteDimensional()._repr_object_names()
'finite dimensional algebras with basis over Rational Field'
sage: Monoids()._repr_object_names()
'monoids'
sage: Semigroups().Unital().Finite()._repr_object_names()
'finite monoids'
sage: Algebras(QQ).Commutative()._repr_object_names()
'commutative algebras over Rational Field'
```

2.3. Axioms
Note: This is implemented by taking _repr_object_names from self._without_axioms(named=True), and adding the names of the relevant axioms in appropriate order.

```python
static _repr_object_names_static(category, axioms)

INPUT:

- base_category - a category
- axioms - a list or iterable of strings

EXAMPLES:

```sage
def from sage.categories.category_with_axiom import CategoryWithAxiom
def CategoryWithAxiom._repr_object_names_static(base_category, axioms):
    return ['flying blue semigroups']
def CategoryWithAxiom._repr_object_names_static(base_category, axioms):
    return ['flying blue algebras with basis over Rational Field']
def CategoryWithAxiom._repr_object_names_static(base_category, axioms):
    return ['algebras with basis over Rational Field']
def CategoryWithAxiom._repr_object_names_static(base_category, axioms):
    return ['subquotients of finite sets']
def CategoryWithAxiom._repr_object_names_static(base_category, axioms):
    return ['subquotients of finite sets']
def CategoryWithAxiom._repr_object_names_static(base_category, axioms):
    return ['algebras with basis over Univariate Polynomial Ring in y over ...']
```

If the axioms is a set or frozen set, then they are first sorted using canonicalize_axioms():

```sage
def CategoryWithAxiom._repr_object_names_static(base_category, axioms):
    return ['facade finite commutative semigroups']
```

See also:

_repr_object_names()

Note: The logic here is shared between _repr_object_names() and category.JoinCategory._repr_object_names()

__test_category_with_axiom(**options)

Run generic tests on this category with axioms.

See also:

TestSuite.

This check that an axiom category of a Category_singleton is a singleton category, and similarwise for Category_over_base_ring.

EXAMPLES:
sage: Sets().Finite()._test_category_with_axiom()
sage: Modules(ZZ).FiniteDimensional()._test_category_with_axiom()

_without_axioms (named=False)

Return the category without the axioms that have been added to create it.

EXAMPLES:

sage: Sets().Finite()._without_axioms()
Category of sets
sage: Monoids().Finite()._without_axioms()
Category of magmas

This is because:

sage: Semigroups().Unital() is Monoids()
True

If named is True, then _without_axioms stops at the first category that has an explicit name of its own:

sage: Sets().Finite()._without_axioms(named=True)
Category of sets
sage: Monoids().Finite()._without_axioms(named=True)
Category of monoids

Technically we test this by checking if the class specifies explicitly the attribute _base_category_class_and_axiom by looking up _base_category_class_and_axiom_origin.

Some more examples:

sage: Algebras(QQ).Commutative()._without_axioms()
Category of magmatic algebras over Rational Field
sage: Algebras(QQ).Commutative()._without_axioms(named=True)
Category of algebras over Rational Field

additional_structure()

Return the additional structure defined by self.

OUTPUT: None

By default, a category with axiom defines no additional structure.

See also:

Category.additional_structure().

EXAMPLES:

sage: Sets().Finite().additional_structure()
sage: Monoids().additional_structure()

axioms()

Return the axioms known to be satisfied by all the objects of self.

See also:

Category.axioms()

EXAMPLES:
Category Framework, Release 10.3

```python
sage: C = Sets.Finite(); C
Category of finite sets
sage: C.axioms()
frozenset({'Finite'})

sage: C = Modules(GF(5)).FiniteDimensional(); C
Category of finite dimensional vector spaces over Finite Field of size 5
sage: sorted(C.axioms())
['AdditiveAssociative', 'AdditiveCommutative', 'AdditiveInverse', 'AdditiveUnital', 'Finite', 'FiniteDimensional']

sage: sorted(FiniteMonoids().Algebras(QQ).axioms())
['AdditiveAssociative', 'AdditiveCommutative', 'AdditiveInverse', 'AdditiveUnital', 'Associative', 'Distributive', 'FiniteDimensional', 'Unital', 'WithBasis']

sage: sorted(FiniteMonoids().Algebras(GF(3)).axioms())
['AdditiveAssociative', 'AdditiveCommutative', 'AdditiveInverse', 'AdditiveUnital', 'Associative', 'Distributive', 'Finite', 'FiniteDimensional', 'Unital', 'WithBasis']

sage: from sage.categories.mags_and_additive_mags import MagmasAndAdditiveMagmas

sage: D = MagmasAndAdditiveMagmas().Distributive().Unital().axioms()
frozenset({'Distributive', 'Unital'})

sage: X = D.AdditiveAssociative().AdditiveCommutative().Associative()
sage: X.Unital().super_categories()[1]
Category of monoids
sage: X.Unital().super_categories()[1] is Monoids()
True
```

`base_category()`

Return the base category of `self`.

**EXAMPLES:**

```python
sage: C = Sets.Finite(); C
Category of finite sets
sage: C.base_category()
Category of sets
sage: C._without_axioms()
Category of sets
```

`extra_super_categories()`

Return the extra super categories of a category with axiom.

Default implementation which returns `[]`.

**EXAMPLES:**

```python
sage: FiniteSets().extra_super_categories()
[]
```

`super_categories()`

Return a list of the (immediate) super categories of `self`, as per `Category.super_categories()`.

This implements the property that if `As` is a subcategory of `Bs`, then the intersection of `As` with `FiniteSets()` is a subcategory of `As` and of the intersection of `Bs` with `FiniteSets()`.

94 Chapter 2. The Sage Category Framework
EXAMPLES:

A finite magma is both a magma and a finite set:

```
sage: Magmas().Finite().super_categories()
[Category of magmas, Category of finite sets]
```

Variants:

```
sage: Sets().Finite().super_categories()
[Category of sets]
sage: Monoids().Finite().super_categories()
[Category of monoids, Category of finite semigroups]
```

EXAMPLES:

```python
class sage.categories.category_with_axiom.CategoryWithAxiom_over_base_ring(base_category):
    Bases: CategoryWithAxiom, Category_over_base_ring

class sage.categories.category_with_axiom.CategoryWithAxiom_singleton(base_category):
    Bases: Category_singleton, CategoryWithAxiom

class sage.categories.category_with_axiom.TestObjects:
    Bases: Category_singleton

    A toy singleton category, for testing purposes.

    See also:

    Blahs

class Commutative(base_category):
    Bases: CategoryWithAxiom

class Facade(base_category):
    Bases: CategoryWithAxiom

class Finite(base_category):
    Bases: CategoryWithAxiom

class FiniteDimensional(base_category):
    Bases: CategoryWithAxiom

class FiniteDimensional(base_category):
    Bases: CategoryWithAxiom

class Finite(base_category):
    Bases: CategoryWithAxiom

class Unital(base_category):
    Bases: CategoryWithAxiom

class Commutative(base_category):
    Bases: CategoryWithAxiom
```

2.3. Axioms
class Unital (base_category)
    Bases: CategoryWithAxiom
super_categories()

class sage.categories.category_with_axiom.TestObjectsOverBaseRing (base,
    name=None)
    Bases: Category_over_base_ring
A toy singleton category, for testing purposes.
See also:
Blahs

class Commutative (base_category)
    Bases: CategoryWithAxiom_over_base_ring
class Facade (base_category)
    Bases: CategoryWithAxiom_over_base_ring
class Finite (base_category)
    Bases: CategoryWithAxiom_over_base_ring
class FiniteDimensional (base_category)
    Bases: CategoryWithAxiom_over_base_ring
class FiniteDimensional (base_category)
    Bases: CategoryWithAxiom_over_base_ring
class Finite (base_category)
    Bases: CategoryWithAxiom_over_base_ring
class Unital (base_category)
    Bases: CategoryWithAxiom_over_base_ring
class Commutative (base_category)
    Bases: CategoryWithAxiom_over_base_ring
class Unital (base_category)
    Bases: CategoryWithAxiom_over_base_ring
super_categories()
sage.categories.category_with_axiom.axiom(axiom)
Return a function/method self \to self._with_axiom(axiom).
This can used as a shorthand to define axioms, in particular in the tests below. Usually one will want to attach
documentation to an axiom, so the need for such a shorthand in real life might not be that clear, unless we start
creating lots of axioms.
In the long run maybe this could evolve into an \@axiom decorator.
EXAMPLES:

```sage
from sage.categories.category_with_axiom import axiom
axiom("Finite")({Semigroups()})
Category of finite semigroups
```

Upon assigning the result to a class this becomes a method:
sage: class As:
....:     def _with_axiom(self, axiom):
....:         return self, axiom
....:     Finite = axiom("Finite")
sage: As().Finite()
(..., 'Finite')

sage.categories.category_with_axiom.axiom_of_nested_class(nested cls)
Given a class and a nested axiom class, return the axiom.

EXAMPLES:

This uses some heuristics like checking if the nested_cls carries the name of the axiom, or is built by appending or prepping the name of the axiom to that of the class:

sage: from sage.categories.category_with_axiom import TestObjects, axiom_of_nested_class
sage: axiom_of_nested_class(TestObjects, TestObjects.FiniteDimensional)  # 'FiniteDimensional'
sage: axiom_of_nested_class(TestObjects.FiniteDimensional, TestObjects.FiniteDimensional.Finite)  # 'Finite'
sage: axiom_of_nested_class(Sets, FiniteSets)  # 'Finite'
sage: axiom_of_nested_class(Algebras, AlgebrasWithBasis)  # 'WithBasis'

In all other cases, the nested class should provide an attribute _base_category_class_and_axiom:

sage: Semigroups._base_category_class_and_axiom
(<class 'sage.categories.magma.Magmas'>, 'Associative')
sage: axiom_of_nested_class(Magmas, Semigroups)  # 'Associative'

sage.categories.category_with_axiom.base_category_class_and_axiom(cls)
Try to deduce the base category and the axiom from the name of cls.

The heuristic is to try to decompose the name as the concatenation of the name of a category and the name of an axiom, and looking up that category in the standard location (i.e. in `sage.categories.hopf_algebras` for `HopfAlgebras`, and in `sage.categories.sets_cat` as a special case for `Sets`).

If the heuristic succeeds, the result is guaranteed to be correct. Otherwise, an error is raised.

EXAMPLES:

sage: from sage.categories.category_with_axiom import base_category_class_and_axiom
sage: base_category_class_and_axiom(FiniteSets)
(<class 'sage.categories.sets_cat.Sets'>, 'Finite')
sage: base_category_class_and_axiom(Sets.Finite)
(<class 'sage.categories.finite_sets.FiniteSets'>, 'Finite')
sage: base_category_class_and_axiom(FiniteDimensionalHopfAlgebrasWithBasis)
(<class 'sage.categories.hopf_algebras_with_basis.HopfAlgebrasWithBasis'>, 'FiniteDimensional')
sage: base_category_class_and_axiom(HopfAlgebrasWithBasis)
(<class 'sage.categories.hopf_algebras.HopfAlgebras'>, 'WithBasis')
Along the way, this does some sanity checks:

```python
sage: class FacadeSemigroups(CategoryWithAxiom):
    ....:     pass
sage: base_category_class_and_axiom(FacadeSemigroups)
Traceback (most recent call last):
...  
AssertionError: Missing (lazy import) link
for '<class 'sage.categories.semigroups.Semigroups'>'
to '<class '__main__.FacadeSemigroups'> for axiomFacade?
sage: Semigroups.Facade = FacadeSemigroups
sage: base_category_class_and_axiom(FacadeSemigroups)
(<class 'sage.categories.semigroups.Semigroups'>, 'Facade')
```

Note: In the following example, we could possibly retrieve Sets from the class name. However this cannot be implemented robustly until github issue #9107 is fixed. Anyway this feature has not been needed so far:

```python
sage: Sets.Infinite
<class 'sage.categories.sets_cat.Sets.Infinite'>
sage: base_category_class_and_axiom(Sets.Infinite)
Traceback (most recent call last):
...  
TypeError: Could not retrieve the base category class and axiom
for '<class 'sage.categories.sets_cat.Sets.Infinite'>'.
```

```python
sage.categories.category_with_axiom.uncamelcase(s, separator='')
```

**EXAMPLES:**

```python
sage: sage.categories.category_with_axiom.uncamelcase("FiniteDimensionalAlgebras")
'finite dimensional algebras'
sage: sage.categories.category_with_axiom.uncamelcase("JTrivialMonoids")
'j trivial monoids'
sage: sage.categories.category_with_axiom.uncamelcase("FiniteDimensionalAlgebras", 
    ..., 
    "_")
'finite_dimensional_algebras'
```

## 2.4 Functors

**AUTHORS:**

- David Kohel and William Stein
- David Joyner (2005-12-17): examples
- Simon King (2010-04-30): more examples, several bug fixes, re-implementation of the default call method, making functors applicable to morphisms (not only to objects)
- Simon King (2010-12): Pickling of functors without losing domain and codomain

```python
sage.categories.functor.ForgetfulFunctor(domain, codomain)
```

Construct the forgetful function from one category to another.
INPUT:
C, D - two categories

OUTPUT:
A functor that returns the corresponding object of D for any element of C, by forgetting the extra structure.

ASSUMPTION:
The category C must be a sub-category of D.

EXAMPLES:

```
sage: rings = Rings()
sage: abgrps = CommutativeAdditiveGroups()
sage: F = ForgetfulFunctor(rings, abgrps)
sage: F
```
The forgetful functor from Category of rings
to Category of commutative additive groups

It would be a mistake to call it in opposite order:

```
sage: F = ForgetfulFunctor(abgrps, rings)
Traceback (most recent call last):
... ValueError: Forgetful functor not supported for domain Category of commutative additive groups
```

If both categories are equal, the forgetful functor is the same as the identity functor:

```
sage: ForgetfulFunctor(abgrps, abgrps) == IdentityFunctor(abgrps)
True
```

```
class sage.categories.functor.ForgetfulFunctor_generic
    Bases: Functor
    The forgetful functor, i.e., embedding of a subcategory.
    NOTE:
    Forgetful functors should be created using ForgetfulFunctor(), since the init method of this class does not
    check whether the domain is a subcategory of the codomain.
    EXAMPLES:

    sage: F = ForgetfulFunctor(FiniteFields(), Fields())  # indirect doctest
    sage: F
    The forgetful functor
    from Category of finite enumerated fields
to Category of fields
    sage: F(GF(3))
    Finite Field of size 3
```

```
class sage.categories.functor.Functor
    Bases: SageObject
    A class for functors between two categories
    NOTE:
    • In the first place, a functor is given by its domain and codomain, which are both categories.
```

2.4. Functors
- When defining a sub-class, the user should not implement a call method. Instead, one should implement three methods, which are composed in the default call method:

  - `_coerce_into_domain(self, x)`: Return an object of `self`'s domain, corresponding to `x`, or raise a `TypeError`.
    - Default: Raise `TypeError` if `x` is not in `self`'s domain.
  - `_apply_functor(self, x)`: Apply `self` to an object `x` of `self`'s domain.
    - Default: Conversion into `self`'s codomain.
  - `_apply_functor_to_morphism(self, f)`: Apply `self` to a morphism `f` in `self`'s domain.
    - Default: Return `self(f.domain()) . hom(f, self(f.codomain()))`.

**EXAMPLES:**

```python
sage: rings = Rings()
sage: abgrps = CommutativeAdditiveGroups()
sage: F = ForgetfulFunctor(rings, abgrps)
sage: F.domain()
Category of rings
sage: F.codomain()
Category of commutative additive groups
sage: from sage.categories.functor import is_Functor
sage: is_Functor(F)
True
sage: I = IdentityFunctor(abgrps)
sage: I
The identity functor on Category of commutative additive groups
sage: I.domain()
Category of commutative additive groups
sage: is_Functor(I)
True
```

Note that by default, an instance of the class `Functor` is coercion from the domain into the codomain. The above subclasses overloaded this behaviour. Here we illustrate the default:

```python
sage: from sage.categories.functor import Functor
sage: F = Functor(Rings(), Fields())
sage: F
Functor from Category of rings to Category of fields
sage: F(ZZ)
Rational Field
sage: F(GF(2))
Finite Field of size 2
```

Functors are not only about the objects of a category, but also about their morphisms. We illustrate it, again, with the coercion functor from rings to fields.

```python
sage: R1.<x> = ZZ[]
sage: R2.<a,b> = QQ[]
sage: f = R1.hom([a + b], R2)
sage: f
Ring morphism:
  From: Univariate Polynomial Ring in x over Integer Ring
  To:   Multivariate Polynomial Ring in a, b over Rational Field
  Defn: x |--> a + b
sage: f
Ring morphism:
  From: Univariate Polynomial Ring in x over Integer Ring
  To:   Multivariate Polynomial Ring in a, b over Rational Field
  Defn: x |--> a + b
```

(continues on next page)
We can also apply a polynomial ring construction functor to our homomorphism. The result is a homomorphism that is defined on the base ring:

```sage```
F = QQ['t'].construction()[0]
F
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
```
sage: rings = Rings()
sage: F = IdentityFunctor(rings)
sage: F(ZZ['x','y']) is ZZ['x','y']
True
```

```python
class sage.categories.functor.IdentityFunctor_generic(C)
    Bases: ForgetfulFunctor_generic
    Generic identity functor on any category
    NOTE:
    This usually is created using IdentityFunctor().
    EXAMPLES:

    sage: F = IdentityFunctor(Fields()) # indirect doctest
    sage: F
    The identity functor on Category of fields
    sage: F(RR) is RR
    True
    sage: F(ZZ)
    Traceback (most recent call last):
    ...:
    TypeError: x (=Integer Ring) is not in Category of fields
```

```
sage.categories.functor.is_Functor(x)
    Test whether the argument is a functor
    NOTE:
    There is a deprecation warning when using it from top level. Therefore we import it in our doctest.
    EXAMPLES:

    sage: from sage.categories.functor import is_Functor
    sage: F1 = QQ.construction()[0]
    sage: F1
    FractionField
    sage: is_Functor(F1)
    True
    sage: is_Functor(FractionField)
    False
    sage: F2 = ForgetfulFunctor(Fields(), Rings())
    sage: F2
    The forgetful functor from Category of fields to Category of rings
    sage: is_Functor(F2)
    True
```
2.5 Implementing a new parent: a tutorial

The easiest approach for implementing a new parent is to start from a close example in sage.categories.examples. Here, we will get through the process of implementing a new finite semigroup, taking as starting point the provided example:

```
sage: S = FiniteSemigroups().example()
sage: S
An example of a finite semigroup: the left regular band generated by ('a', 'b', 'c', 'd')
```

You may lookup the implementation of this example with:

```
sage: S

# not tested
```

Or by browsing the source code of `sage.categories.examples.finite_semigroups.LeftRegularBand`.

Copy-paste this code into, say, a cell of the notebook, and replace every occurrence of `FiniteSemigroups().example(...)` in the documentation by `LeftRegularBand`. This will be equivalent to:

```
sage: from sage.categories.examples.finite_semigroups import LeftRegularBand
```

Now, try:

```
sage: S = LeftRegularBand(); S
An example of a finite semigroup: the left regular band generated by ('a', 'b', 'c', 'd')
```

and play around with the examples in the documentation of `S` and of `FiniteSemigroups`.

Rename the class to `ShiftSemigroup`, and modify the product to implement the semigroup generated by the given alphabet such that `a u = u` for any `u` of length 3.

Use `TestSuite` to test the newly implemented semigroup; draw its Cayley graph.

Add another option to the constructor to generalize the construction to any `u` of length `k`.

Look up the Sloane for the sequence of the sizes of those semigroups.

Now implement the commutative monoid of subsets of `{1, ..., n}` endowed with union as product. What is its category? What are the extra functionalities available there? Implement iteration and cardinality.

**Todo:** The tutorial should explain there how to reuse the enumerated set of subsets, and endow it with more structure.
3.1 Base class for maps

AUTHORS:

- Robert Bradshaw: initial implementation
- Sebastien Besnier (2014-05-5): FormalCompositeMap contains a list of Map instead of only two Map. See github issue #16291.

class sage.categories.map.FormalCompositeMap

Bases: Map

Formal composite maps.

A formal composite map is formed by two maps, so that the codomain of the first map is contained in the domain of the second map.

Note: When calling a composite with additional arguments, these arguments are only passed to the second underlying map.

EXAMPLES:

```sage
code
```
From: Univariate Polynomial Ring in x over Rational Field
To: Univariate Polynomial Ring in x over Rational Field
Defn: Generic morphism:
  From: Univariate Polynomial Ring in x over Rational Field
  To: Univariate Polynomial Ring in a over Rational Field
  then
  Ring morphism:
  From: Univariate Polynomial Ring in a over Rational Field
  To: Univariate Polynomial Ring in x over Rational Field
  Defn: a |--> 2*x
sage: (f*g)(2*a^2+5)
5*a^2
sage: (g*f)(2*x^2+5)
20*x^2

domains()
Iterate over the domains of the factors of this map.
(This is useful in particular to check for loops in coercion maps.)

See also:
Map.domains()

EXAMPLES:

sage: f = QQ.coerce_map_from(ZZ)
sage: g = MatrixSpace(QQ, 2, 2).coerce_map_from(QQ)
#← needs sage.modules
sage: list((g * f).domains())
[Integer Ring, Rational Field]

first()
Return the first map in the formal composition.
If self represents \( f_n \circ f_{n-1} \circ \cdots \circ f_1 \circ f_0 \), then self.first() returns \( f_0 \). We have self == self.then() * self.first().

EXAMPLES:

sage: R.<x> = QQ[]
sage: S.<a> = QQ[]
sage: from sage.categories.morphism import SetMorphism
sage: f = SetMorphism(Hom(R, S, Rings()), lambda p: p[0]*a^p.degree())
sage: g = S.hom([2*x])
sage: fg = f * g
sage: fg.first() == g
True
sage: fg == fg.then() * fg.first()
True

is_injective()
Tell whether self is injective.
It raises \( \text{NotImplementedError} \) if it cannot be determined.

EXAMPLES:
If both constituents are injective, the composition is injective:

```
sage: from sage.categories.map import FormalCompositeMap
sage: c1 = FormalCompositeMap(Hom(QQ^1, V2, phi1.category_for()), phi1, phi2)
```

```
sage: c1.is_injective()  # needs sage.modules
True
```

If it cannot be determined whether the composition is injective, an error is raised:

```
sage: psi1 = V2.hom(Matrix([[1, 2], [3, 4], [5, 6]]), V1)
```

```
sage: c2 = FormalCompositeMap(Hom(V1, V1, phi2.category_for()), phi2, psi1)
sage: c2.is_injective()  # needs sage.modules
Traceback (most recent call last):...
NotImplementedError: not enough information to deduce injectivity
```

If the first map is surjective and the second map is not injective, then the composition is not injective:

```
sage: psi2 = V1.hom([[1], [1]], QQ^1)
```

```
sage: c3 = FormalCompositeMap(Hom(V2, QQ^1, phi2.category_for()), psi2, psi1)
```

```
sage: c3.is_injective()  # needs sage.modules
False
```

`is_surjective()`

Tell whether self is surjective.

It raises `NotImplementedError` if it cannot be determined.

EXAMPLES:
sage: # needs sage.modules
sage: phi32 = V3.hom(Matrix(
        [[1, 2],
         [3, 4],
         [5, 6]]), V2)
sage: phi21 = V2.hom(Matrix(
        [[1],
         [1]]), V1)
sage: c_phi = FormalCompositeMap(Hom(V3, V1, phi32.category_for()), phi32, phi21)
sage: c_phi.is_surjective()
True

If the second map is not surjective, the composition is not surjective:

sage: FormalCompositeMap(Hom(V3, V1, phi32.category_for()), phi32, phi21).is_surjective()
False

If the second map is an isomorphism and the first map is not surjective, then the composition is not surjective:

sage: FormalCompositeMap(Hom(V2, V1, phi32.category_for()), V2.hom(Matrix(
        [[0],
         [0]]), V1), V1.hom(Matrix(
        [[1]], V1)).is_surjective()
False

Otherwise, surjectivity of the composition cannot be determined:

sage: FormalCompositeMap(Hom(V2, V1, phi32.category_for()), V2.hom(Matrix(
        [[1, 1],
         [1, 1]]), V2), V2.hom(Matrix(
        [[1],
         [1]]), V1)).is_surjective()
Traceback (most recent call last):
  ... Not ImplementedError: not enough information to deduce surjectivity

section()

Compute a section map from sections of the factors of self if they have been implemented.

EXAMPLES:

sage: P.<x> = QQ[]
sage: incl = P.coerce_map_from(ZZ)
sage: sect = incl.section(); sect
Composite map:
    From: Univariate Polynomial Ring in x over Rational Field
    To: Integer Ring
    Defn: Generic map:
          From: Univariate Polynomial Ring in x over Rational Field
          To: Rational Field
          then
          Generic map:
          From: Rational Field
          To: Integer Ring
sage: sect(p-q)
3

the following example has been attached to _integer_() of sage.rings.polynomial.polynomial_element.Polynomial before (see comment there):
sage: k = GF(47)
sage: R.<x> = PolynomialRing(k)
sage: R.coerce_map_from(ZZ).section()

Composite map:
  From: Univariate Polynomial Ring in x over Finite Field of size 47
  To:   Integer Ring
  Defn:  Generic map:
  From: Univariate Polynomial Ring in x over Finite Field of size 47
  To:   Finite Field of size 47
    then
    Lifting map:
    From: Finite Field of size 47
    To:   Integer Ring
sage: ZZ(R(45))  # indirect doctest
45
sage: ZZ(3*x + 45)  # indirect doctest
Traceback (most recent call last):
  ...TypeError: not a constant polynomial

then()

Return the tail of the list of maps.

If self represents \( f_n \circ f_{n-1} \circ \cdots \circ f_1 \circ f_0 \), then self.first() returns \( f_n \circ f_{n-1} \circ \cdots \circ f_1 \). We have self == self.then() * self.first().

EXAMPLES:

sage: R.<x> = QQ[]
sage: S.<a> = QQ[]
sage: from sage.categories.morphism import SetMorphism
sage: f = SetMorphism(Hom(R, S, Rings()), lambda p: p[0]*a^p.degree())
sage: g = S.hom([2*x])

(f*g).then() == f
True

sage: f = QQ.coerce_map_from(ZZ)
sage: f = f.extend_domain(ZZ).extend_codomain(QQ)
sage: f.then()

Composite map:
  From: Integer Ring
  To:   Rational Field
  Defn:  Natural morphism:
  From: Integer Ring
  To:   Rational Field
  then
  Identity endomorphism of Rational Field

class sage.categories.map.Map

Bases: Element

Basic class for all maps.

Note: The call method is of course not implemented in this base class. This must be done in the sub classes, by overloading _call_ and possibly also _call_with_args.

EXAMPLES:

3.1. Base class for maps
Usually, instances of this class will not be constructed directly, but for example like this:

```
sage: from sage.categories.morphism import SetMorphism
sage: X.<x> = ZZ
sage: Y = ZZ
sage: phi = SetMorphism(Hom(X, Y, Rings()), lambda p: p[0])
sage: phi(x^2+2*x-1)
-1
sage: R.<x,y> = QQ
sage: f = R.hom([x+y, x-y], R)
sage: f(x^2+2*x-1)
x^2 + 2*x*y + y^2 + 2*x + 2*y - 1
```

category_for()

Returns the category self is a morphism for.

**Note:** This is different from the category of maps to which this map belongs as an object.

**EXAMPLES:**

```
sage: from sage.categories.morphism import SetMorphism
sage: X.<x> = ZZ
sage: Y = ZZ
sage: phi = SetMorphism(Hom(X, Y, Rings()), lambda p: p[0])
sage: phi.category_for()
Category of rings
sage: phi.category()
Category of homsets of unital magmas and additive unital additive magmas
sage: R.<x,y> = QQ
sage: f = R.hom([x+y, x-y], R)
sage: f.category_for()
Join of Category of unique factorization domains and Category of commutative algebras and Category of infinite sets
sage: f.category()
Category of endsets of unital magmas and right modules over (number fields and quotient fields and metric spaces) and left modules over (number fields and quotient fields and metric spaces)
```

FIXME: find a better name for this method

codomain
domain
domains()

Iterate over the domains of the factors of a (composite) map.

This default implementation simply yields the domain of this map.

See also:

* FormalCompositeMap.domains()

**EXAMPLES:**
extend_codomain(new_codomain)

**INPUT:**
- `self` — a member of Hom(X, Y)
- `new_codomain` — an object Z such that there is a canonical coercion \( \phi \) in Hom(Y, Z)

**OUTPUT:**
An element of Hom(X, Z) obtained by composing self with \( \phi \). If no canonical \( \phi \) exists, a `TypeError` is raised.

**EXAMPLES:**

```python
sage: mor = QQ.coerce_map_from(ZZ)
sage: mor.extend_codomain(RDF)
Composite map:
  From: Integer Ring
  To:  Real Double Field
  Defn: Natural morphism:
    From: Integer Ring
    To:  Rational Field
    then
    Native morphism:
    From: Rational Field
    To:  Real Double Field

sage: mor.extend_codomain(GF(7))
Traceback (most recent call last):
  ...TypeError: No coercion from Rational Field to Finite Field of size 7
```

extend_domain(new_domain)

**INPUT:**
- `self` — a member of Hom(Y, Z)
- `new_domain` — an object X such that there is a canonical coercion \( \phi \) in Hom(X, Y)

**OUTPUT:**
An element of Hom(X, Z) obtained by composing self with \( \phi \). If no canonical \( \phi \) exists, a `TypeError` is raised.

**EXAMPLES:**

```python
sage: # needs sage.rings.complex_double
sage: mor = CDF.coerce_map_from(RDF)
sage: mor.extend_domain(QQ)
Composite map:
  From: Rational Field
  To:  Complex Double Field
  Defn: Native morphism:
    From: Rational Field
    To:  Real Double Field
    then
    Native morphism:
    From: Real Double Field
    To:  Complex Double Field
```

(continues on next page)
To: Complex Double Field

```
sage: mor.extend_domain(ZZ['x'])
Traceback (most recent call last):
...
TypeError: No coercion from Univariate Polynomial Ring in x over Integer Ring to Real Double Field
```

is_surjective()

Tells whether the map is surjective (not implemented in the base class).

parent()

Return the homset containing this map.

**Note:** The method `_make_weak_references()`, that is used for the maps found by the coercion system, needs to remove the usual strong reference from the coercion map to the homset containing it. As long as the user keeps strong references to domain and codomain of the map, we will be able to reconstruct the homset. However, a strong reference to the coercion map does not prevent the domain from garbage collection!

**EXAMPLES:**

```
sage: Q = QuadraticField(-5)  # needs sage.rings.number_field
    #˓→ needs sage.rings.number_field
sage: phi = CDF._internal_convert_map_from(Q)  # needs sage.rings.number_field
    #˓→ needs sage.rings.number_field
sage: print(phi.parent())  #˓→ needs sage.rings.number_field
Set of field embeddings from Number Field in a with defining polynomial x^2 + 5
    with a = 2.236067977499790?*I
to Complex Double Field
```

We now demonstrate that the reference to the coercion map \(\phi\) does not prevent \(Q\) from being garbage collected:

```
sage: import gc
sage: del Q  # needs sage.rings.number_field
    #˓→ needs sage.rings.number_field
sage: _ = gc.collect()
sage: phi.parent()  #˓→ needs sage.rings.number_field
Traceback (most recent call last):
...
ValueError: This map is in an invalid state, the domain has been garbage collected
```

You can still obtain copies of the maps used by the coercion system with strong references:

```
sage: # needs sage.rings.number_field
sage: Q = QuadraticField(-5)
sage: phi = CDF.convert_map_from(Q)
sage: print(phi.parent())
Set of field embeddings from Number Field in a with defining polynomial x^2 + 5
```
with \( a = 2.236067977499790?I \) to Complex Double Field

```python
sage: import gc
sage: del Q
sage: _ = gc.collect()
```

```python
sage: phi.parent()
```

Set of field embeddings

from Number Field in \( a \) with defining polynomial \( x^2 + 5 \)

with \( a = 2.236067977499790?I \) to Complex Double Field

```
post_compose(left)
```

**INPUT:**

- `self` – a Map in some \( \text{Hom}(X, Y, \text{category}\_\text{right}) \)
- `left` – a Map in some \( \text{Hom}(Y, Z, \text{category}\_\text{left}) \)

Returns the composition of `self` followed by `left` as a morphism in \( \text{Hom}(X, Z, \text{category}) \) where `category` is the meet of `category\_left` and `category\_right`.

Caveat: see the current restrictions on `Category.meet()`

**EXAMPLES:**

```python
sage: from sage.categories.morphism import SetMorphism
sage: X.<x> = ZZ[]
```

```python
sage: Y = ZZ
sage: Z = QQ
```

```python
sage: phi\_xy = SetMorphism(Hom(X, Y, Rings()), lambda p: p[0])
```

```python
sage: phi\_yz = SetMorphism(Hom(Y, Z, Monoids()), lambda y: QQ(y**2))
```

```python
sage: phi\_xz = phi\_xy.post\_compose(phi\_yz); phi\_xz
```

Composite map:

From: Univariate Polynomial Ring in \( x \) over Integer Ring
To: Rational Field

Defn: Generic morphism:

From: Univariate Polynomial Ring in \( x \) over Integer Ring
To: Integer Ring
then
Generic morphism:

From: Integer Ring
To: Rational Field

```
pre_compose(right)
```

**INPUT:**

- `self` – a Map in some \( \text{Hom}(Y, Z, \text{category}\_\text{left}) \)
- `left` – a Map in some \( \text{Hom}(X, Y, \text{category}\_\text{right}) \)

Returns the composition of `right` followed by `self` as a morphism in \( \text{Hom}(X, Z, \text{category}) \) where `category` is the meet of `category\_left` and `category\_right`.

**EXAMPLES:**

```python
sage: from sage.categories.morphism import SetMorphism
sage: X.<x> = ZZ[]
```

(continues on next page)
\begin{verbatim}
sage: Y = ZZ
go to the next line
sage: Z = QQ

sage: phi_xy = SetMorphism(Hom(X, Y, Rings()), lambda p: p[0])
sage: phi_yz = SetMorphism(Hom(Y, Z, Monoids()), lambda y: QQ(y**2))
sage: phi_xz = phi_yz.pre_compose(phi_xy); phi_xz

Composite map:
  From: Univariate Polynomial Ring in x over Integer Ring
  To: Rational Field
  Defn: Generic morphism:
           From: Univariate Polynomial Ring in x over Integer Ring
           To: Integer Ring
           then
           Generic morphism:
           From: Integer Ring
           To: Rational Field

sage: phi_xz.category_for()

Category of monoids

section()

Return a section of self.

Note: By default, it returns None. You may override it in subclasses.

class sage.categories.map.Section

Bases: Map

A formal section of a map.

Note: Call methods are not implemented for the base class Section.

EXAMPLES:

\begin{verbatim}
sage: from sage.categories.map import Section
sage: R.<x,y> = ZZ[]

sage: S.<a,b> = QQ[]

sage: f = R.hom([a+b, a-b])

sage: sf = Section(f); sf

Section map:
  From: Multivariate Polynomial Ring in a, b over Rational Field
  To: Multivariate Polynomial Ring in x, y over Integer Ring

sage: sf(a)

Traceback (most recent call last):
...
NotImplementedError: <class 'sage.categories.map.Section'>
\end{verbatim}

inverse()

Return inverse of self.

sage.categories.map.is_Map(x)

Auxiliary function: Is the argument a map?

EXAMPLES:

114 Chapter 3. Maps and Morphisms
sage: R.<x,y> = QQ[]
sage: f = R.hom([x+y, x-y], R)
sage: from sage.categories.map import is_Map
sage: is_Map(f)
True

sage.categories.map.unpickle_map(_class, parent, _dict, _slots)
Auxiliary function for unpickling a map.

### 3.2 Homsets

The class \( Hom \) is the base class used to represent sets of morphisms between objects of a given category. \( Hom \) objects are usually “weakly” cached upon creation so that they don’t have to be generated over and over but can be garbage collected together with the corresponding objects when these are not strongly ref’ed anymore.

**EXAMPLES:**

In the following, the \( Hom \) object is indeed cached:

```sage
sage: K = GF(17)
sage: H = Hom(ZZ, K)
sage: H
Set of Homomorphisms from Integer Ring to Finite Field of size 17
sage: H is Hom(ZZ, K)
True
```

Nonetheless, garbage collection occurs when the original references are overwritten:

```sage
sage: for p in prime_range(200):
    ....:     K = GF(p)
    ....:     H = Hom(ZZ, K)

sage: import gc
sage: _ = gc.collect()

sage: from sage.rings.finite_rings.finite_field_prime_modn import FiniteField_prime_modn
sage: L = [x for x in gc.get_objects() if isinstance(x, FF)]
sage: len(L)
1
```

**AUTHORS:**

- David Kohel and William Stein
- David Joyner (2005-12-17): added examples
- Nicolas M. Thiery (2008-12-): Updated for the new category framework
- Simon King (2011-12): Use a weak cache for homsets
- Simon King (2013-02): added examples
sage.categories.homset.End(X, category=None)

Create the set of endomorphisms of \( X \) in the category category.

INPUT:

- \( X \) – anything
- \( \text{category} \) – (optional) category in which to coerce \( X \)

OUTPUT:

A set of endomorphisms in category

EXAMPLES:

```
sage: V = VectorSpace(QQ, 3)
    # needs sage.modules
sage: End(V)
    # needs sage.modules
Set of Morphisms (Linear Transformations)
    from Vector space of dimension 3 over Rational Field
to Vector space of dimension 3 over Rational Field
```

```
sage: # needs sage.groups
sage: G = AlternatingGroup(3)
sage: S = End(G); S
Set of Morphisms from Alternating group of order 3!/2 as a permutation group
to Alternating group of order 3!/2 as a permutation group
in Category of finite enumerated permutation groups
sage: from sage.categories.homset import is_Endset
sage: is_Endset(S)
True
sage: S.domain()
Alternating group of order 3!/2 as a permutation group
```

To avoid creating superfluous categories, a homset in a category \( \text{Cs}() \) is in the homset category of the lowest full super category \( \text{Bs}() \) of \( \text{Cs}() \) that implements \( \text{Bs}.\text{Homsets} \) (or the join thereof if there are several). For example, finite groups form a full subcategory of unital magmas: any unital magma morphism between two finite groups is a finite group morphism. Since finite groups currently implement nothing more than unital magmas about their homsets, we have:

```
sage: # needs sage.groups
sage: G = GL(3, 3)
sage: G.category()
Category of finite groups
sage: H = Hom(G, G)
sage: H.homset_category()
Category of endsets of unital magmas
```

Similarly, a ring morphism just needs to preserve addition, multiplication, zero, and one. Accordingly, and since the category of rings implements nothing specific about its homsets, a ring homset is currently constructed in the category of homsets of unital magmas and unital additive magmas:

```
sage: H = Hom(ZZ, ZZ, Rings())
sage: H.category()
Category of endsets of unital magmas and additive unital additive magmas
```
sage.categories.homset.Hom(X, Y, category=None, check=True)

Create the space of homomorphisms from $X$ to $Y$ in the category $\text{category}$.

INPUT:

- $X$ – an object of a category
- $Y$ – an object of a category
- $\text{category}$ – a category in which the morphisms must be. (default: the meet of the categories of $X$ and $Y$) Both $X$ and $Y$ must belong to that category.
- $\text{check}$ – a boolean (default: True): whether to check the input, and in particular that $X$ and $Y$ belong to $\text{category}$.

OUTPUT: a homset in $\text{category}$

EXAMPLES:

```
sage: V = VectorSpace(QQ, 3)
    # needs sage.modules
sage: Hom(V, V)
    # needs sage.modules
Set of Morphisms (Linear Transformations) from
Vector space of dimension 3 over Rational Field to
Vector space of dimension 3 over Rational Field
sage: G = AlternatingGroup(3)
    # needs sage.groups
sage: Hom(G, G)
    # needs sage.groups
Set of Morphisms
from Alternating group of order 3!/2 as a permutation group
to Alternating group of order 3!/2 as a permutation group
in Category of finite enumerated permutation groups
sage: Hom(ZZ, QQ, Sets())
Set of Morphisms from Integer Ring to Rational Field in Category of sets
sage: Hom(FreeModule(ZZ, 1), FreeModule(QQ, 1))
    # needs sage.modules
Set of Morphisms
from Ambient free module of rank 1 over the principal ideal domain Integer Ring
to Vector space of dimension 1 over Rational Field
in Category of commutative additive groups
sage: Hom(FreeModule(QQ, 1), FreeModule(ZZ, 1))
    # needs sage.modules
Set of Morphisms
from Vector space of dimension 1 over Rational Field
to Ambient free module of rank 1 over the principal ideal domain Integer Ring
in Category of commutative additive groups
```

Here, we test against a memory leak that has been fixed at github issue #11521 by using a weak cache:

```
sage: # needs sage.libs.pari
sage: for p in prime_range(10^3):
    ....:     K = GF(p)
    ....:     a = K(0)
    sage: import gc
    sage: gc.collect()  # random
    624
sage: from sage.rings.finite_rings.finite_field_prime_modn import FiniteField_
```
To illustrate the choice of the category, we consider the following parents as running examples:

```python
sage: X = ZZ; X
Integer Ring
sage: Y = SymmetricGroup(3); Y
# needs sage.groups
Symmetric group of order 3! as a permutation group
```

By default, the smallest category containing both $X$ and $Y$, is used:

```python
sage: Hom(X, Y)
# needs sage.groups
Set of Morphisms from Integer Ring to Symmetric group of order 3! as a permutation group in Category of enumerated monoids
```

Otherwise, if `category` is specified, then `category` is used, after checking that $X$ and $Y$ are indeed in category:

```python
sage: Hom(X, Y, Magmas())
# needs sage.groups
Set of Morphisms from Integer Ring to Symmetric group of order 3! as a permutation group in Category of magmas
sage: Hom(X, Y, Groups())
# needs sage.groups
Traceback (most recent call last):
... ValueError: Integer Ring is not in Category of groups
```

A parent (or a parent class of a category) may specify how to construct certain homsets by implementing a method `_Hom_(self, codomain, category)`. This method should either construct the requested homset or raise a `TypeError`. This hook is currently mostly used to create homsets in some specific subclass of `Homset` (e.g. `sage.rings.homset.RingHomset`):

```python
sage: Hom(QQ, QQ).__class__
<class 'sage.rings.homset.RingHomset_generic_with_category'>
```

Do not call this hook directly to create homsets, as it does not handle unique representation:

```python
sage: Hom(QQ, QQ) == QQ._Hom_(QQ, category=QQ.category())
True
sage: Hom(QQ, QQ) is QQ._Hom_(QQ, category=QQ.category())
False
```

Todo:

- Design decision: how much of the homset comes from the category of $X$ and $Y$, and how much from the specific $X$ and $Y$. In particular, do we need several parent classes depending on $X$ and $Y$, or does the difference
only lie in the elements (i.e., the morphism), and of course how the parent calls their constructors.

- Specify the protocol for the \_Hom\_ hook in case of ambiguity (e.g., if both a parent and some category thereof provide one).

```python
class sage.categories.homset.Homset(X, Y, category=None, base=None, check=True)
```

The class for collections of morphisms in a category.

**EXAMPLES:**

```python
sage: H = Hom(QQ^2, QQ^3)  #...
˓→needs sage.modules
sage: loads(H.dumps()) is H  #...
˓→needs sage.modules
True
```

Homsets of unique parents are unique as well:

```python
sage: H = End(AffineSpace(2, names='x,y'))
sage: loads(dumps(AffineSpace(2, names='x,y'))) is AffineSpace(2, names='x,y')
True
sage: loads(dumps(H)) is H
True
```

Conversely, homsets of non-unique parents are non-unique:

```python
sage: P11 = ProductProjectiveSpaces(QQ, [1, 1])
sage: H = End(P11)
sage: loads(dumps(P11)) is ProductProjectiveSpaces(QQ, [1, 1])
False
sage: loads(dumps(P11)) == ProductProjectiveSpaces(QQ, [1, 1])
True
sage: loads(dumps(H)) is H
False
sage: loads(dumps(H)) == H
True
```

codomain()

Return the codomain of this homset.

**EXAMPLES:**

```python
sage: P.<t> = ZZ[]
sage: f = P.hom([1/2*t])
sage: f.parent().codomain()  
Univariate Polynomial Ring in t over Rational Field
sage: f.codomain() is f.parent().codomain()
True
```

domain()

Return the domain of this homset.

**EXAMPLES:**

```python
sage: P.<t> = ZZ[]
sage: f = P.hom([1/2*t])
(continues on next page)
```
element_class_set_morphism()

A base class for elements of this homset which are also SetMorphism, i.e. implemented by mean of a Python function.

This is currently plain SetMorphism, without inheritance from categories.

Todo: Refactor during the upcoming homset cleanup.

EXAMPLES:

```python
sage: H = Hom(ZZ, ZZ)
sage: H.element_class_set_morphism
<class 'sage.categories.morphism.SetMorphism'>
```

homset_category()

Return the category that this is a Hom in, i.e., this is typically the category of the domain or codomain object.

EXAMPLES:

```python
sage: H = Hom(AlternatingGroup(4), AlternatingGroup(7))  # needs sage.groups
sage: H.homset_category()                               # needs sage.groups
Category of finite enumerated permutation groups
```

identity()

The identity map of this homset.

Note: Of course, this only exists for sets of endomorphisms.

EXAMPLES:

```python
sage: H = Hom(QQ, QQ)
sage: H.identity()
Identity endomorphism of Rational Field
```

natural_map()

Return the “natural map” of this homset.
Note: By default, a formal coercion morphism is returned.

EXAMPLES:

```
sage: H = Hom(ZZ['t'],QQ['t'], CommutativeAdditiveGroups())
sage: H.natural_map()
Coercion morphism:
    From: Univariate Polynomial Ring in t over Integer Ring
    To:   Univariate Polynomial Ring in t over Rational Field
sage: H = Hom(QQ['t'], GF(3)['t'])
sage: H.natural_map()
Traceback (most recent call last):
  ...  
TypeError: natural coercion morphism  
from Univariate Polynomial Ring in t over Rational Field  
to Univariate Polynomial Ring in t over Finite Field of size 3 not defined
```

one()

The identity map of this homset.

Note: Of course, this only exists for sets of endomorphisms.

EXAMPLES:

```
sage: K = GaussianIntegers()
# needs sage.rings.number_field
sage: End(K).one()  
Identity endomorphism of Gaussian Integers generated by I  
in Number Field in I with defining polynomial x^2 + 1 with I = 1*I
```

reversed()

Return the corresponding homset, but with the domain and codomain reversed.

EXAMPLES:

```
sage: # needs sage.modules
sage: H = Hom(ZZ^2, ZZ^3); H
Set of Morphisms from Ambient free module of rank 2 over  
the principal ideal domain Integer Ring to Ambient free module  
of rank 3 over the principal ideal domain Integer Ring in  
Category of finite dimensional modules with basis over (Dedekind  
domains and euclidean domains  
and infinite enumerated sets and metric spaces)
sage: type(H)
<class 'sage.modules.free_module_homspace.FreeModuleHomspace_with_category'>
sage: H.reversed()
Set of Morphisms from Ambient free module of rank 3 over  
the principal ideal domain Integer Ring to Ambient free module  
of rank 2 over the principal ideal domain Integer Ring in  
Category of finite dimensional modules with basis over (Dedekind  
domains and euclidean domains  
and infinite enumerated sets and metric spaces)
sage: type(H.reversed())
<class 'sage.modules.free_module_homspace.FreeModuleHomspace_with_category'>
```
Category Framework, Release 10.3

class sage.categories.homset.HomsetWithBase (X, Y, category=None, check=True, base=None)
Bases: Homset

sage.categories.homset.end(X,f)
Return \( \text{End}(X)(f) \), where \( f \) is data that defines an element of \( \text{End}(X) \).

EXAMPLES:

```python
sage: R.<x> = QQ[]
sage: phi = end(R, [x + 1])
sage: phi
Ring endomorphism of Univariate Polynomial Ring in x over Rational Field
  Defn: x |--> x + 1
sage: phi(x^2 + 5)
x^2 + 2*x + 6
```

sage.categories.homset.hom(X, Y,f)
Return \( \text{Hom}(X, Y)(f) \), where \( f \) is data that defines an element of \( \text{Hom}(X, Y) \).

EXAMPLES:

```python
sage: R.<x> = QQ[]
sage: phi = hom(R, QQ, [2])
sage: phi(x^2 + 3)
7
```

sage.categories.homset.is_Endset(x)
Return \( \text{True} \) if \( x \) is a set of endomorphisms in a category.

EXAMPLES:

```python
sage: from sage.categories.homset import is_Endset
sage: f = P.hom([1/2*t])
False
sage: g = P.hom([2*t])
True
```

sage.categories.homset.is_Homset(x)
Return \( \text{True} \) if \( x \) is a set of homomorphisms in a category.

EXAMPLES:

```python
sage: from sage.categories.homset import is_Homset
sage: f = P.hom([1/2*t])
False
sage: f.category()()
False
sage: f.parent()()
True
```
3.3 Morphisms

This module defines the base classes of morphisms between objects of a given category.

EXAMPLES:

Typically, a morphism is defined by the images of the generators of the domain.

```python
sage: X.<a, b> = ZZ[]
sage: Y.<c> = ZZ[]
sage: X.hom([c, c^2])
Ring morphism:
    From: Multivariate Polynomial Ring in a, b over Integer Ring
    To:   Univariate Polynomial Ring in c over Integer Ring
    Defn: a |--> c
           b |--> c^2
```

AUTHORS:

- William Stein (2005): initial version
- David Joyner (2005-12-17): added examples

```python
class sage.categories.morphism.CallMorphism
    Bases: Morphism

class sage.categories.morphism.FormalCoercionMorphism
    Bases: Morphism

class sage.categories.morphism.IdentityMorphism
    Bases: Morphism

is_identity()
    Return True if this morphism is the identity morphism.
```

EXAMPLES:

```python
sage: E = End(Partitions(5))  # needs sage.combinat
sage: E.identity().is_identity()  # needs sage.combinat
True
```

Check that github issue #15478 is fixed:

```python
sage: # needs sage.rings.finite_rings
sage: K.<z> = GF(4)
sage: phi = End(K)([z^2])
sage: R.<t> = K[]
sage: psi = End(R)(phi)
sage: psi.is_identity()  # needs sage.combinat
False
```

```python
is_injective()
    Return whether this morphism is injective.
```

EXAMPLES:
is_injective()  
Return whether this morphism is injective.

EXAMPLES:

```python
sage: Hom(ZZ, ZZ).identity().is_injective()
True
```

is_surjective()  
Return whether this morphism is surjective.

EXAMPLES:

```python
sage: Hom(ZZ, ZZ).identity().is_surjective()
True
```

section()  
Return a section of this morphism.

EXAMPLES:

```python
sage: T = Hom(ZZ, ZZ).identity()
sage: T.section() is T
True
```

class sage.categories.morphism.Morphism  
Bases: Map

category()  
Return the category of the parent of this morphism.

EXAMPLES:

```python
sage: R.<t> = ZZ[]
sage: f = R.hom([t**2])
sage: f.category()
Category of endsets of unital magmas and right modules over
(Dedekind domains and euclidean domains
and infinite enumerated sets and metric spaces)
and left modules over (Dedekind domains and euclidean domains
and infinite enumerated sets and metric spaces)

sage: # needs sage.rings.number_field
sage: K = CyclotomicField(12)
sage: L = CyclotomicField(132)
sage: phi = L._internal_coerce_map_from(K)
sage: phi.category()
Category of homsets of number fields
```

is_endomorphism()  
Return True if this morphism is an endomorphism.

EXAMPLES:

```python
sage: R.<t> = ZZ[]
sage: f = R.hom([t])
sage: f.is_endomorphism()
True

sage: # needs sage.rings.number_field
sage: K = CyclotomicField(12)
sage: L = CyclotomicField(132)
```
**is_identity()**

Return True if this morphism is the identity morphism.

**Note:** Implemented only when the domain has a method `gens()`

**EXAMPLES:**

```python
sage: R.<t> = ZZ[]
sage: f = R.hom([t])
sage: f.is_identity()
True
sage: g = R.hom([t + 1])
sage: g.is_identity()
False
```

A morphism between two different spaces cannot be the identity:

```python
sage: R2.<t2> = QQ[]
sage: h = R.hom([t2])
sage: h.is_identity()
False
```

**pushforward()**

**register_as_coercion()**

Register this morphism as a coercion to Sage’s coercion model (see `sage.structure.coerce`).

**EXAMPLES:**

By default, adding polynomials over different variables triggers an error:

```python
sage: X.<x> = ZZ[]
sage: Y.<y> = ZZ[]
sage: x^2 + y
Traceback (most recent call last):
  ... TypeError: unsupported operand parent(s) for +:
'Univariate Polynomial Ring in x over Integer Ring' and
'Univariate Polynomial Ring in y over Integer Ring'
```

Let us declare a coercion from $\mathbb{Z}[x]$ to $\mathbb{Z}[z]$:

```python
sage: Z.<z> = ZZ[]
sage: phi = Hom(X, Z)(z)
sage: phi(x^2+1)
z^2 + 1
```

Now we can add elements from $\mathbb{Z}[x]$ and $\mathbb{Z}[z]$, because the elements of the former are allowed to be implicitly coerced into the later:
Category Framework, Release 10.3

```sage
sage: x^2 + z
z^2 + z
```

Caveat: the registration of the coercion must be done before any other coercion is registered or discovered:

```sage
sage: phi = Hom(X, Z)(z^2)
sage: phi.register_as_coercion()
Traceback (most recent call last):
...  
AssertionError: coercion from Univariate Polynomial Ring in x over Integer Ring to Univariate Polynomial Ring in z over Integer Ring already registered or discovered
```

```sage
sage: phi.register_as_conversion()
```

Register this morphism as a conversion to Sage's coercion model

(see `sage.structure.coerce`).

EXCEPTS:

Let us declare a conversion from the symmetric group to \( \mathbb{Z} \) through the sign map:

```sage
sage: # needs sage.groups
sage: S = SymmetricGroup(4)
sage: phi = Hom(S, ZZ)(
    lambda x: ZZ(x.sign()),
)
sage: x = S.an_element(); x
(2,3,4)
sage: phi(x)
1
sage: phi.register_as_conversion()
sage: ZZ(x)
1
```

```sage
class sage.categories.morphism.SetMorphism

Bases: Morphism

INPUT:

- parent – a Homset
- function – a Python function that takes elements of the domain as input and returns elements of the domain.

EXAMPLES:

```sage
sage: from sage.categories.morphism import SetMorphism
sage: f = SetMorphism(Hom(QQ, ZZ, Sets()), numerator)
sage: f.parent()
Set of Morphisms from Rational Field to Integer Ring in Category of sets
sage: f.domain()
Rational Field
sage: f.codomain()
Integer Ring
sage: TestSuite(f).run()
```

```sage
sage.categories.morphism.is_Morphism(x)
```

126 Chapter 3. Maps and Morphisms
3.4 Coercion via construction functors

```
class sage.categories.pushout.AlgebraicClosureFunctor
    Bases: ConstructionFunctor
    Algebraic Closure.
    EXAMPLES:

    sage: # needs sage.rings.complex_double sage.rings.number_field
    sage: F = CDF.construction()[0]
    sage: F(QQ)
    Algebraic Field
    sage: F(RR)  # needs sage.rings.real_mpfr
    Complex Field with 53 bits of precision
    sage: F(F(QQ)) is F(QQ)
    True

    merge(other)

    Mathematically, Algebraic Closure subsumes Algebraic Extension. However, it seems that people do want to work with algebraic extensions of RR. Therefore, we do not merge with algebraic extension.

    rank = 3

class sage.categories.pushout.AlgebraicExtensionFunctor(polys, names, embeddings=None, structures=None, cyclotomic=None, precs=None, implementations=None, *, residue=None, latex_names=None, **kwds)
    Bases: ConstructionFunctor
    Algebraic extension (univariate polynomial ring modulo principal ideal).
    EXAMPLES:

    sage: x = polygen(QQ, 'x')
    sage: K.<a> = NumberField(x^3 + x^2 + 1)  # needs sage.rings.number_field
    sage: F = K.construction()[0]  # needs sage.rings.number_field
    sage: F(ZZ['t'])
    Univariate Quotient Polynomial Ring in a over Univariate Polynomial Ring in t over Integer Ring with modulus a^3 + a^2 + 1

    Note that, even if a field is algebraically closed, the algebraic extension will be constructed as the quotient of a univariate polynomial ring:

    sage: F(CC)  # needs sage.rings.number_field
    Univariate Quotient Polynomial Ring in a over Complex Field with 53 bits of precision with modulus a^3 + a^2 + 1.00000000000000
    sage: F(RR)  # needs sage.rings.real_mpfr
    (continues on next page)
```
Note that the construction functor of a number field applied to the integers returns an order (not necessarily maximal) of that field, similar to the behaviour of `ZZ.extension(...)`:

```python
sage: F(ZZ) # needs sage.rings.number_field
Order generated by a in Number Field in a with defining polynomial x^3 + x^2 + 1
```

This also holds for non-absolute number fields:

```python
sage: # needs sage.rings.number_field
sage: x = polygen(QQ, 'x')
sage: K.<a,b> = NumberField([x^3 + x^2 + 1, x^2 + x + 1])
sage: F = K.construction()[0]
sage: O = F(ZZ); O
Relative Order generated by [(b - 2)*a^2 + (3*b - 1)*a + 3*b + 4, a - b]
in Number Field in a with defining polynomial x^3 + x^2 + 1
over its base field
sage: O.ambient() is K
True
```

Special cases are made for cyclotomic fields and residue fields:

```python
sage: # needs sage.rings.number_field
sage: C = CyclotomicField(8)
sage: F, R = C.construction()
sage: F
AlgebraicExtensionFunctor
sage: R
Rational Field
sage: F(R)
Cyclotomic Field of order 8 and degree 4
sage: F(ZZ)
Maximal Order generated by zeta8 in Cyclotomic Field of order 8 and degree 4
```

```python
sage: # needs sage.rings.number_field
sage: K.<z> = CyclotomicField(7)
sage: P = K.factor(17)[0][0]
sage: k = K.residue_field(P)
sage: F, R = k.construction()
sage: F
AlgebraicExtensionFunctor
sage: R
Cyclotomic Field of order 7 and degree 6
sage: F(R) is k
True
sage: F(ZZ)
Residue field of Integers modulo 17
sage: F(CyclotomicField(49))
Residue field in zbar of Fractional ideal (17)
```

`expand()`
Decompose the functor $F$ into sub-functors, whose product returns $F$.

**EXAMPLES:**

```sage
sage: # needs sage.rings.number_field
sage: P.<x> = QQ[]
sage: K.<a> = NumberField(x^3 - 5, embedding=0)
sage: L.<b> = K.extension(x^2 + a)
sage: F, R = L.construction()
sage: prod(F.expand())(R) == L
True
sage: K = NumberField([x^2 - 2, x^2 - 3], 'a')
sage: F, R = K.construction()
sage: F
AlgebraicExtensionFunctor
sage: L = F.expand(); L
[AlgebraicExtensionFunctor, AlgebraicExtensionFunctor]
sage: L[-1](QQ)
Number Field in a1 with defining polynomial x^2 - 3
```

**merge**(other)

Merging with another *AlgebraicExtensionFunctor*.

**INPUT:**

- other – Construction Functor.

**OUTPUT:**

- If `self==other`, `self` is returned.
- If `self` and `other` are simple extensions and both provide an embedding, then it is tested whether one of the number fields provided by the functors coerces into the other; the functor associated with the target of the coercion is returned. Otherwise, the construction functor associated with the pushout of the codomains of the two embeddings is returned, provided that it is a number field.
- If these two extensions are defined by Conway polynomials over finite fields, merges them into a single extension of degree the lcm of the two degrees.
- Otherwise, `None` is returned.

**REMARK:**

Algebraic extension with embeddings currently only works when applied to the rational field. This is why we use the admittedly strange rule above for merging.

**EXAMPLES:**

The following demonstrate coercions for finite fields using Conway or pseudo-Conway polynomials:

```sage
sage: k = GF(3^2, prefix='z'); a = k.gen()  # needs sage.rings.finite_rings
sage: l = GF(3^3, prefix='z'); b = l.gen()  # needs sage.rings.finite_rings
sage: a + b  # indirect doctest  # needs sage.rings.finite_rings
z6^5 + 2*z6^4 + 2*z6^3 + z6^2 + 2*z6 + 1
```

Note that embeddings are compatible in lattices of such finite fields.
Coercion is also available for number fields:

```python
sage: # needs sage.rings.number_field
sage: P.<x> = QQ[]
sage: L.<b> = NumberField(x^8 - x^4 + 1, embedding=CDF.0)
sage: M1.<c1> = NumberField(x^2 + x + 1, embedding=b^4 - 1)
sage: M2.<c2> = NumberField(x^2 + x + 1, embedding=-b^6)
sage: M1.coerce_map_from(M2)
sage: M2.coerce_map_from(M1)
sage: c1 + c2; parent(c1 + c2)  # indirect doctest
-b^6 + b^4 - 1
Number Field in b with defining polynomial x^8 - x^4 + 1
with b = -0.2588190451025208? + 0.9659258262890683?*I
sage: pushout(M1["x"], M2["x"])  # needs sage.rings.finite_rings
Univariate Polynomial Ring in x
over Number Field in b with defining polynomial x^8 - x^4 + 1
with b = -0.2588190451025208? + 0.9659258262890683?*I
```

In the previous example, the number field \( L \) becomes the pushout of \( M_1 \) and \( M_2 \) since both are provided with an embedding into \( L \), and since \( L \) is a number field. If two number fields are embedded into a field that is not a numberfield, no merging occurs:

```python
sage: # needs sage.rings.complex_double sage.rings.number_field
sage: crbt2 = CDF(2)^(1/3)
sage: zeta3 = CDF.zeta(3)
sage: K.<a> = NumberField(x^3 - 2, embedding=crbt2 * zeta3)
sage: L.<b> = NumberField(x^6 - 2, embedding=1.1)
sage: L.coerce_map_from(K)
sage: K.coerce_map_from(L)
sage: pushout(K, L)  # needs sage.rings.finite_rings
```

```
Traceback (most recent call last):
...
CoercionException: ('Ambiguous Base Extension', Number Field in a with
defining polynomial x^3 - 2 with a = -0.6299605249474365? + 1.091123635971722?*I,
Number Field in b with defining polynomial x^6 - 2 with b = 1.122462048309373?)
```

```python
rank = 3
```

```python
class sage.categories.pushout.BlackBoxConstructionFunctor(box)
    Bases: ConstructionFunctor

    Construction functor obtained from any callable object.
```

EXAMPLES:
```
sage: from sage.categories.pushout import BlackBoxConstructionFunctor
sage: FG = BlackBoxConstructionFunctor(gap)

sage: FS = BlackBoxConstructionFunctor(singular)

sage: FG
BlackBoxConstructionFunctor

sage: FG(ZZ)
#→needs sage.libs.gap
Integers

sage: FG(ZZ).parent()
#→needs sage.libs.gap
Gap

sage: FS(QQ['t'])
#→needs sage.libs.singular
polynomial ring, over a field, global ordering
// coefficients: QQ
// number of vars : 1
//   block 1 : ordering lp
//      : names t
//   block 2 : ordering C

sage: FG == FS
#→needs sage.libs.gap sage.libs.singular
False

sage: FG == loads(dumps(FG))
#→needs sage.libs.gap
True
```

rank = 100

class sage.categories.pushout.CompletionFunctor(p, prec, extras=None)

Bases: ConstructionFunctor

Completion of a ring with respect to a given prime (including infinity).

EXAMPLES:

```
sage: # needs sage.rings.padics
sage: R = Zp(5)

sage: R
5-adic Ring with capped relative precision 20

sage: F1 = R.construction()[0]

sage: F1
Completion[5, prec=20]

sage: F1(ZZ) is R
True

sage: F1(QQ)
5-adic Field with capped relative precision 20

sage: F2 = RR.construction()[0]

sage: F2
Completion[+Infinity, prec=53]

sage: F2(QQ) is RR
True

sage: P.<x> = ZZ[]

sage: Px = P.completion(x) # currently the only implemented completion of P
sage: Px
Power Series Ring in x over Integer Ring

sage: F3 = Px.construction()[0]
```

(continues on next page)
sage: F3(GF(3)['x'])
Power Series Ring in x over Finite Field of size 3

**commutes** *(other)*

Completion commutes with fraction fields.

**EXAMPLES:**

```python
sage: F1 = Zp(5).construction()[0]  # needs sage.rings.padics
sage: F2 = QQ.construction()[0]
sage: F1.commutes(F2)  # needs sage.rings.padics
True
```

**merge** *(other)*

Two Completion functors are merged, if they are equal. If the precisions of both functors coincide, then a Completion functor is returned that results from updating the *extras* dictionary of *self* by *other*. *extras*. Otherwise, if the completion is at infinity then merging does not increase the set precision, and if the completion is at a finite prime, merging does not decrease the capped precision.

**EXAMPLES:**

```python
sage: # needs sage.rings.padics
sage: R1.<a> = Zp(5, prec=20)[]
sage: R2 = Qp(5, prec=40)
sage: R2(1) + a  # indirect doctest
(1 + O(5^20))*a + 1 + O(5^40)
sage: R3 = RealField(30)
sage: R4 = RealField(50)
sage: R3(1) + R4(1)  # indirect doctest
2.0000000
```

**rank = 4**

```python
class sage.categories.pushout.CompositeConstructionFunctor(*args)
Bases: ConstructionFunctor

A Construction Functor composed by other Construction Functors.

**INPUT:**

F1, F2, ...: A list of Construction Functors. The result is the composition F1 followed by F2 followed by ...

**EXAMPLES:**

```python
sage: from sage.categories.pushout import CompositeConstructionFunctor
sage: F = CompositeConstructionFunctor(QQ.construction()[0], ZZ['x'].
  QQ.construction()[0], ZZ['y'].
  QQ.construction()[0])
sage: F
Poly[y](FractionField(Poly[x](FractionField(...))))
sage: F == loads(dumps(F))
True
```
```python
sage: F == CompositeConstructionFunctor(*F.all)
True
sage: F(GF(2)['t'])
˓→needs sage.libsntl
Univariate Polynomial Ring in y
over Fraction Field of Univariate Polynomial Ring in x
over Fraction Field of Univariate Polynomial Ring in t
over Finite Field of size 2 (using GF2X)
```

`expand()`

Return expansion of a CompositeConstructionFunctor.

**Note:** The product over the list of components, as returned by the `expand()` method, is equal to `self`.

**EXAMPLES:**

```python
sage: from sage.categories.pushout import CompositeConstructionFunctor
sage: F = CompositeConstructionFunctor(QQ.construction()[0],
        ....: ZZ['x'].construction()[0],
        ....: QQ.construction()[0],
        ....: ZZ['y'].construction()[0])
sage: F
Poly[y](FractionField(Poly[x](FractionField(...))))
sage: prod(F.expand()) == F
True
```

```python
class sage.categories.pushout.ConstructionFunctor
Bases: Functor

Base class for construction functors.

A construction functor is a functorial algebraic construction, such as the construction of a matrix ring over a given ring or the fraction field of a given ring.

In addition to the class `Functor`, construction functors provide rules for combining and merging constructions. This is an important part of Sage's coercion model, namely the pushout of two constructions: When a polynomial \( p \) in a variable \( x \) with integer coefficients is added to a rational number \( q \), then Sage finds that the parents \( \mathbb{Z}[x] \) and \( \mathbb{Q} \) are obtained from \( \mathbb{Z} \) by applying a polynomial ring construction respectively the fraction field construction. Each construction functor has an attribute `rank`, and the rank of the polynomial ring construction is higher than the rank of the fraction field construction. This means that the pushout of \( \mathbb{Q} \) and \( \mathbb{Z}[x] \), and thus a common parent in which \( p \) and \( q \) can be added, is \( \mathbb{Q}[x] \), since the construction functor with a lower rank is applied first.

```
Poly[x](FractionField(...))
sage: F3(R)
Univariate Polynomial Ring in x over Rational Field

sage: from sage.categories.pushout import pushout
sage: P.<x> = ZZ[]
sage: pushout(QQ,P)
Univariate Polynomial Ring in x over Rational Field

sage: ((x+1) + 1/2).parent()
Univariate Polynomial Ring in x over Rational Field

When composing two construction functors, they are sometimes merged into one, as is the case in the Quotient construction:

sage: Q15, R = (ZZ.quo(15*ZZ)).construction()
sage: Q15
QuotientFunctor

sage: Q35, R = (ZZ.quo(35*ZZ)).construction()
sage: Q35
QuotientFunctor

sage: Q15.merge(Q35)
QuotientFunctor

sage: Q15.merge(Q35)(ZZ)
Ring of integers modulo 5

Functors can not only be applied to objects, but also to morphisms in the respective categories. For example:

sage: P.<x,y> = ZZ[]
sage: F = P.construction()[0]; F
MPoly[x,y]
sage: A.<a,b> = GF(5)[]
sage: f = A.hom([a + b, a - b], A)
sage: F(A)
Multivariate Polynomial Ring in x, y
over Multivariate Polynomial Ring in a, b over Finite Field of size 5

sage: F(f)
Ring endomorphism of Multivariate Polynomial Ring in x, y
over Multivariate Polynomial Ring in a, b over Finite Field of size 5
Defn: Induced from base ring by
  Ring endomorphism of Multivariate Polynomial Ring in a, b
  over Finite Field of size 5
  Defn: a |--> a + b
     b |--> a - b

coercion_reversed = False

common_base (other_functor, self_bases, other_bases)

This function is called by pushout() when no common parent is found in the construction tower.

Note: The main use is for multivariate construction functors, which use this function to implement recursion for pushout().

INPUT:

- other_functor – a construction functor.
• **self_bases** – the arguments passed to this functor.
• **other_bases** – the arguments passed to the functor **other_functor**.

**OUTPUT:**

Nothing, since a **CoercionException** is raised.

**Note:** Overload this function in derived class, see e.g. **MultivariateConstructionFunctor**.

---

**commutes** (**other**)  
Determine whether **self** commutes with another construction functor.

**Note:** By default, **False** is returned in all cases (even if the two functors are the same, since in this case **merge()** will apply anyway). So far there is no construction functor that overloads this method. Anyway, this method only becomes relevant if two construction functors have the same rank.

**EXAMPLES:**

```python  
sage: F = QQ.construction()[0]  
sage: P = ZZ['t'].construction()[0]  
sage: F.commutes(P)  
False  
sage: P.commutes(F)  
False  
sage: F.commutes(F)  
False  
```

---

**expand()**  
Decompose **self** into a list of construction functors.

**Note:** The default is to return the list only containing **self**.

**EXAMPLES:**

```python  
sage: F = QQ.construction()[0]  
sage: F.expand()  
[FractionField]  
sage: Q = ZZ.quo(2).construction()[0]  
sage: Q.expand()  
[QuotientFunctor]  
sage: P = ZZ['t'].construction()[0]  
sage: F*P  
sage: F.expand()  
[FractionField, Poly[t]]  
```

---

**merge** (**other**)  
Merge **self** with another construction functor, or return **None**.

**Note:** The default is to merge only if the two functors coincide. But this may be overloaded for subclasses, such as the quotient functor.

**EXAMPLES:**

---

3.4. **Coercion via construction functors**
pushout \( \text{(other)} \)
Composition of two construction functors, ordered by their ranks.

**Note:**
- This method seems not to be used in the coercion model.
- By default, the functor with smaller rank is applied first.

```python
class sage.categories.pushout.EquivariantSubobjectConstructionFunctor(S, action=<built-in function mul>, side='left', other_action=None, other_side='left')
```

Bases: `ConstructionFunctor`

Constructor for subobjects invariant or equivariant under given semigroup actions.

Let \( S \) be a semigroup that - acts on a parent \( X \) as \( s \cdot x \) (action, side='left') or - acts on \( X \) as \( x \cdot s \) (action, side='right'), and (possibly trivially) - acts on \( X \) as \( s \cdot x \) (other_action, other_side='left') or - acts on \( X \) as \( x \cdot s \) (other_action, other_side='right').

The \( S \)-equivariant subobject is the subobject

\[
X^S := \{ x \in X : s \cdot x = s \ast x, \forall s \in S \}
\]

when side = other_side = 'left' and mutatis mutandis for the other values of side and other_side.

When other_action is trivial, \( X^S \) is called the \( S \)-invariant subobject.

**EXAMPLES:**

Monoterm symmetries of a tensor, here only for matrices: row (index 0), column (index 1); the order of the extra element 2 in a permutation determines whether it is a symmetry or an antisymmetry:

```python
sage: # needs sage.groups sage.modules
sage: GSym01 = PermutationGroup([[1, 2], [3, 4]]); GSym01
Permutation Group with generators [(1,2), (3,4)]
```

```python
sage: from sage.categories.action import Action
sage: from sage.categories.action import Matrix
sage: class TensorIndexAction(Action):
.....:     def _act_(self, g, x):
```
if isinstance(x, Matrix):
    if g(0) == 1:
        if g(2) == 2:
            return x.transpose()
        else:
            return -x.transpose()
    else:
        return x
raise NotImplementedError

sage: M = matrix([[1, 2], [3, 4]]); M
[1 2]
[3 4]
sage: GSym01_action = TensorIndexAction(GSym01, M.parent())
sage: GASym01_action = TensorIndexAction(GASym01, M.parent())
sage: GSym01_action.act(GSym01.0, M)
[1 3]
[2 4]
sage: GASym01_action.act(GASym01.0, M)
[-1 -3]
[-2 -4]
sage: Sym01 = M.parent().invariant_module(GSym01, action=GSym01_action); Sym01
(Permutation Group with generators [(0,1)])-invariant submodule
of Full MatrixSpace of 2 by 2 dense matrices over Integer Ring
sage: list(Sym01.basis())
[B[0], B[1], B[2]]
sage: list(Sym01.basis().map(Sym01.lift))
[
[1 0] [0 1] [0 0]
[0 0], [1 0], [0 1]
]
sage: ASym01 = M.parent().invariant_module(GASym01, action=GASym01_action)
sage: ASym01
(Permutation Group with generators [(0,1)(2,3)])-invariant submodule
of Full MatrixSpace of 2 by 2 dense matrices over Integer Ring
sage: list(ASym01.basis())
[B[0]]
sage: list(ASym01.basis().map(ASym01.lift))
[
[0 1]
[-1 0]
]
sage: from sage.categories.pushout import pushout
sage: pushout(Sym01, QQ)
(Permutation Group with generators [(0,1)])-invariant submodule
of Full MatrixSpace of 2 by 2 dense matrices over Rational Field

class sage.categories.pushout.FractionField

    Bases: ConstructionFunctor

    Construction functor for fraction fields.

    EXAMPLES:

    sage: F = QQ.construction()[0]
sage: F
    FractionField
    sage: F.domain()
Category of integral domains
sage: F.codomain()
Category of fields
sage: F(GF(5)) is GF(5)
True
sage: F(ZZ['t'])
Fraction Field of Univariate Polynomial Ring in t over Integer Ring
sage: P.<x,y> = QQ[]
Sage: f = P.hom([x+2*y,3*x-y],P)
sage: F(f)
Ring endomorphism of
   Fraction Field of Multivariate Polynomial Ring in x, y over Rational Field
   Defn: x |--> x + 2*y
   y |--> 3*x - y
sage: F(f)(1/x)
1/(x + 2*y)
sage: F == loads(dumps(F))
True

rank = 5

class sage.categories.pushout.IdentityConstructionFunctor
    Bases: ConstructionFunctor
    A construction functor that is the identity functor.

rank = -100

class sage.categories.pushout.InfinitePolynomialFunctor(gens, order, implementation)
    Bases: ConstructionFunctor
    A ConstructionFunctor for Infinite Polynomial Rings (see infinite_polynomial_ring).

AUTHOR:

– Simon King

This construction functor is used to provide uniqueness of infinite polynomial rings as parent structures. As usual, the construction functor allows for constructing pushouts.

Another purpose is to avoid name conflicts of variables of the to-be-constructed infinite polynomial ring with variables of the base ring, and moreover to keep the internal structure of an Infinite Polynomial Ring as simple as possible: If variables \( v_1, ..., v_n \) of the given base ring generate an ordered sub-monoid of the monomials of the ambient Infinite Polynomial Ring, then they are removed from the base ring and merged with the generators of the ambient ring. However, if the orders don’t match, an error is raised, since there was a name conflict without merging.

EXAMPLES:

sage: A.<a,b> = InfinitePolynomialRing(ZZ['t'])
sage: A.construction()

[InfPoly([a,b], "lex", "dense"),
   Univariate Polynomial Ring in t over Integer Ring]
sage: type(_[0])
<class 'sage.categories.pushout.InfinitePolynomialFunctor'>
sage: B.<x,y,a_3,a_1> = PolynomialRing(QQ, order='lex')
sage: B.construction()

(MPoly[x,y,a_3,a_1], Rational Field)
Apparently the variables \(a_1, a_3\) of the polynomial ring are merged with the variables \(a_0, a_1, a_2, \ldots\) of the infinite polynomial ring; indeed, they form an ordered sub-structure. However, if the polynomial ring was given a different ordering, merging would not be allowed, resulting in a name conflict:

```
sage: R = PolynomialRing(QQ, names=['x', 'y', 'a_3', 'a_1'], order='lex')
sage: A.construction()[0] * R.construction()[0]
```

Traceback (most recent call last):
...  
CoercionException: Overlapping variables ((a, 'b'),['a_1', 'a_3']) are incompatible

In an infinite polynomial ring with generator \(a_*\), the variable \(a_3\) will always be greater than the variable \(a_1\). Hence, the orders are incompatible in the next example as well:

```
sage: R = PolynomialRing(QQ, names=['x', 'y', 'a_1', 'a_3'], order='lex')
sage: A.construction()[0] * R.construction()[0]
```

Traceback (most recent call last):
...  
CoercionException: Overlapping variables ((a, 'b'),['a_1', 'a_3']) are incompatible

Another requirement is that after merging the order of the remaining variables must be unique. This is not the case in the following example, since it is not clear whether the variables \(x, y\) should be greater or smaller than the variables \(b_*\):

```
sage: R = PolynomialRing(QQ, names=['a_3', 'a_1', 'x', 'y'], order='lex')
sage: A.construction()[0] * R.construction()[0]
```

Traceback (most recent call last):
...  
CoercionException: Overlapping variables ((a, 'b'),['a_3', 'a_1']) are incompatible

Since the construction functors are actually used to construct infinite polynomial rings, the following result is no surprise:

```
sage: C.<a,b> = InfinitePolynomialRing(B); C
Infinite polynomial ring in a, b
over Multivariate Polynomial Ring in x, y over Rational Field
```

There is also an overlap in the next example:

```
sage: X.<w,x,y> = InfinitePolynomialRing(ZZ)
sage: Y.<x,y,z> = InfinitePolynomialRing(QQ)
```

\(X\) and \(Y\) have an overlapping generators \(x_*, y_*\). Since the default lexicographic order is used in both rings, it gives rise to isomorphic sub-monoids in both \(X\) and \(Y\). They are merged in the pushout, which also yields a common parent for doing arithmetic:

```
sage: P = sage.categories.pushout.pushout(Y,X); P
Infinite polynomial ring in w, x, y, z over Rational Field
w_2 + z_3
sage: _.parent() is P
True
```

3.4. Coercion via construction functors 139
expand()  
Decompose the functor \( F \) into sub-functors, whose product returns \( F \).

EXAMPLES:

sage: A = InfinitePolynomialRing(QQ, ['x','y'], order='degrevlex')
sage: F = A.construction()[0]; F
InfPoly([x,y], "degrevlex", "dense")
sage: F.expand()
[InfPoly([y], "degrevlex", "dense"), InfPoly([x], "degrevlex", "dense")]
sage: A = InfinitePolynomialRing(QQ, ['x','y','z'], order='degrevlex')
sage: F = A.construction()[0]; F
InfPoly([x,y,z], "degrevlex", "dense")
sage: F.expand()
[InfPoly([z], "degrevlex", "dense"), InfPoly([y], "degrevlex", "dense"), InfPoly([x], "degrevlex", "dense")]
sage: prod(F.expand())==F
True

merge(other)  
Merge two construction functors of infinite polynomial rings, regardless of monomial order and implementation.

The purpose is to have a pushout (and thus, arithmetic) even in cases when the parents are isomorphic as rings, but not as ordered rings.

EXAMPLES:

sage: X.<x,y> = InfinitePolynomialRing(QQ, implementation='sparse')
sage: Y.<x,y> = InfinitePolynomialRing(QQ, order='degrevlex')
sage: X.construction()
[InfPoly([x,y], "lex", "sparse"), Rational Field]
sage: Y.construction()
[InfPoly([x,y], "degrevlex", "dense"), Rational Field]
sage: Y.construction()[0].merge(Y.construction()[0])
InfPoly([x,y], "degrevlex", "dense")
sage: y[3] + X(x[2])
x_2 + y_3
sage: _.parent().construction()
[InfPoly([x,y], "degrevlex", "dense"), Rational Field]

rank = 9.5

class sage.categories.pushout.LaurentPolynomialFunctor(var, multi_variate=False)  
Bases: ConstructionFunctor

Construction functor for Laurent polynomial rings.

EXAMPLES:

sage: L.<t> = LaurentPolynomialRing(ZZ)
sage: F = L.construction()[0]
sage: F
LaurentPolynomialFunctor
sage: F(QQ)
Univariate Laurent Polynomial Ring in t over Rational Field
sage: K.<x> = LaurentPolynomialRing(ZZ)
sage: F(K)

(continues on next page)
Univariate Laurent Polynomial Ring in \( t \)  
over Univariate Laurent Polynomial Ring in \( x \) over Integer Ring

\[
sage: P.<x,y> = ZZ[]
\]
\[
sage: \varphi = P.hom([x + 2*y, 3*x - y],P)
\]
\[
sage: F(\varphi)
\]

Ring endomorphism of Univariate Laurent Polynomial Ring in \( t \)  
over Multivariate Polynomial Ring in \( x, y \) over Integer Ring

\[
\begin{align*}
\text{Defn:} \quad & \text{Induced from base ring by} \\
& \text{Ring endomorphism of Multivariate Polynomial Ring in } x, y \text{ over Integer } \\
& \quad \begin{align*}
& x \mapsto x + 2*y \\
& y \mapsto 3*x - y
\end{align*}
\end{align*}
\]

\[
sage: F(\varphi)(x*P.gens()[0]**-2 + y*P.gens()[1]**3)
\]
\[
(\varphi(t^2)*x + \varphi(t^3)*y)
\]

merge \( (\text{other}) \)

Two Laurent polynomial construction functors merge if the variable names coincide.

The result is multivariate if one of the arguments is multivariate.

EXAMPLES:

\[
sage: from sage.categories.pushout import LaurentPolynomialFunctor
\]
\[
sage: F1 = LaurentPolynomialFunctor('t')
\]
\[
sage: F2 = LaurentPolynomialFunctor('t', multivariate=True)
\]
\[
sage: F1.merge(F2)
\]

Univariate Laurent Polynomial Ring in \( t \) over Univariate Laurent Polynomial Ring in \( x \) over Finite Field of size 2

class \( \text{sage.categories.pushout.MatrixFunctor}(\text{nrows, ncols, is_sparse=False}) \)

Bases: ConstructionFunctor

A construction functor for matrices over rings.

EXAMPLES:

\[
sage: MS = MatrixSpace(ZZ, 2, 3)
\]
\[
sage: F = MS.construction()[0]; F
\]
\[
\text{Full MatrixSpace of 2 by 3 dense matrices}
\]

3.4. Coercion via construction functors
of Full MatrixSpace of 2 by 2 dense matrices
over Multivariate Polynomial Ring in x, y over Rational Field
Defn: Induced from base ring by
    Ring endomorphism
        of Multivariate Polynomial Ring in x, y over Rational Field
        Defn: x |--> x + y
        y |--> x - y

```
sage: M = R([x, y, x*y, x + y])
sage: F(f)(M)
[   x + y   x - y]
[  x^2 - y^2  2*x]
```

**merge (other)**

Merging is only happening if both functors are matrix functors of the same dimension.

The result is sparse if and only if both given functors are sparse.

**EXAMPLES:**

```
sage: # needs sage.modules
sage: F1 = MatrixSpace(ZZ, 2, 2).construction()[0]
sage: F2 = MatrixSpace(ZZ, 2, 3).construction()[0]
sage: F3 = MatrixSpace(ZZ, 2, 2, sparse=True).construction()[0]
sage: F1.merge(F2)
MatrixFunctor
sage: F13 = F1.merge(F3)
MatrixFunctor
sage: F13.is_sparse
False
sage: F1.is_sparse
False
sage: F3.is_sparse
True
sage: F3.merge(F3).is_sparse
True
```

**rank = 10**

class sage.categories.pushout.MultivariateFunctor

**EXAMPLES:**

```
sage: P.<x,y> = ZZ[]
sage: F = P.construction()[0]; F
MPoly[x,y]
sage: A.<a,b> = GF(5)[]
sage: F(a)
Multivariate Polynomial Ring in x, y
    over Multivariate Polynomial Ring in a, b over Finite Field of size 5
sage: F = A.hom([[a+b, a-b], A])
sage: F(f)
Ring endomorphism of Multivariate Polynomial Ring in x, y
    over Multivariate Polynomial Ring in a, b over Finite Field of size 5
    Defn: Induced from base ring by
```
Ring endomorphism of Multivariate Polynomial Ring in a, b over Finite...
Field of size 5
Defn: a |--> a + b
b |--> a - b
sage: F(f)(F(A)(x)*a)
(a + b)*x

expand()
Decompose self into a list of construction functors.

EXAMPLES:
sage: F = QQ['x,y,z,t'].construction()[0]; F
MPoly[x,y,z,t]
sage: F.expand()
[MPoly[t], MPoly[z], MPoly[y], MPoly[x]]

Now an actual use case:
sage: R.<x,y,z> = ZZ[]
sage: S.<z,t> = QQ[]
x + t
x + t
sage: parent(x+t)
Multivariate Polynomial Ring in x, y, z over Rational Field
sage: T.<y,s> = QQ[]
x + s
Traceback (most recent call last):
...
TypeError: unsupported operand parent(s) for +:
'Multivariate Polynomial Ring in x, y, z over Integer Ring' and
'Multivariate Polynomial Ring in y, s over Rational Field'
sage: R = PolynomialRing(ZZ, 'x', 50)
sage: S = PolynomialRing(GF(5), 'x', 20)
x + s
sage: R.gen(0) + S.gen(0)
2*x0

merge(other)
Merge self with another construction functor, or return None.

EXAMPLES:
sage: F = sage.categories.pushout.MultiPolynomialFunctor(['x','y'], None)
sage: G = sage.categories.pushout.MultiPolynomialFunctor(['t'], None)
sage: F.merge(G) is None
True
sage: F.merge(F)
MPoly[x,y]

rank = 9

class sage.categories.pushout.MultivariateConstructionFunctor
Bases: ConstructionFunctor

An abstract base class for functors that take multiple inputs (e.g. Cartesian products).

3.4. Coercion via construction functors
**common_base** *(other_functor, self_bases, other_bases)*

This function is called by `pushout()` when no common parent is found in the construction tower.

**INPUT:**

- `other_functor` — a construction functor.
- `self_bases` — the arguments passed to this functor.
- `other_bases` — the arguments passed to the functor `other_functor`.

**OUTPUT:**

A parent.

If no common base is found a `sage.structure.coerce_exceptions.CoercionException` is raised.

**Note:** Overload this function in derived class, see e.g. `MultivariateConstructionFunctor`.

```python
class sage.categories.pushout.PermutationGroupFunctor(gens, domain):
    Bases: ConstructionFunctor

    EXAMPLES:

    sage: from sage.categories.pushout import PermutationGroupFunctor
    sage: PF = PermutationGroupFunctor([PermutationGroupElement([(1,2)])], #...
    ....: [1,2]); PF
    PermutationGroupFunctor([(1,2)])

    gens() 

    EXAMPLES:

    sage: P1 = PermutationGroup([(1,2)])
    ....: # needs sage.groups
    sage: PF, P = P1.construction()
    ....: # needs sage.groups
    sage: PF.gens()
    ....: # needs sage.groups
    ((1,2),)

    merge(other)

    Merge self with another construction functor, or return None.

    EXAMPLES:

    sage: # needs sage.groups
    sage: P1 = PermutationGroup([(1,2)])
    sage: PF1, P = P1.construction()
    sage: P2 = PermutationGroup([(1,3)])
    sage: PF2, P = P2.construction()
    sage: PF1.merge(PF2)
    PermutationGroupFunctor([(1,2), (1,3)]

    rank = 10
```
class sage.categories.pushout.PolynomialFunctor(var, multi_variate=False, sparse=False, implementation=None)

    Bases: ConstructionFunctor

    Construction functor for univariate polynomial rings.

    EXAMPLES:

    sage: P = ZZ['t'].construction()[0]
    sage: P(GF(3))
    Univariate Polynomial Ring in t over Finite Field of size 3
    sage: P == loads(dumps(P))
    True
    sage: R.<x,y> = GF(5)[]
    sage: f = R.hom([x + 2*y, 3*x - y], R)
    sage: P(f)((x+y) * P(R).0)
    (-x + y)*t

    By github issue #9944, the construction functor distinguishes sparse and dense polynomial rings. Before, the following example failed:

    sage: R.<x> = PolynomialRing(GF(5), sparse=True)
    sage: F, B = R.construction()
    sage: F(B)
    is R
    True
    sage: S.<x> = PolynomialRing(ZZ)
    sage: R.has_coerce_map_from(S)
    False
    sage: S.has_coerce_map_from(R)
    False
    sage: S.0 + R.0
    2*x
    sage: (S.0 + R.0).parent()
    Univariate Polynomial Ring in x over Finite Field of size 5
    sage: (S.0 + R.0).parent().is_sparse()
    False

    merge(other)

    Merge self with another construction functor, or return None.

    Note: Internally, the merging is delegated to the merging of multipolynomial construction functors. But in effect, this does the same as the default implementation, that returns None unless the to-be-merged functors coincide.

    EXAMPLES:

    sage: P = ZZ['x'].construction()[0]
    sage: Q = ZZ['y','x'].construction()[0]
    sage: P.merge(Q)
    sage: P.merge(P)
    is P
    True

    rank = 9

class sage.categories.pushout.QuotientFunctor(I, names=None, as_field=False, domain=None, codomain=None, **kwds)

    Bases: ConstructionFunctor

3.4. Coercion via construction functors

145
Construction functor for quotient rings.

**Note:** The functor keeps track of variable names. Optionally, it may keep track of additional properties of the quotient, such as its category or its implementation.

**EXAMPLES:**

```sage
definitions:

sage: P.<x,y> = ZZ[

sage: Q = P.quo([x^2 + y^2] * P)

sage: F = Q.construction()[0]

sage: F(QQ[x,y])

Quotient of Multivariate Polynomial Ring in x, y over Rational Field

by the ideal (x^2 + y^2)

sage: F(QQ['x','y'])

True

sage: F(QQ['x','y','z'])

Traceback (most recent call last):
...

CoercionException: Cannot apply this quotient functor to

Multivariate Polynomial Ring in x, y, z over Rational Field

sage: F(QQ['y','z'])

# needs sage.rings.finite_rings

Traceback (most recent call last):
...

TypeError: Could not find a mapping of the passed element to this ring.
```

**merge (other)**

Two quotient functors with coinciding names are merged by taking the gcd of their moduli, the meet of their domains, and the join of their codomains.

In particular, if one of the functors being merged knows that the quotient is going to be a field, then the merged functor will return fields as well.

**EXAMPLES:**

```sage
definitions:

sage: P.<x> = QQ[

sage: Q1 = P.quo([(x^2+1)^2*(x^2-3)])

sage: Q2 = P.quo([(x^2+1)^2*(x^5+3)])

sage: from sage.categories.pushout import pushout

sage: pushout(Q1,Q2) # indirect doctest

Univariate Quotient Polynomial Ring in xbar over Rational Field

with modulus x^4 + 2*x^2 + 1

The following was fixed in github issue #8800:

```

```sage

sage: pushout(GF(5), Integers(5)) #...

# needs sage.libs.pari

Finite Field of size 5
```

**rank = 4.5**

**class** `sage.categories.pushout.SubspaceFunctor (basis)`

**Bases:** `ConstructionFunctor`

Constructing a subspace of an ambient free module, given by a basis.
Note: This construction functor keeps track of the basis. It can only be applied to free modules into which this basis coerces.

EXAMPLES:

```sage
sage: # needs sage.modules
sage: M = ZZ^3
sage: S = M.submodule([(1,2,3), (4,5,6)]); S
Free module of degree 3 and rank 2 over Integer Ring
Echelon basis matrix:
[1 2 3]
[0 3 6]
sage: F = S.construction()[0]
sage: F(GF(2)^3)
Vector space of degree 3 and dimension 2 over Finite Field of size 2
User basis matrix:
[1 0 1]
[0 1 0]
```

coercion_reversed = True

merge(\texttt{other})

Two Subspace Functors are merged into a construction functor of the sum of two subspaces.

EXAMPLES:

```sage
sage: # needs sage.modules
sage: M = GF(5)^3
sage: S1 = M.submodule([(1,2,3),(4,5,6)])
sage: S2 = M.submodule([(2,2,3)])
sage: F1 = S1.construction()[0]
sage: F2 = S2.construction()[0]
sage: F1.merge(F2)
SubspaceFunctor
sage: F1.merge(F2)(GF(5)^3) == S1 + S2
True
```

```sage
sage: F1.merge(F2)(GF(5)[t]^3)
Free module of degree 3 and rank 3 over Univariate Polynomial Ring in t over Finite Field of size 5
User basis matrix:
[1 0 0]
[0 1 0]
```

rank = 11

class \texttt{sage.categories.pushout.VectorFunctor}\n(n=None, is_sparse=False, inner_product_matrix=None, *, with_basis='standard', basis_keys=None, name_mapping=None, latex_name_mapping=None)

Bases: \texttt{ConstructionFunctor}

A construction functor for free modules over commutative rings.

EXAMPLES:

3.4. Coercion via construction functors 147
merge(other)

Two constructors of free modules merge, if the module ranks and the inner products coincide. If both have explicitly given inner product matrices, they must coincide as well.

EXAMPLES:

Two modules without explicitly given inner product allow coercion:

```python
sage: M1 = QQ^3  # needs sage.modules
sage: P.<t> = ZZ[]
sage: M2 = FreeModule(P, 3)  # needs sage.modules
sage: M1([1,1/2,1/3]) + M2([t,t^2+t,3])  # indirect doctest  # needs sage.modules
(t + 1, t^2 + t + 1/2, 10/3)
```

If only one summand has an explicit inner product, the result will be provided with it:

```python
sage: M3 = FreeModule(P, 3, inner_product_matrix=Matrix(3, 3, range(9)))  # needs sage.modules
sage: M1([1,1/2,1/3]) + M3([t,t^2+t,3])  # needs sage.modules
(t + 1, t^2 + t + 1/2, 10/3)
```

If both summands have an explicit inner product (even if it is the standard inner product), then the products must coincide. The only difference between M1 and M4 in the following example is the fact that the default inner product was explicitly requested for M4. It is therefore not possible to coerce with a different inner product:

```python
sage: # needs sage.modules
sage: M4 = FreeModule(QQ, 3, inner_product_matrix=Matrix(3, 3, 1))
```

```
Traceback (most recent call last):
  ...TypeError: unsupported operand parent(s) for +:
'Ambient quadratic space of dimension 3 over Rational Field
inner product matrix:
```

(continues on next page)
Names are removed when they conflict:

```python
sage: from sage.categories.pushout import VectorFunctor, pushout
sage: M_ZZx = FreeModule(ZZ['x'], 4, with_basis=None, name='M_ZZx')
```

```

sage: N_ZZx = FreeModule(ZZ['x'], 4, with_basis=None, name='N_ZZx')
```

```python
sage: pushout(M_ZZx, QQ)
Rank-4 free module M_ZZx_base_ext
over the Univariate Polynomial Ring in x over Rational Field
```

```

sage: pushout(M_ZZx, N_ZZx)
Rank-4 free module
over the Univariate Polynomial Ring in x over Integer Ring
```

```

sage: pushout(pushout(M_ZZx, N_ZZx), QQ)
Rank-4 free module
over the Univariate Polynomial Ring in x over Rational Field
```

`\text{rank} = 10`

```
sage.categories.pushout.construction_tower(R)
```

An auxiliary function that is used in `pushout()` and `pushout_lattice()`.

**INPUT:**
An object

**OUTPUT:**
A constructive description of the object from scratch, by a list of pairs of a construction functor and an object to which the construction functor is to be applied. The first pair is formed by `None` and the given object.

**EXAMPLES:**

```
sage: from sage.categories.pushout import construction_tower
sage: construction_tower(MatrixSpace(FractionField(QQ['t']), 2))
((None, Full MatrixSpace of 2 by 2 dense matrices over Fraction Field of Univariate Polynomial Ring in t over Rational Field), (MatrixFunctor, Fraction Field of Univariate Polynomial Ring in t over Rational Field), (FractionField, Univariate Polynomial Ring in t over Rational Field), (Poly[t], Rational Field), (FractionField, Integer Ring))
```

```
sage.categories.pushout.expand_tower(tower)
```

An auxiliary function that is used in `pushout()`.

**INPUT:**
A construction tower as returned by `construction_tower()`.

**OUTPUT:**
A new construction tower with all the construction functors expanded.

EXAMPLES:

```python
sage: from sage.categories.pushout import construction_tower, expand_tower
sage: construction_tower(QQ['x,y,z'])
[(None, Multivariate Polynomial Ring in x, y, z over Rational Field),
 (MPoly[x,y,z], Rational Field),
 (FractionField, Integer Ring)]

sage: expand_tower(construction_tower(QQ['x,y,z']))
[(None, Multivariate Polynomial Ring in x, y, z over Rational Field),
 (MPoly[z], Univariate Polynomial Ring in x over Rational Field),
 (MPoly[y], Univariate Polynomial Ring in x over Rational Field),
 (MPoly[x], Rational Field),
 (FractionField, Integer Ring)]
```

`sage.categories.pushout.pushout(R, S)`

Given a pair of objects \( R \) and \( S \), try to construct a reasonable object \( Y \) and return maps such that canonically \( R \leftarrow Y \rightarrow S \).

ALGORITHM:

This incorporates the idea of functors discussed at Sage Days 4. Every object \( R \) can be viewed as an initial object and a series of functors (e.g. polynomial, quotient, extension, completion, vector/matrix, etc.). Call the series of increasingly simple objects (with the associated functors) the “tower” of \( R \). The construction method is used to create the tower.

Given two objects \( R \) and \( S \), try to find a common initial object \( Z \). If the towers of \( R \) and \( S \) meet, let \( Z \) be their join. Otherwise, see if the top of one coerces naturally into the other.

Now we have an initial object and two ordered lists of functors to apply. We wish to merge these in an unambiguous order, popping elements off the top of one or the other tower as we apply them to \( Z \).

- If the functors are of distinct types, there is an absolute ordering given by the rank attribute. Use this.
- Otherwise:
  - If the tops are equal, we (try to) merge them.
  - If exactly one occurs lower in the other tower, we may unambiguously apply the other (hoping for a later merge).
  - If the tops commute, we can apply either first.
  - Otherwise fail due to ambiguity.

The algorithm assumes by default that when a construction \( F \) is applied to an object \( X \), the object \( F(X) \) admits a coercion map from \( X \). However, the algorithm can also handle the case where \( F(X) \) has a coercion map to \( X \) instead. In this case, the attribute `coercion_reversed` of the class implementing \( F \) should be set to `True`.

EXAMPLES:

Here our “towers” are \( R = \text{Complete}_7(\text{Frac}(\mathbb{Z})) \) and \( \text{Frac}(\text{Poly}_6(\mathbb{Z})) \), which give us \( \text{Frac}(\text{Poly}_6(\text{Complete}_7(\text{Frac}(\mathbb{Z})))) \):

```python
sage: from sage.categories.pushout import pushout
sage: pushout(Qp(7), Frac(ZZ['x']))
# needs sage.rings.padics
```

Note we get the same thing with
Note that polynomial variable ordering must be unambiguously determined.

Some other examples:

```python
sage: pushout(Zp(7)[y], Frac(QQ)[t])[x,y,z])
Traceback (most recent call last):
... CoercionException: ('Ambiguous Base Extension',
Multivariate Polynomial Ring in x, y, z over Integer Ring,
Multivariate Polynomial Ring in w, z, t over Rational Field)
```

```
sage: pushout(ZZ[x,y,z], ZZ[[x]])
Univariate Polynomial Ring in y
over Power Series Ring in x over Rational Field
```

A construction with coercion_reversed=True (currently only the SubspaceFunctor construction) is only applied if it leads to a valid coercion:

```python
sage: # needs sage.modules
sage: A = ZZ^2
sage: V = span([[1, 2]], QQ)
sage: P = sage.categories.pushout.pushout(A, V)
sage: P
Vector space of dimension 2 over Rational Field
sage: P.has_coerce_map_from(A)
True
sage: # needs sage.modules
```
```
sage: V = (QQ^3).span([[1, 2, 3/4]])
sage: A = ZZ^3
sage: pushout(A, V)
Vector space of dimension 3 over Rational Field
sage: B = A.span([[0, 0, 2/3]])
sage: pushout(B, V)
Vector space of degree 3 and dimension 2 over Rational Field
User basis matrix:
[1 2 0]
[0 0 1]
```

Some more tests with coercion_reversed=True:
```
sage: from sage.categories.pushout import ConstructionFunctor
class EvenPolynomialRing(type(QQ['x'])):
    def __init__(self, base, var):
        super().__init__(base, var)
        self.register_embedding(base[var])
    def __repr__(self):
        return "Even Power " + super().__repr__()
    def construction(self):
        return EvenPolynomialFunctor(), self.base()[self.variable_name()]
    def _coerce_map_from_(self, R):
        return self.base().has_coerce_map_from(R)
class EvenPolynomialFunctor(ConstructionFunctor):
    rank = 10
    coercion_reversed = True
    def __init__(self):
        ConstructionFunctor.__init__(self, Rings(), Rings())
    def _apply Functor(self, R):
        return EvenPolynomialRing(R.base(), R.variable_name())
sage: pushout(EvenPolynomialRing(QQ, 'x'), ZZ)
Even Power Univariate Polynomial Ring in x over Rational Field
sage: pushout(EvenPolynomialRing(QQ, 'x'), QQ)
Even Power Univariate Polynomial Ring in x over Rational Field
sage: pushout(EvenPolynomialRing(QQ, 'x'), RR)
Even Power Univariate Polynomial Ring in x over Real Field with 53 bits of
precision
sage: pushout(EvenPolynomialRing(QQ, 'x'), ZZ['x'])
Univariate Polynomial Ring in x over Rational Field
sage: pushout(EvenPolynomialRing(QQ, 'x'), QQ['x'])
Univariate Polynomial Ring in x over Rational Field
sage: pushout(EvenPolynomialRing(QQ, 'x'), RR['x'])
Univariate Polynomial Ring in x over Real Field with 53 bits of
precision
```
Some more tests related to univariate/multivariate constructions. We consider a generalization of polynomial rings, where in addition to the coefficient ring $C$ we also specify an additive monoid $E$ for the exponents of the indeterminate. In particular, the elements of such a parent are given by

$$\sum_{i=0}^{I} c_i x^{e_i}$$

with $c_i \in C$ and $e_i \in E$. We define

```python
sage: class GPolynomialRing(Parent):
    ....:    def __init__(self, coefficients, var, exponents):
    ....:        self.coefficients = coefficients
    ....:        self.var = var
    ....:        self.exponents = exponents
    ....:        super().__init__(category=Rings())
    ....:    def __repr__(self):
    ....:        return 'Generalized Polynomial Ring in %s^(%s) over %s' % (self.var, self.exponents, self.coefficients)
    ....:    def construction(self):
    ....:        return GPolynomialFunctor(self.var, self.exponents), self.coefficients
    ....:    def _coerce_map_from_(self, R):
    ....:        return self.coefficients.has_coerce_map_from(R)
```

and

```python
sage: class GPolynomialFunctor(ConstructionFunctor):
    ....:    rank = 10
    ....:    def __init__(self, var, exponents):
    ....:        self.var = var
    ....:        self.exponents = exponents
    ....:        ConstructionFunctor.__init__(self, Rings(), Rings())
    ....:    def __repr__(self):
    ....:        return 'GPoly[%s^(%s)]' % (self.var, self.exponents)
    ....:    def _apply_functor(self, coefficients):
    ....:        return GPolynomialRing(coefficients, self.var, self.exponents)
    ....:    def merge(self, other):
    ....:        if isinstance(other, GPolynomialFunctor) and self.var == other.var:
    ....:            exponents = pushout(self.exponents, other.exponents)
    ....:        return GPolynomialFunctor(self.var, exponents)
```

We can construct a parent now in two different ways:

```python
sage: G = GPolynomialRing(QQ, 'X', ZZ)
Generalized Polynomial Ring in X^(Integer Ring) over Rational Field
sage: GP_ZZ = GPolynomialFunctor('X', ZZ); GP_ZZ
GPoly[X^(Integer Ring)]
```

(continues on next page)
Since the construction

```python
sage: GP_ZZ(QQ).construction()
(GPoly[X^(Integer Ring)], Rational Field)
```

uses the coefficient ring, we have the usual coercion with respect to this parameter:

```python
sage: pushout(GP_ZZ(ZZ), GP_ZZ(QQ))
Generalized Polynomial Ring in X^(Integer Ring) over Rational Field
sage: pushout(GP_ZZ(ZZ['t']), GP_ZZ(QQ))
Generalized Polynomial Ring in X^(Integer Ring)
  over Univariate Polynomial Ring in t over Rational Field
sage: pushout(GP_ZZ(ZZ['a,b']), GP_ZZ(QQ['b,c']))
Generalized Polynomial Ring in X^(Integer Ring)
  over Multivariate Polynomial Ring in a, b, c over Integer Ring
sage: pushout(GP_ZZ(ZZ['a,b']), GP_ZZ(QQ['b,c']))
Traceback (most recent call last):
  ... CoercionException: ('Ambiguous Base Extension', ...)
sage: GP_QQ = GPolynomialFunctor('X', QQ)
sage: pushout(GP_ZZ(ZZ), GP_QQ(ZZ))
Generalized Polynomial Ring in X^(Rational Field) over Integer Ring
sage: pushout(GP_QQ(ZZ), GP_ZZ(ZZ))
Generalized Polynomial Ring in X^(Rational Field) over Integer Ring
sage: pushout(GP_ZZt(QQ), GP_QQ(ZZ))
Generalized Polynomial Ring in X^(Univariate Polynomial Ring in t over Rational Field) over Integer Ring
sage: pushout(GP_ZZt(ZZ['a,b']), GP_QQ(ZZ['c,d']))
Traceback (most recent call last):
  ... CoercionException: ('Ambiguous Base Extension', ...)
```
Some tests with Cartesian products:

```
sage: from sage.sets.cartesian_product import CartesianProduct
sage: A = CartesianProduct((ZZ['x'], QQ['y'], QQ['z']),
....:                        Sets().CartesianProducts())
sage: B = CartesianProduct((ZZ['x'], ZZ['y'], ZZ['t']['z']),
....:                        Sets().CartesianProducts())

sage: A.construction()
(The cartesian_product functorial construction,
 (Univariate Polynomial Ring in x over Integer Ring,
  Univariate Polynomial Ring in y over Rational Field,
  Univariate Polynomial Ring in z over Rational Field))

sage: pushout(A, B)
The Cartesian product of
 (Univariate Polynomial Ring in x over Integer Ring,
  Univariate Polynomial Ring in y over Rational Field,
  Univariate Polynomial Ring in z over Rational Field)

sage: pushout(ZZ, cartesian_product([ZZ, QQ]))
Traceback (most recent call last):
  ... CoercionException: 'NoneType' object is not iterable
```

```
sage: from sage.categories.pushout import PolynomialFunctor
sage: from sage.sets.cartesian_product import CartesianProduct
sage: class CartesianProductPoly(CartesianProduct):
    ....:     def __init__(self, polynomial_rings):
    ....:         sort = sorted(polynomial_rings,
    ....:                        key=lambda P: P.variable_name())
    ....:         super().__init__(sort, Sets().CartesianProducts())
    ....:     def vars(self):
    ....:         return tuple(P.variable_name()
    ....:                        for P in self.cartesian_factors())
    ....:     def _pushout_(self, other):
    ....:         if isinstance(other, CartesianProductPoly):
    ....:             s_vars = self.vars()
    ....:             o_vars = other.vars()
    ....:             if s_vars == o_vars:
    ....:                 return pushout(CartesianProductPoly(
    ....:                     self.cartesian_factors() +
    ....:                     tuple(f for f in other.cartesian_factors()
    ....:                         if f.variable_name() not in s_vars),
    ....:                     CartesianProductPoly(
    ....:                     other.cartesian_factors() +
    ....:                     tuple(f for f in self.cartesian_factors()
    ....:                         if f.variable_name() not in o_vars)))
    ....:             C = other.construction()
    ....:             if C is None:
    ....:                 return
    ....:             elif isinstance(C[0], PolynomialFunctor):
    ....:                 return pushout(self, CartesianProductPoly((other,)))

sage: pushout(CartesianProductPoly((ZZ['x'],)),
....:          CartesianProductPoly((ZZ['y'],)))
The Cartesian product of
 (Univariate Polynomial Ring in x over Integer Ring,
  Univariate Polynomial Ring in y over Integer Field)
```

(continues on next page)
Univariate Polynomial Ring in y over Integer Ring)
sage: pushout(CartesianProductPoly((ZZ['x'], ZZ['y'])),
....: CartesianProductPoly((ZZ['x'], ZZ['z'])))
The Cartesian product of
(Univariate Polynomial Ring in x over Integer Ring,
Univariate Polynomial Ring in y over Integer Ring,
Univariate Polynomial Ring in z over Integer Ring)
sage: pushout(CartesianProductPoly((QQ['a,b'] ['x'], QQ['y'])),
˓→needs sage.symbolic
....: CartesianProductPoly((ZZ['b,c'] ['x'], SR['z'])))
The Cartesian product of
(Univariate Polynomial Ring in x over
Multivariate Polynomial Ring in a, b, c over Rational Field,
Univariate Polynomial Ring in y over Rational Field,
Univariate Polynomial Ring in z over Symbolic Ring)
sage: pushout(CartesianProductPoly((ZZ['x'],)), ZZ['y'])
The Cartesian product of
(Univariate Polynomial Ring in x over Integer Ring,
Univariate Polynomial Ring in y over Integer Ring)
sage: pushout(QQ['b,c']['y'], CartesianProductPoly((ZZ['a,b']['x'],)))
The Cartesian product of
(Multivariate Polynomial Ring in a, b over Integer Ring,
Multivariate Polynomial Ring in y over
Multivariate Polynomial Ring in b, c over Rational Field)
sage: pushout(CartesianProductPoly((ZZ['x'],)), ZZ)
Traceback (most recent call last):
...
CoercionException: No common base ("join") found for
The cartesian_product functorial construction(...) and None(Integer Ring):
(Multivariate) functors are incompatible.

AUTHORS:
• Robert Bradshaw
• Peter Bruin
• Simon King
• Daniel Krenn
• David Roe

sage.categories.pushout.pushout_lattice(R, S)
Given a pair of objects $R$ and $S$, try to construct a reasonable object $Y$ and return maps such that canonically
$R \leftarrow Y \rightarrow S$.

ALGORITHM:
This is based on the model that arose from much discussion at Sage Days 4. Going up the tower of constructions
of $R$ and $S$ (e.g. the reals come from the rationals come from the integers), try to find a common parent, and then
try to fill in a lattice with these two towers as sides with the top as the common ancestor and the bottom will be the
desired ring.
See the code for a specific worked-out example.

EXAMPLES:
AUTHOR:

- Robert Bradshaw

**sage.categories.pushout.type_to_parent**(*P*)

An auxiliary function that is used in **pushout**.

INPUT:

A type

OUTPUT:

A Sage parent structure corresponding to the given type

3.4 Coercion via construction functors
4.1 Group, ring, etc. actions on objects

The terminology and notation used is suggestive of groups acting on sets, but this framework can be used for modules, algebras, etc.

A group action $G \times S \to S$ is a functor from $G$ to Sets.

**Warning:** An `Action` object only keeps a weak reference to the underlying set which is acted upon. This decision was made in [github issue #715](https://github.com/sagemath/sage/issues/715) in order to allow garbage collection within the coercion framework (this is where actions are mainly used) and avoid memory leaks.

```sage
def f(x):
    return x**2

f(2)
```

To avoid garbage collection of the underlying set, it is sufficient to create a strong reference to it before the action is created.

```sage
def f(x):
    return x**2

f(2)
```

**AUTHOR:**

- Robert Bradshaw: initial version

```python
class sage.categories.action.Action
    Bases: Functor

    The action of $G$ on $S$.

    INPUT:
```
• $G$ – a parent or Python type
• $S$ – a parent or Python type
• is_left – (boolean, default: True) whether elements of $G$ are on the left
• op – (default: None) operation. This is not used by $Action$ itself, but other classes may use it

$G$ act $(g, x)$

This is a consistent interface for acting on $x$ by $g$, regardless of whether it’s a left or right action.

If needed, $g$ and $x$ are converted to the correct parent.

EXAMPLES:

```python
sage: R.<x> = ZZ []
sage: from sage.structure.coerce_actions import IntegerMulAction
sage: A = IntegerMulAction(ZZ, R, True)  # Left action
sage: A.act(5, x)
5*x
sage: A.act(int(5), x)
5*x
sage: A = IntegerMulAction(ZZ, R, False)  # Right action
sage: A.act(5, x)
5*x
sage: A.act(int(5), x)
5*x
```

actor()
codomain()
domain()
is_left()
left_domain()
op
operation()
right_domain()

class sage.categories.action.ActionEndomorphism

Bases: Morphism

The endomorphism defined by the action of one element.

EXAMPLES:

```python
sage: A = ZZ['x'].get_action(QQ, self_on_left=False, op=operator.mul)
sage: A
Left scalar multiplication by Rational Field on Univariate Polynomial Ring in x over Integer Ring
sage: A(1/2)
Action of 1/2 on Univariate Polynomial Ring in x over Integer Ring under Left scalar multiplication by Rational Field on Univariate Polynomial Ring in x over Integer Ring.
```
class sage.categories.action.InverseAction

Bases: Action

An action that acts as the inverse of the given action.

EXAMPLES:

```python
sage: V = QQ^3
sage: v = V((1, 2, 3))
sage: cm = get_coercion_model()
sage: a = cm.get_action(V, QQ, operator.mul)
sage: a
Right scalar multiplication by Rational Field
on Vector space of dimension 3 over Rational Field
sage: ~a
Right inverse action by Rational Field
on Vector space of dimension 3 over Rational Field
sage: (~a)(v, 1/3)
(3, 6, 9)
sage: b = cm.get_action(QQ, V, operator.mul)
sage: b
Left scalar multiplication by Rational Field
on Vector space of dimension 3 over Rational Field
sage: ~b
Left inverse action by Rational Field
on Vector space of dimension 3 over Rational Field
sage: (~b)(1/3, v)
(3, 6, 9)
sage: c = cm.get_action(ZZ, list, operator.mul)
sage: c
Left action by Integer Ring on <... list>
sage: ~c
Traceback (most recent call last):
  ... TypeError: no inverse defined for Left action by Integer Ring on <... 'list'>
```

codomain()

class sage.categories.action.PrecomposedAction

Bases: Action

A precomposed action first applies given maps, and then applying an action to the return values of the maps.

EXAMPLES:

We demonstrate that an example discussed on github issue #14711 did not become a problem:

```python
sage: E = ModularSymbols(11).2
sage: s = E.modular_symbol_rep()
sage: del E, s
sage: import gc
```

(continues on next page)
sage: _ = gc.collect()
sage: E = ModularSymbols(11).2
sage: v = E.manin_symbol_rep()
sage: c, x = v[0]
sage: y = x.modular_symbol_rep()
sage: coercion_model.get_action(QQ, parent(y), op=operator.mul)
Left scalar multiplication by Rational Field
on Abelian Group of all Formal Finite Sums over Rational Field
with precomposition on right by Coercion map:
From: Abelian Group of all Formal Finite Sums over Integer Ring
To: Abelian Group of all Formal Finite Sums over Rational Field

codomain()

domain()

\textbf{left\_precomposition}

The left map to precompose with, or \texttt{None} if there is no left precomposition map.

\textbf{right\_precomposition}

The right map to precompose with, or \texttt{None} if there is no right precomposition map.

\section{Additive groups}

\begin{verbatim}
class sage.categories.additive_groups.AdditiveGroups(base_category):
    Bases: CategoryWithAxiom_singleton

    The category of additive groups.

    An additive group is a set with an internal binary operation $+$ which is associative, admits a zero, and where every element can be negated.

    EXAMPLES:

    sage: from sage.categories.additive_groups import AdditiveGroups
    sage: from sage.categories.additive_monoids import AdditiveMonoids
    sage: AdditiveGroups()
    Category of additive groups
    sage: AdditiveGroups().super_categories()
    [Category of additive inverse additive unital additive magmas,
     Category of additive monoids]
    sage: AdditiveGroups().all_super_categories()
    [Category of additive groups,
     Category of additive inverse additive unital additive magmas,
     Category of additive monoids,
     Category of additive unital additive magmas,
     Category of additive semigroups,
     Category of additive magmas,
     Category of sets,
     Category of sets with partial maps,
     Category of objects]
    sage: AdditiveGroups().axioms()
    frozenset({'AdditiveAssociative', 'AdditiveInverse', 'AdditiveUnital'})
\end{verbatim}
sage: AdditiveGroups() is AdditiveMonoids().AdditiveInverse()
True

AdditiveCommutative
   alias of CommutativeAdditiveGroups
class Algebras(category, *args)
   Bases: AlgebrasCategory
class ParentMethods
   Bases: object
group()
   Return the underlying group of the group algebra.
   EXAMPLES:
   sage: GroupAlgebras(QQ).example(GL(3, GF(11))).group()  
   ␣ ˓→ # needs sage.groups sage.modules
   General Linear Group of degree 3 over Finite Field of size 11
   sage: SymmetricGroup(10).algebra(QQ).group()  
   ␣ ˓→ # needs sage.groups sage.modules
   Symmetric group of order 10! as a permutation group

class Finite(base_category)
   Bases: CategoryWithAxiom_singleton
class Algebras(category, *args)
   Bases: AlgebrasCategory
class ParentMethods
   Bases: object
   extra_super_categories()
   Implement Maschke’s theorem.
   In characteristic 0 all finite group algebras are semisimple.
   EXAMPLES:
   sage: FiniteGroups().Algebras(QQ).is_subcategory(Algebras(QQ).Semisimple())
   True
   sage: FiniteGroups().Algebras(FiniteField(7)).is_subcategory(Algebras(FiniteField(7)).Semisimple())
   False
   sage: FiniteGroups().Algebras(ZZ).is_subcategory(Algebras(ZZ).Semisimple())
   False
   sage: FiniteGroups().Algebras(Fields()).is_subcategory(Algebras(Fields()).Semisimple())
   False
   sage: Cat = CommutativeAdditiveGroups().Finite()
sage: Cat.Algebras(QQ).is_subcategory(Categories.Algebras(QQ).Semisimple())
   True
   sage: Cat.Algebras(GF(7)).is_subcategory(Categories.Algebras(GF(7)).Semisimple())
   False

4.2. Additive groups
4.3 Additive magmas

```python
class sage.categories.additive_magmas.AdditiveMagmas
    Bases: Category_singleton

    The category of additive magmas.

    An additive magma is a set endowed with a binary operation +.

    EXAMPLES:

    sage: AdditiveMagmas()
    Category of additive magmas
    sage: AdditiveMagmas().super_categories()
    [Category of sets]
    sage: AdditiveMagmas().all_super_categories()
    [Category of additive magmas, 
     Category of sets, 
     Category of sets with partial maps, 
     Category of objects]
```

The following axioms are defined by this category:

```python
sage: AdditiveMagmas().AdditiveAssociative()
Category of additive semigroups
sage: AdditiveMagmas().AdditiveUnital()
Category of additive unital additive magmas
sage: AdditiveMagmas().AdditiveCommutative()
Category of additive commutative additive magmas
sage: AdditiveMagmas().AdditiveUnital().AdditiveInverse()
Category of additive inverse additive unital additive magmas
sage: C = AdditiveMagmas().AdditiveAssociative().AdditiveCommutative(); C
Category of commutative additive semigroups
sage: C.AdditiveUnital()
Category of commutative additive monoids
sage: C.AdditiveUnital().AdditiveInverse()
Category of commutative additive groups
```

**AdditiveAssociative**

alias of `AdditiveSemigroups`

**class AdditiveCommutative** *(base_category)*

Bases: `CategoryWithAxiom_singleton`

**class Algebras** *(category, *args)*

Bases: `AlgebrasCategory`
extra_super_categories()
Implement the fact that the algebra of a commutative additive magmas is commutative.

EXAMPLES:
```python
sage: C = AdditiveMagmas().AdditiveCommutative().Algebras(QQ)
sage: C.extra_super_categories()
[Category of commutative magmas]
sage: C.super_categories()
[Category of additive magma algebras over Rational Field, Category of commutative magmas]
```

class CartesianProducts(category, *args)
Bases: CartesianProductsCategory
extra_super_categories()
Implement the fact that a Cartesian product of commutative additive magmas is a commutative additive magma.

EXAMPLES:
```python
sage: C = AdditiveMagmas().AdditiveCommutative().CartesianProducts()
sage: C.extra_super_categories()
[Category of additive commutative additive magmas]
sage: C.axioms()
frozenset({'AdditiveCommutative'})
```

class AdditiveUnital(base_category)
Bases: CategoryWithAxiom_singleton

class AdditiveInverse(base_category)
Bases: CategoryWithAxiom_singleton

class CartesianProducts(category, *args)
Bases: CartesianProductsCategory

class ElementMethods
Bases: object
extra_super_categories()
Implement the fact that a Cartesian product of additive magmas with inverses is an additive magma with inverse.

EXAMPLES:
```python
sage: C = AdditiveMagmas().AdditiveUnital().AdditiveInverse().CartesianProducts()
sage: C.extra_super_categories()
[Category of additive inverse additive unital additive magmas]
sage: sorted(C.axioms())
['AdditiveInverse', 'AdditiveUnital']
```

class Algebras(category, *args)
Bases: AlgebrasCategory

class ParentMethods
Bases: object
one_basis()

Return the zero of this additive magma, which index the one of this algebra, as per
AlgebrasWithBasis.ParentMethods.one_basis().

EXAMPLES:

```
sage: # needs sage.modules
sage: S = CommutativeAdditiveMonoids().example(); S
An example of a commutative monoid:
the free commutative monoid generated by ('a', 'b', 'c', 'd')
sage: A = S.algebra(ZZ)
sage: A.one_basis()
0
sage: A.one()
B[0]
sage: A(3)
3*B[0]
```

extra_super_categories()

EXAMPLES:

```
sage: C = AdditiveMagmas().AdditiveUnital().Algebras(QQ)
sage: C.extra_super_categories()
[Category of unital magmas]
sage: C.super_categories()
[Category of unital algebras with basis over Rational Field, 
Category of additive magma algebras over Rational Field]
```

class CartesianProducts(category, *args)

Bases: CartesianProductsCategory

class ParentMethods

Bases: object

zero()

Returns the zero of this group

EXAMPLES:

```
sage: GF(8, 'x').cartesian_product(GF(5)).zero()
# needs sage.rings.finite_rings
(0, 0)
```

extra_super_categories()

Implement the fact that a Cartesian product of unital additive magmas is a unital additive magma.

EXAMPLES:

```
sage: C = AdditiveMagmas().AdditiveUnital().CartesianProducts()
sage: C.extra_super_categories()
[Category of additive unital additive magmas]
sage: C.axioms()
frozenset({'AdditiveUnital'})
```

class ElementMethods

Bases: object
class Homsets(category, *args)
    Bases: HomsetsCategory

class ParentMethods
    Bases: object
    zero()

    EXAMPLES:
    sage: R = QQ['x']
    sage: H = Hom(ZZ, R, AdditiveMagmas().AdditiveUnital())
    sage: f = H.zero()
    sage: f
    Generic morphism:
        From: Integer Ring
        To:   Univariate Polynomial Ring in x over Rational Field
    sage: f(3)
    0
    sage: f(3) is R.zero()
    True

extra_super_categories()

    Implement the fact that a homset between two unital additive magmas is a unital additive magma.

    EXAMPLES:
    sage: AdditiveMagmas().AdditiveUnital().Homsets().extra_super_categories()
    [Category of additive unital additive magmas]
    sage: AdditiveMagmas().AdditiveUnital().Homsets().super_categories()
    [Category of additive unital additive magmas, Category of homsets]

class ParentMethods
    Bases: object
    is_empty()

    Return whether this set is empty.

    Since this set is an additive magma it has a zero element and hence is not empty. This method thus always returns False.

    EXAMPLES:
    sage: # needs sage.modules
    sage: A = AdditiveAbelianGroup([3, 3])
    sage: A in AdditiveMagmas()
    True
    sage: A.is_empty()
    False
    sage: B = CommutativeAdditiveMonoids().example()
    sage: B.is_empty()
    False

    zero()

    Return the zero of this additive magma, that is the unique neutral element for +.

    The default implementation is to coerce 0 into self.

    It is recommended to override this method because the coercion from the integers:
• is not always meaningful (except for 0), and
• often uses self.zero() otherwise.

EXAMPLES:

```sage
cat = CommutativeAdditiveMonoids().example()
cat.zero()
0
```

class SubcategoryMethods

Bases: object

AdditiveInverse()

Return the full subcategory of the additive inverse objects of self.

An inverse additive magma is a unital additive magma such that every element admits both an additive inverse on the left and on the right. Such an additive magma is also called an additive loop.

See also:

Wikipedia article Inverse_element, Wikipedia article Quasigroup

EXAMPLES:

```sage
AdditiveMags().AdditiveUnital().AdditiveInverse()
Category of additive inverse additive unital additive magmas
cat = AdditiveMonoids().AdditiveInverse()
cat
Category of additive groups
```

class WithRealizations (category, *args)

Bases: WithRealizationsCategory

class ParentMethods

Bases: object

zero()

Return the zero of this unital additive magma.

This default implementation returns the zero of the realization of self given by a_realization().

EXAMPLES:

```sage
A = Sets().WithRealizations().example(); A
The subset algebra of {1, 2, 3} over Rational Field
A.zero.__module__
'sage.categories.additive_magmas'
A.zero()
0
```

additional_structure()

Return whether self is a structure category.

See also:

Category.additional_structure()
The category of unital additive magmas defines the zero as additional structure, and this zero shall be preserved by morphisms.

EXAMPLES:

```python
sage: AdditiveMagmas().AdditiveUnital().additional_structure()
Category of additive unital additive magmas
```

```python
class Algebras(category, *args)
    Bases: AlgebrasCategory

class ParentMethods
    Bases: object

    algebra_generators()
    The generators of this algebra, as per MagmaticAlgebras.ParentMethods.
    algebra_generators().

    They correspond to the generators of the additive semigroup.

    EXAMPLES:

    ```python
    sage: S = CommutativeAdditiveSemigroups().example(); S
    An example of a commutative semigroup: the free commutative semigroup generated by ('a', 'b', 'c', 'd')
    sage: A = S.algebra(QQ)  # needs sage.modules
    sage: A.algebra_generators()  # needs sage.modules
    Family (B[a], B[b], B[c], B[d])
    ```

Todo: This doctest does not actually test this method, but rather the method of the same name for AdditiveSemigroups. Find a better doctest!

```python
product_on_basis(gl, g2)
Product, on basis elements, as per MagmaticAlgebras.WithBasis.ParentMethods.
product_on_basis().

The product of two basis elements is induced by the addition of the corresponding elements of the group.

EXAMPLES:

```python
sage: S = CommutativeAdditiveSemigroups().example(); S
An example of a commutative semigroup: the free commutative semigroup generated by ('a', 'b', 'c', 'd')
```

Todo: This doctest does not actually test this method, but rather the method of the same name for AdditiveSemigroups. Find a better doctest!
extra_super_categories()

EXAMPLES:

```
sage: AdditiveMagmas().Algebras(QQ).extra_super_categories()
[Category of magmatic algebras with basis over Rational Field]

sage: AdditiveMagmas().Algebras(QQ).super_categories()
[Category of magmatic algebras with basis over Rational Field,
 Category of set algebras over Rational Field]
```

class CartesianProducts (category, *args)

Bases: CartesianProductsCategory

class ElementMethods

Bases: object

element.extra_super_categories()

Implement the fact that a Cartesian product of additive magmas is an additive magma.

EXAMPLES:

```
sage: C = AdditiveMagmas().CartesianProducts()
sage: C.extra_super_categories()
[Category of additive magmas]
sage: C.super_categories()
[Category of additive magmas, Category of Cartesian products of sets]
sage: C.axioms()
frozenset()
```

class ElementMethods

Bases: object

class Homsets (category, *args)

Bases: HomsetsCategory

element.extra_super_categories()

Implement the fact that a homset between two magmas is a magma.

EXAMPLES:

```
sage: AdditiveMagmas().Homsets().extra_super_categories()
[Category of additive magmas]
sage: AdditiveMagmas().Homsets().super_categories()
[Category of additive magmas, Category of homsets]
```

class ParentMethods

Bases: object

addition_table (names='letters', elements=None)

Return a table describing the addition operation.

Note: The order of the elements in the row and column headings is equal to the order given by the table’s column_keys() method. The association can also be retrieved with the translation() method.

INPUT:
• names—the type of names used:
  – 'letters'—lowercase ASCII letters are used for a base 26 representation of the elements’
    positions in the list given by column_keys(), padded to a common width with leading ‘a’s.
  – 'digits'—base 10 representation of the elements’ positions in the list given by col-
    umn_keys(), padded to a common width with leading zeros.
  – 'elements'—the string representations of the elements themselves.
  – a list—a list of strings, where the length of the list equals the number of elements.
• elements—(default: None)A list of elements of the additive magma, in forms that can be coerced
  into the structure, eg. their string representations. This may be used to impose an alternate ordering
  on the elements, perhaps when this is used in the context of a particular structure. The default is to
  use whatever ordering the S.list method returns. Or the elements can be a subset which is
  closed under the operation. In particular, this can be used when the base set is infinite.

OUTPUT:

The addition table as an object of the class OperationTable which defines several methods for
manipulating and displaying the table. See the documentation there for full details to supplement the
documentation here.

EXAMPLES:

All that is required is that an algebraic structure has an addition defined. The default is to represent el-
ements as lowercase ASCII letters.

```sage
sage: R = IntegerModRing(5)
sage: R.addition_table()  #--
    + a b c d e
   |---------
 a| a b c d e
 b| b c d e a
 c| c d e a b
 d| d e a b c
 e| e a b c d
```

The names argument allows displaying the elements in different ways. Requesting elements will use
the representation of the elements of the set. Requesting digits will include leading zeros as padding.

```sage
sage: R = IntegerModRing(11)
sage: P = R.addition_table(names='elements'); P  #--
    + 0 1 2 3 4 5 6 7 8 9 10
    |-----------------------
 0| 0 1 2 3 4 5 6 7 8 9 10
 1| 1 2 3 4 5 6 7 8 9 10 0
 2| 2 3 4 5 6 7 8 9 10 0 1
 3| 3 4 5 6 7 8 9 10 0 1 2
 4| 4 5 6 7 8 9 10 0 1 2 3
 5| 5 6 7 8 9 10 0 1 2 3 4
 6| 6 7 8 9 10 0 1 2 3 4 5
 7| 7 8 9 10 0 1 2 3 4 5 6
 8| 8 9 10 0 1 2 3 4 5 6 7
 9| 9 10 0 1 2 3 4 5 6 7 8
10| 10 0 1 2 3 4 5 6 7 8 9

sage: T = R.addition_table(names='digits'); T  #--
    + 00 01 02 03 04 05 06 07 08 09 10
    |-------------------------
 00| 00 01 02 03 04 05 06 07 08 09 10
 01| 01 02 03 04 05 06 07 08 09 10 00
 02| 02 03 04 05 06 07 08 09 10 01
 03| 03 04 05 06 07 08 09 10 02
 04| 04 05 06 07 08 09 10 03
 05| 05 06 07 08 09 10 04
 06| 06 07 08 09 10 05
 07| 07 08 09 10 06
 08| 08 09 10 07
 09| 09 10 08
 10| 10 09
```

(continues on next page)
Specifying the elements in an alternative order can provide more insight into how the operation behaves.

```
sage: S = IntegerModRing(7)
sage: elts = [0, 3, 6, 2, 5, 1, 4]
sage: S.addition_table(elements=elts) # needs sage.modules
+ a b c d e f g
+------------
a| a b c d e f g
b| b c d e f g a
  c| c d e f g a b
d| d e f g a b c
e| e f g a b c d
f| f g a b c d e
g| g a b c d e
```

The `elements` argument can be used to provide a subset of the elements of the structure. The subset must be closed under the operation. Elements need only be in a form that can be coerced into the set. The `names` argument can also be used to request that the elements be represented with their usual string representation.

```
sage: T = IntegerModRing(12)
sage: elts = [0, 3, 6, 9]
sage: T.addition_table(names='elements', elements=elts) # needs sage.modules
+ 0 3 6 9
+--------
0| 0 3 6 9
3| 3 6 9 0
6| 6 9 0 3
9| 9 0 3 6
```

The table returned can be manipulated in various ways. See the documentation for `OperationTable` for more comprehensive documentation.

```
sage: # needs sage.modules
sage: R = IntegerModRing(3)
sage: T = R.addition_table()
sage: T.column_keys()
(0, 1, 2)
sage: sorted(T.translation().items())[['a', 0], ['b', 1], ['c', 2]]
sage: T.change_names(['x', 'y', 'z'])
sage: sorted(T.translation().items())
```

(continues on next page)
summation \( (x, y) \)

Return the sum of \( x \) and \( y \).

The binary addition operator of this additive magma.

INPUT:

- \( x, y \) – elements of this additive magma

EXAMPLES:

```
sage: S = CommutativeAdditiveSemigroups().example()
sage: (a,b,c,d) = S.additive_semigroup_generators()
sage: S.summation(a, b)
a + b
```

A parent in `AdditiveMagmas()` must either implement `summation()` in the parent class or `_add_` in the element class. By default, the addition method on elements \( x._add_(y) \) calls \( S.\) summation\((x,y)\), and reciprocally.

As a bonus effect, \( S.\) summation by itself models the binary function from \( S \) to \( S \):

```
sage: bin = S.summation
sage: bin(a,b)
a + b
```

Here, \( S.\) summation is just a bound method. Whenever possible, it is recommended to enrich \( S.\) summation with extra mathematical structure. Lazy attributes can come handy for this.

**Todo:** Add an example.

summation\_from\_element\_class\_add \( (x, y) \)

Return the sum of \( x \) and \( y \).

The binary addition operator of this additive magma.

INPUT:

- \( x, y \) – elements of this additive magma

EXAMPLES:

```
sage: S = CommutativeAdditiveSemigroups().example()
sage: (a,b,c,d) = S.additive_semigroup_generators()
sage: S.summation(a, b)
a + b
```

A parent in `AdditiveMagmas()` must either implement `summation()` in the parent class or `_add_` in the element class. By default, the addition method on elements \( x._add_(y) \) calls \( S.\) summation\((x,y)\), and reciprocally.

As a bonus effect, \( S.\) summation by itself models the binary function from \( S \) to \( S \):
Here, \texttt{S.summation} is just a bound method. Whenever possible, it is recommended to enrich \texttt{S.summation} with extra mathematical structure. Lazy attributes can come handy for this.

\textbf{Todo:} Add an example.

```python
class SubcategoryMethods:
    Bases: object

    AdditiveAssociative():
        Return the full subcategory of the additive associative objects of self.
        An additive magma \( M \) is associative if, for all \( x, y, z \in M \),
        \[
        x + (y + z) = (x + y) + z
        \]

        See also:
        Wikipedia article Associative_property

        EXAMPLES:
        sage: AdditiveMagmas().AdditiveAssociative()
        Category of additive semigroups

    AdditiveCommutative():
        Return the full subcategory of the commutative objects of self.
        An additive magma \( M \) is commutative if, for all \( x, y \in M \),
        \[
        x + y = y + x
        \]

        See also:
        Wikipedia article Commutative_property

        EXAMPLES:
        sage: AdditiveMagmas().AdditiveCommutative()
        Category of additive commutative additive magmas
        sage: C = AdditiveMagmas().AdditiveAssociative().AdditiveUnital()
        sage: C.AdditiveCommutative()
        Category of commutative additive monoids
        sage: C.AdditiveCommutative() is CommutativeAdditiveMonoids()
        True

    AdditiveUnital():
        Return the subcategory of the unital objects of self.
        An additive magma \( M \) is unital if it admits an element 0, called neutral element, such that for all \( x \in M \),
        \[
        0 + x = x + 0 = x
        \]
This element is necessarily unique, and should be provided as $M.zero()$.

See also:
Wikipedia article Unital magma

EXAMPLES:

```python
sage: AdditiveMagmas().AdditiveUnital()
Category of additive unital additive magmas
sage: from sage.categories.additive_semigroups import AdditiveSemigroups
sage: AdditiveSemigroups().AdditiveUnital()
Category of additive monoids
sage: CommutativeAdditiveMonoids().AdditiveUnital()
Category of commutative additive monoids
```

```
super_categories()

EXAMPLES:
```python
sage: AdditiveMagmas().super_categories()
[Category of sets]
```

### 4.4 Additive monoids

**class** `sage.categories.additive_monoids.AdditiveMonoids` *(base_category)*

Bases: `CategoryWithAxiom_singleton`

The category of additive monoids.

An *additive monoid* is a unital *additive semigroup*, that is a set endowed with a binary operation $+$ which is associative and admits a zero (see Wikipedia article Monoid).

**EXAMPLES:**

```python
sage: from sage.categories.additive_monoids import AdditiveMonoids
sage: C = AdditiveMonoids(); C
Category of additive monoids
sage: C.super_categories()
[Category of additive unital additive magmas, Category of additive semigroups]
sage: sorted(C.axioms())
[AdditiveAssociative, AdditiveUnital]
sage: from sage.categories.additive_semigroups import AdditiveSemigroups
sage: C is AdditiveSemigroups().AdditiveUnital()
True
```

**AdditiveCommutative**

alias of `CommutativeAdditiveMonoids`

**AdditiveInverse**

alias of `AdditiveGroups`

**class** `Homsets` *(category, *args)*

Bases: `HomsetsCategory`

```
extra_super_categories()
```

Implement the fact that a homset between two monoids is associative.

**EXAMPLES:**

4.4. Additive monoids
Todo: This could be deduced from `AdditiveSemigroups.Homsets. extra_super_categories()`. See comment in `Objects.SubcategoryMethods.Homsets()`.

class ParentMethods
Bases: object

```
sage: S = CommutativeAdditiveMonoids().example()
sage: (a,b,c,d) = S.additive_semigroup_generators()
sage: S.sum((a,b,a,c,a,b))
3*a + 2*b + c
sage: S.sum(())
0
sage: S.sum(()).parent() == S
True
```

4.5 Additive semigroups

class sage.categories.additive_semigroups.AdditiveSemigroups(base_category)
Bases: CategoryWithAxiom_singleton

The category of additive semigroups.

An additive semigroup is an associative additive magma, that is a set endowed with an operation + which is associative.

EXAMPLES:

```
sage: from sage.categories.additive_semigroups import AdditiveSemigroups
sage: C = AdditiveSemigroups(); C
Category of additive semigroups
sage: C.super_categories()
[Category of additive magmas]
sage: C.all_super_categories()
[Category of additive semigroups,
 Category of additive magmas,
 Category of sets,
 Category of sets with partial maps,
 Category of objects]
```
AdditiveCommutative
   alias of CommutativeAdditiveSemigroups

AdditiveUnital
   alias of AdditiveMonoids

class Algebras(category, *args)
   Bases: AlgebrasCategory

class ParentMethods
   Bases: object

    algebra_generators()
    Return the generators of this algebra, as per MagmaticAlgebras.ParentMethods.
    algebra_generators().

    They correspond to the generators of the additive semigroup.

    EXAMPLES:

    sage: S = CommutativeAdditiveSemigroups().example(); S
    An example of a commutative semigroup:
    the free commutative semigroup generated by ('a', 'b', 'c', 'd')
    sage: A = S.algebra(QQ)  #...
    sage: A.algebra_generators()  #...
    Family (B[a], B[b], B[c], B[d])

    product_on_basis(g1, g2)
    Product, on basis elements, as per MagmaticAlgebras.WithBasis.ParentMethods.
    product_on_basis().

    The product of two basis elements is induced by the addition of the corresponding elements of the group.

    EXAMPLES:

    sage: S = CommutativeAdditiveSemigroups().example(); S
    An example of a commutative semigroup:
    the free commutative semigroup generated by ('a', 'b', 'c', 'd')
    sage: A = S.algebra(QQ)  #...
    sage: a, b, c, d = A.algebra_generators()  #...
    sage: b * d * c  #...
    B[b + c + d]

    extra_super_categories()

    EXAMPLES:

4.5. Additive semigroups
4.6 Affine Weyl groups

class sage.categories.affine_weyl_groups.AffineWeylGroups

Bases: Category_singleton

The category of affine Weyl groups

Todo: add a description of this category

See also:
- Wikipedia article Affine_weyl_group
- WeylGroups, WeylGroup
EXAMPLES:

```python
sage: C = AffineWeylGroups(); C
Category of affine Weyl groups
sage: C.super_categories()
[Category of infinite Weyl groups]

sage: C.example()
NotImplemented

sage: W = WeylGroup(['A', 4, 1]); W
Weyl Group of type ['A', 4, 1] (as a matrix group acting on the root space)
sage: W.category()
Category of irreducible affine Weyl groups
```

```python
class ElementMethods
    Bases: object

    affine_grassmannian_to_core()

    Bijection between affine Grassmannian elements of type $A_k^{(1)}$ and $(k+1)$-cores.

    INPUT:
    • self – an affine Grassmannian element of some affine Weyl group of type $A_k^{(1)}$

    Recall that an element $w$ of an affine Weyl group is affine Grassmannian if all its all reduced words end in 0, see `is_affine_grassmannian()`.

    OUTPUT:
    • a $(k+1)$-core

    See also:

    affine_grassmannian_to_partition()
```

```python
EXAMPLES:

```python
sage: W = WeylGroup(['A', 2, 1])
sage: w = W.from_reduced_word([0,2,1,0])
sage: la = w.affine_grassmannian_to_core(); la
[4, 2]
sage: type(la)
<class 'sage.combinat.cores.Cores_length_with_category.element_class'>
sage: la.to_grassmannian() == w
True
```

```python
sage: w = W.from_reduced_word([0,2,1])
Traceback (most recent call last):
...
ValueError: this only works on type 'A' affine Grassmannian elements
```

```python
affine_grassmannian_to_partition()

Bijection between affine Grassmannian elements of type $A_k^{(1)}$ and $k$-bounded partitions.

INPUT:
• self is affine Grassmannian element of the affine Weyl group of type $A_k^{(1)}$ (i.e. all reduced words end in 0)
```
• \( k \)-bounded partition

See also:

`affine_grassmannian_to_core()`

**EXAMPLES:**

```sage
# needs sage.combinat sage.groups
sage: k = 2
sage: W = WeylGroup(['A', k, 1])
sage: w = W.from_reduced_word([0,2,1,0])
sage: la = w.affine_grassmannian_to_partition(); la
[2, 2]
sage: la.from_kbounded_to_grassmannian(k) == w
True
```

`is_affine_grassmannian()`

Test whether `self` is affine Grassmannian.

An element of an affine Weyl group is *affine Grassmannian* if any of the following equivalent properties holds:

• all reduced words for `self` end with 0.
• `self` is the identity, or 0 is its single right descent.
• `self` is a minimal coset representative for \( W / \text{cl} \ W \).

**EXAMPLES:**

```sage
# needs sage.combinat sage.groups
sage: W = WeylGroup(['A', 3, 1])
sage: w = W.from_reduced_word([2,1,0])
sage: w.is_affine_grassmannian()
True
sage: w = W.from_reduced_word([2,0])
sage: w.is_affine_grassmannian()
False
sage: W.one().is_affine_grassmannian()
True
```

**class ParentMethods**

**Bases:** object

**affine_grassmannian_elements_of_given_length\( (k) \)**

Return the affine Grassmannian elements of length \( k \).

This is returned as a finite enumerated set.

**EXAMPLES:**

```sage
# needs sage.combinat sage.groups
sage: W = WeylGroup(['A', 3, 1])
#˓→ needs sage.combinat sage.groups
sage: [x.reduced_word() for x in W.affine_grassmannian_elements_of_given_length(3)]
[[2, 1, 0], [3, 1, 0], [2, 3, 0]]
```

See also:

`AffineWeylGroups.ElementMethods.is_affine_grassmannian()`
special_node()

Return the distinguished special node of the underlying Dynkin diagram.

EXAMPLES:

```sage
sage: W = WeylGroup(['A', 3, 1])
    # needs sage.combinat sage.groups
sage: W.special_node()    # needs sage.combinat sage.groups
0
```

additional_structure()

Return None.

Indeed, the category of affine Weyl groups defines no additional structure: affine Weyl groups are a special class of Weyl groups.

See also:

Category.additional_structure()

Todo: Should this category be a CategoryWithAxiom?

EXAMPLES:

```sage
sage: AffineWeylGroups().additional_structure()
```

super_categories()

EXAMPLES:

```sage
sage: AffineWeylGroups().super_categories()
[Category of infinite Weyl groups]
```

4.7 Algebra ideals

class sage.categories.algebra_ideals.AlgebraIdeals(A)

Bases: Category_ideal

The category of two-sided ideals in a fixed algebra $A$.

EXAMPLES:

```sage
sage: AlgebraIdeals(QQ['a'])
Category of algebra ideals in Univariate Polynomial Ring in a over Rational Field
```

Todo:

- Add support for non commutative rings (this is currently not supported by the subcategory `AlgebraModules`).
- Make `AlgebraIdeals(R).return CommutativeAlgebraIdeals(R)` when $R$ is commutative.
- If useful, implement `AlgebraLeftIdeals` and `AlgebraRightIdeals` of which `AlgebraIdeals` would be a subcategory.
algebra()  
EXAMPLES:

```python
sage: AlgebraIdeals(QQ['x']).algebra()
Univariate Polynomial Ring in x over Rational Field
```

super_categories()  
The category of algebra modules should be a super category of this category.  
However, since algebra modules are currently only available over commutative rings, we have to omit it if our ring is non-commutative.  
EXAMPLES:

```python
sage: AlgebraIdeals(QQ['x']).super_categories()  # needs sage.combinat sage.modules
[Category of algebra modules over Univariate Polynomial Ring in x over Rational Field]
```

## 4.8 Algebra modules

```python
# needs sage.combinat sage.modules
sage: C = AlgebraIdeals(FreeAlgebra(QQ, 2, 'a,b'))  # needs sage.combinat sage.modules
sage: C.super_categories()
[]
```

class  
sage.categories.algebra_modules.AlgebraModules(A)  
Bases: Category_module  
The category of modules over a fixed algebra $A$.  
EXAMPLES:

```python
sage: AlgebraModules(QQ['a'])
Category of algebra modules over Univariate Polynomial Ring in a over Rational Field
```

Note: as of now, $A$ is required to be commutative, ensuring that the categories of left and right modules are isomorphic. Feedback and use cases for potential generalizations to the non commutative case are welcome.

algebra()  
EXAMPLES:

```python
sage: AlgebraModules(QQ['x']).algebra()
Univariate Polynomial Ring in x over Rational Field
```

classmethod an_instance()  
Returns an instance of this class  
EXAMPLES:

```python
sage: AlgebraModules.an_instance()
Category of algebra modules over Univariate Polynomial Ring in x over Rational Field
```
**super_categories()**

EXAMPLES:

```python
sage: AlgebraModules(QQ['x']).super_categories()
[Category of modules over Univariate Polynomial Ring in x over Rational Field]
```

## 4.9 Algebras

AUTHORS:

- David Kohel & William Stein (2005): initial revision

```python
class sage.categories.algebras.Algebras(base_category)
    Bases: CategoryWithAxiom_over_base_ring
    The category of associative and unital algebras over a given base ring.
    An associative and unital algebra over a ring $R$ is a module over $R$ which is itself a ring.
```

**Warning:** *Algebras* will be eventually be replaced by *magmatic_algebras.MagmaticAlgebras* for consistency with e.g. Wikipedia article *Algebras* which assumes neither associativity nor the existence of a unit (see github issue #15043).

**Todo:** Should $R$ be a commutative ring?

EXAMPLES:

```python
class CartesianProducts(category, *args)
    Bases: CartesianProductsCategory
    The category of algebras constructed as Cartesian products of algebras
    This construction gives the direct product of algebras. See discussion on:
    - http://groups.google.fr/group/sage-devel/browse_thread/thread/35a72b1d0a2fc77a/348f42ac77a66d16#348f42ac77a66d16
    - Wikipedia article Direct_product
    extra_super_categories()
    A Cartesian product of algebras is endowed with a natural algebra structure.
    EXAMPLES:
```

4.9. Algebras 183
Category Framework, Release 10.3

```python
sage: C = Algebras(QQ).CartesianProducts()
sage: C.extra_super_categories()
[Category of algebras over Rational Field]
sage: sorted(C.super_categories(), key=str)
[Category of Cartesian products of monoids,
 Category of Cartesian products of unital algebras over Rational Field,
 Category of algebras over Rational Field]
```

**Commutative**

alias of `CommutativeAlgebras`

class `DualObjects` *(category, *args)*

Bases: `DualObjectsCategory`

`extra_super_categories()`

Return the dual category

**EXAMPLES:**

The category of algebras over the Rational Field is dual to the category of coalgebras over the same field:

```python
sage: C = Algebras(QQ)
sage: C.dual()
Category of duals of algebras over Rational Field
sage: C.dual().extra_super_categories()
[Category of coalgebras over Rational Field]
```

**Warning:** This is only correct in certain cases (finite dimension, …). See github issue #15647.

class `ElementMethods`

Bases: object

**Filtered**

alias of `FilteredAlgebras`

**Graded**

alias of `GradedAlgebras`

class `ParentMethods`

Bases: object

`characteristic()`

Return the characteristic of this algebra, which is the same as the characteristic of its base ring.

**EXAMPLES:**

```python
sage: # needs sage.modules
sage: ZZ.characteristic()
0
sage: A = GF(7^3, 'a')
˓→ # needs sage.rings.finite_rings
sage: A.characteristic()
7
```
**has_standard_involution()**

Return `True` if the algebra has a standard involution and `False` otherwise.

This algorithm follows Algorithm 2.10 from John Voight’s *Identifying the Matrix Ring*. Currently the only type of algebra this will work for is a quaternion algebra. Though this function seems redundant, once algebras have more functionality, in particular have a method to construct a basis, this algorithm will have more general purpose.

**EXAMPLES:**

```sage
# needs sage.combinat sage.modules
sage: B = QuaternionAlgebra(2)
sage: B.has_standard_involution()
True
sage: R.<x> = PolynomialRing(QQ)
sage: K.<u> = NumberField(x**2 - 2)
→ # needs sage.rings.number_field
sage: A = QuaternionAlgebra(K, -2, 5)
→ # needs sage.rings.number_field
sage: A.has_standard_involution()
→ # needs sage.rings.number_field
True
sage: L.<a,b> = FreeAlgebra(QQ, 2)
sage: L.has_standard_involution()
Traceback (most recent call last):
... NotImplementedError: has_standard_involution is not implemented for this...
→ algebra
```

class **Quotients** *(category, *args)*

**Bases:** `QuotientsCategory`

```python
class ParentMethods

Bases: object

algebra_generators()

Return algebra generators for self.

This implementation retracts the algebra generators from the ambient algebra.

**EXAMPLES:**

```sage
# needs sage.graphs sage.modules
sage: A = FiniteDimensionalAlgebrasWithBasis(QQ).example(); A
An example of a finite dimensional algebra with basis:
the path algebra of the Kronecker quiver
(containing the arrows a:x->y and b:x->y) over Rational Field
sage: S = A.semisimple_quotient()
sage: S.algebra_generators()
Finite family {"x": B["x"], "y": B["y"], "a": 0, "b": 0}
```

**Todo:** this could possibly remove the elements that retract to zero.

**Semisimple**

alias of *SemisimpleAlgebras*

---

4.9. Algebras 185
class SubcategoryMethods
    Bases: object
    Semisimple()
    Return the subcategory of semisimple objects of self.
    
    Note: This mimics the syntax of axioms for a smooth transition if Semisimple becomes one.

EXAMPLES:

```
sage: Algebras(QQ).Semisimple()
Category of semisimple algebras over Rational Field
sage: Algebras(QQ).WithBasis().FiniteDimensional().Semisimple()
Category of finite dimensional semisimple algebras with basis over Rational Field
```

Supercommutative()
    Return the full subcategory of the supercommutative objects of self.
    This is shorthand for creating the corresponding super category.

EXAMPLES:

```
sage: Algebras(ZZ).Supercommutative()
Category of supercommutative algebras over Integer Ring
sage: Algebras(ZZ).WithBasis().Supercommutative()
Category of supercommutative super algebras with basis over Integer Ring
sage: Cat = Algebras(ZZ).Supercommutative()
sage: Cat is Algebras(ZZ).Super().Supercommutative()
True
```

Super
    alias of SuperAlgebras

class TensorProducts (category, *args)
    Bases: TensorProductsCategory

class ElementMethods
    Bases: object

class ParentMethods
    Bases: object
    extra_super_categories()
    EXAMPLES:

```
sage: Algebras(QQ).TensorProducts().extra_super_categories()
[Category of algebras over Rational Field]
sage: Algebras(QQ).TensorProducts().super_categories()
[Category of algebras over Rational Field, Category of tensor products of vector spaces over Rational Field]
```

Meaning: a tensor product of algebras is an algebra

WithBasis
    alias of AlgebrasWithBasis
4.10 Algebras With Basis

```python
class sage.categories.algebras_with_basis.AlgebrasWithBasis(base_category):
    Bases: CategoryWithAxiom_over_base_ring

The category of algebras with a distinguished basis.

EXAMPLES:

sage: C = AlgebrasWithBasis(QQ); C
Category of algebras with basis over Rational Field
sage: sorted(C.super_categories(), key=str)
[Category of algebras over Rational Field,
 Category of unital algebras with basis over Rational Field]
```

We construct a typical parent in this category, and do some computations with it:

```python
sage: A = C.example(); A
# needs sage.combinat sage.modules
An example of an algebra with basis:
the free algebra on the generators ('a', 'b', 'c') over Rational Field
sage: A.category()
# needs sage.combinat sage.modules
Category of algebras with basis over Rational Field
sage: A.one_basis()
# needs sage.combinat sage.modules
word:
sage: A.one()
# needs sage.combinat sage.modules
B[word: ]
sage: A.base_ring()
# needs sage.combinat sage.modules
Rational Field
sage: A.basis().keys()
# needs sage.combinat sage.modules
Finite words over {'a', 'b', 'c'}
```

```
4.10. Algebras With Basis 187
```
B[word: abb]

```python
sage: TestSuite(A).run(assume=True)  #...
    # needs sage.combinat sage.modules
running ._test_additive_associativity() ... pass
running ._test_an_element() ... pass
running ._test_associativity() ... pass
running ._test_cardinality() ... pass
running ._test_category() ... pass
running ._test_characteristic() ... pass
running ._test_construction() ... pass
running ._test_distributivity() ... pass
running ._test_elements() ...
    Running the test suite of self.an_element()
running ._test_category() ... pass
running ._test_eq() ... pass
running ._test_new() ... pass
running ._test_nonzero_equal() ... pass
running ._test_not_implemented_methods() ... pass
running ._test_pickling() ... pass
    pass
running ._test_elements_eq_reflexive() ... pass
running ._test_elements_eq_symmetric() ... pass
running ._test_elements_eq_transitive() ... pass
running ._test_elements_neq() ... pass
running ._test_eq() ... pass
running ._test_new() ... pass
running ._test_not_implemented_methods() ... pass
running ._test_one() ... pass
running ._test_pickling() ... pass
running ._test_prod() ... pass
running ._test_some_elements() ... pass
running ._test_zero() ... pass
sage: A.__class__  #...
    # needs sage.combinat sage.modules
<class sage.categories.examples.algebras_with_basis.FreeAlgebra_with_category>
sage: A.element_class  #...
    # needs sage.combinat sage.modules
<class 'sage.categories.examples.algebras_with_basis.FreeAlgebra_with_category.element_class'>
```

Please see the source code of `A` (with `A??`) for how to implement other algebras with basis.

**class CartesianProducts**(category, *args)

Bases: CartesianProductsCategory

The category of algebras with basis, constructed as Cartesian products of algebras with basis.

Note: this construction give the direct products of algebras with basis. See comment in `Algebras`.

**CartesianProducts**

```python
class ParentMethods
    Bases: object

    one()

    one_from_cartesian_product_of_one_basis()
        Return the one of this Cartesian product of algebras, as per Monoids.ParentMethods.one
```
It is constructed as the Cartesian product of the ones of the summands, using their one_basis() methods.

This implementation does not require multiplication by scalars nor calling cartesian_product. This might help keeping things as lazy as possible upon initialization.

EXAMPLES:

```python
sage: A = AlgebrasWithBasis(QQ).example(); A

An example of an algebra with basis: the free algebra on the generators ('a', 'b', 'c') over Rational Field

sage: A.one_basis()

word:

sage: B = cartesian_product((A, A, A))

B[(0, word: )] + B[(1, word: )] + B[(2, word: )]

sage: B.one()

B[(0, [1, 2, 3])] + B[(1, [1, 2, 3, 4])]
```

extra_super_categories()

A Cartesian product of algebras with basis is endowed with a natural algebra with basis structure.

EXAMPLES:

```python
sage: AlgebrasWithBasis(QQ).CartesianProducts().extra_super_categories()

[Category of algebras with basis over Rational Field]

sage: AlgebrasWithBasis(QQ).CartesianProducts().super_categories()

[Category of algebras with basis over Rational Field, 
 Category of Cartesian products of algebras over Rational Field, 
 Category of Cartesian products of vector spaces with basis over Rational...]
```

class ElementMethods

Bases: object

Filtered
  alias of FilteredAlgebrasWithBasis

FiniteDimensional
  alias of FiniteDimensionalAlgebrasWithBasis

Graded
  alias of GradedAlgebrasWithBasis

class ParentMethods

Bases: object
hochschild_complex($M$)

Return the Hochschild complex of self with coefficients in $M$.

See also:
HochschildComplex

EXAMPLES:

```
sage: R.<x> = QQ[]
sage: A = algebras.DifferentialWeyl(R)  # needs sage.modules
sage: H = A.hochschild_complex(A)  # needs sage.modules
sage: SGA = SymmetricGroupAlgebra(QQ, 3)  # needs sage.combinat, sage.modules
sage: T = SGA.trivial_representation()  # needs sage.combinat, sage.modules
sage: H = SGA.hochschild_complex(T)  # needs sage.combinat, sage.modules
```

one()

Return the multiplicative unit element.

EXAMPLES:

```
sage: A = AlgebrasWithBasis(QQ).example()  # needs sage.combinat, sage.modules
sage: A.one_basis()  # needs sage.combinat, sage.modules
word:
sage: A.one()  # needs sage.combinat, sage.modules
B[word: ]
```

Super

alias of SuperAlgebrasWithBasis

class TensorProducts(category, *args)

Bases: TensorProductsCategory

The category of algebras with basis constructed by tensor product of algebras with basis

class ElementMethods

Bases: object

Implements operations on elements of tensor products of algebras with basis

class ParentMethods

Bases: object

Implements operations on tensor products of algebras with basis

one_basis()

Returns the index of the one of this tensor product of algebras, as per AlgebrasWithBasis.ParentMethods.one_basis

It is the tuple whose operands are the indices of the ones of the operands, as returned by their one_basis() methods.
EXAMPLES:

```
sage: # needs sage.combinat sage.modules
sage: A = AlgebrasWithBasis(QQ).example(); A
An example of an algebra with basis: the free algebra
on the generators ('a', 'b', 'c') over Rational Field
sage: A.one_basis()
word:
sage: B = tensor((A, A, A))
sage: B.one_basis()
(word: , word: , word: )
sage: B.one()
```

**product_on_basis**(\(t_1, t_2\))

The product of the algebra on the basis, as per \texttt{AlgebrasWithBasis.ParentMethods.product_on_basis}.

EXAMPLES:

```
sage: A = AlgebrasWithBasis(QQ).example(); A
# needs sage.combinat sage.modules
An example of an algebra with basis: the free algebra
on the generators ('a', 'b', 'c') over Rational Field
sage: (a,b,c) = A.algebra_generators()
# needs sage.combinat sage.modules
sage: x = tensor((a, b, c)); x
# needs sage.combinat sage.modules
sage: y = tensor((c, b, a)); y
# needs sage.combinat sage.modules
sage: x * y
# needs sage.combinat sage.modules
sage: x = tensor(((a + 2*b), c)); x
# needs sage.combinat sage.modules
sage: y = tensor((c, a)) + 1; y
# needs sage.combinat sage.modules
sage: x * y
# needs sage.combinat sage.modules
```

TODO: optimize this implementation!

**extra_super_categories**()

EXAMPLES:

```
sage: AlgebrasWithBasis(QQ).TensorProducts().extra_super_categories()
[Category of algebras with basis over Rational Field]
sage: AlgebrasWithBasis(QQ).TensorProducts().super_categories()
[Category of algebras with basis over Rational Field, Category of tensor products of algebras over Rational Field]
```
example(alphabet=('a', 'b', 'c'))

Return an example of algebra with basis.

EXAMPLES:

```
sage: AlgebrasWithBasis(QQ).example()  # needs sage.combinat sage.modules
An example of an algebra with basis:
the free algebra on the generators ('a', 'b', 'c') over Rational Field
```

An other set of generators can be specified as optional argument:

```
sage: AlgebrasWithBasis(QQ).example((1,2,3))  # needs sage.combinat sage.modules
An example of an algebra with basis:
the free algebra on the generators (1, 2, 3) over Rational Field
```

### 4.11 Aperiodic semigroups

```
class sage.categories.aperiodic_semigroups.AperiodicSemigroups(base_category)
Bases: CategoryWithAxiom

extra_super_categories()
Implement the fact that an aperiodic semigroup is $H$-trivial.

EXAMPLES:

```
sage: Semigroups().Aperiodic().extra_super_categories()
[Category of h trivial semigroups]
```

### 4.12 Associative algebras

```
class sage.categories.associative_algebras.AssociativeAlgebras(base_category)
Bases: CategoryWithAxiom_over_base_ring

The category of associative algebras over a given base ring.
An associative algebra over a ring $R$ is a module over $R$ which is also a not necessarily unital ring.

**Warning:** Until github issue #15043 is implemented, `Algebras` is the category of associative unital algebras; thus, unlike the name suggests, `AssociativeAlgebras` is not a subcategory of `Algebras` but of `MagmaticAlgebras`.

EXAMPLES:
```sage
def from sage.categories.associative_algebras import AssociativeAlgebras
c = AssociativeAlgebras(ZZ); c
Category of associative algebras over Integer Ring
```

Unital
alias of *Algebras*

## 4.13 Bialgebras

```sage
class sage.categories.bialgebras.Bialgebras(base, name=None)
    Bases: Category_over_base_ring
The category of bialgebras

Examples:
```  
```sage: Bialgebras(ZZ)
Category of bialgebras over Integer Ring
sage: Bialgebras(ZZ).super_categories()
[Category of algebras over Integer Ring, Category of coalgebras over Integer Ring]
```

```sage
class ElementMethods
    Bases: object
    
is_grouplike()
    Return whether self is a grouplike element.
    
    Examples:
```  
```sage: s = SymmetricFunctions(QQ).schur()
    # needs sage.modules
sage: s([5]).is_grouplike()
    # needs sage.modules
False
sage: s([]).is_grouplike()
    # needs sage.modules
True
```

```isprimitive()
    Return whether self is a primitive element.
    
    Examples:
```  
```sage: # needs sage.modules
sage: s = SymmetricFunctions(QQ).schur()
sage: s([5]).is_primitive()
False
sage: p = SymmetricFunctions(QQ).powersum()
sage: p([5]).is_primitive()
True
```

```sage
class Super(base_category)
    Bases: SuperModulesCategory
```

### 4.13. Bialgebras
**WithBasis**

alias of `BialgebrasWithBasis`

**additional_structure()**

Return None.

Indeed, the category of bialgebras defines no additional structure: a morphism of coalgebras and of algebras between two bialgebras is a bialgebra morphism.

See also:

`Category.additional_structure()`

**Todo:** This category should be a `CategoryWithAxiom`.

### Examples:

```python
sage: Bialgebras(QQ).additional_structure()
```

**super_categories()**

**Examples:**

```python
sage: Bialgebras(QQ).super_categories()
```

```
[Category of algebras over Rational Field, Category of coalgebras over Rational Field]
```

### 4.14 Bialgebras with basis

**class** `sage.categories.bialgebras_with_basis.BialgebrasWithBasis(base_category)`

**Bases:** `CategoryWithAxiom_over_base_ring`

The category of bialgebras with a distinguished basis.

**Examples:**

```python
sage: C = BialgebrasWithBasis(QQ); C
Category of bialgebras with basis over Rational Field

sage: sorted(C.super_categories(), key=str)
```

```
[Category of algebras with basis over Rational Field, Category of bialgebras over Rational Field, Category of coalgebras with basis over Rational Field]
```

**class** `ElementMethods`

**Bases:** `object`

**adams_operator(*args, **kwds)**

Deprecated: Use `convolution_power_of_id()` instead. See github issue #36396 for details.

**convolution_power_of_id(n)**

Compute the $n$-th convolution power of the identity morphism $Id$ on $self$.

**INPUT:**

- $n$ – a nonnegative integer

**OUTPUT:**
• the image of self under the convolution power $\text{Id}^n$

**Note:** In the literature, this is also called a Hopf power or Sweedler power, cf. [AL2015].

See also:

sage.categories.bialgebras.ElementMethods.convolution_product()

**Todo:** Remove dependency on modules_with_basis methods.

## EXAMPLES:

```python
sage: h = SymmetricFunctions(QQ).h()
sage: h[5].convolution_power_of_id(2)
sage: h[5].plethysm(2*h[1])
sage: h([]).convolution_power_of_id(0)
h[]
sage: h([]).convolution_power_of_id(1)
h[]
sage: h[3, 2].convolution_power_of_id(0)
0
sage: h[3, 2].convolution_power_of_id(1)
h[3, 2]
sage: S = NonCommutativeSymmetricFunctions(QQ).S() # needs sage.combinat sage.modules
sage: S[4].convolution_power_of_id(5)
sage: m = SymmetricFunctionsNonCommutingVariables(QQ).m() # needs sage.combinat sage.modules
sage: m[[1,3],[2]].convolution_power_of_id(-2)
3*m{{1}, {2, 3}} + 3*m{{1, 2}, {3}} + 6*m{{1, 2, 3}} - 2*m{{1, 3}, {2}}
```

### convolution_product (*maps*)

Return the image of self under the convolution product (map) of the maps.

Let $A$ and $B$ be bialgebras over a commutative ring $R$. Given maps $f_i : A \to B$ for $1 \leq i < n$, define the convolution product

$$(f_1 \ast f_2 \ast \cdots \ast f_n) := \mu^{(n-1)} \circ (f_1 \otimes f_2 \otimes \cdots \otimes f_n) \circ \Delta^{(n-1)},$$

where $\Delta^{(k)} := (\Delta \otimes \text{Id}^{(k-1)}) \circ \Delta^{(k-1)}$, with $\Delta^{(1)} = \Delta$ (the ordinary coproduct in $A$) and $\Delta^{(0)} = \text{Id}$; and with $\mu^{(k)} := \mu \circ (\mu^{(k-1)} \otimes \text{Id})$ and $\mu^{(1)} = \mu$ (the ordinary product in $B$). See [Swe1969].

(In the literature, one finds, e.g., $\Delta^{(2)}$ for what we denote above as $\Delta^{(1)}$. See [KMN2012].)

**INPUT:**

- maps -- any number $n \geq 0$ of linear maps $f_1, f_2, \ldots, f_n$ on self.parent(); or a single list or tuple of such maps

OUTPUT:

- the convolution product of maps applied to self

AUTHORS:

- Amy Pang - 12 June 2015 - Sage Days 65

Todo: Remove dependency on `modules_with_basis` methods.

EXAMPLES:

We compute convolution products of the identity and antipode maps on Schur functions:

```python
sage: Id = lambda x: x
sage: Antipode = lambda x: x.antipode()

sage: s = SymmetricFunctions(QQ).schur()

sage: s[3].convolution_product(Id, Id)
# needs sage.combinat sage.modules
2*s[2, 1] + 4*s[3]

sage: s[3,2].convolution_product(Id) == s[3,2]
# needs sage.combinat sage.modules
True
```

The method accepts multiple arguments, or a single argument consisting of a list of maps:

```python
sage: s[3,2].convolution_product((Id, Id))
# needs sage.combinat sage.modules
2*s[2, 1, 1, 1] + 6*s[2, 2, 1] + 6*s[3, 1, 1] + 12*s[3, 2] + 6*s[4, 1] + ...
-2*s[5]

sage: (s[3,2].convolution_product())
# needs sage.combinat sage.modules
....: == s[3,2].convolution_product(Antipode, Id)
....: == s[3,2].convolution_product(Id, Antipode))
True
```

We test the defining property of the antipode morphism; namely, that the antipode is the inverse of the identity map in the convolution algebra whose identity element is the composition of the counit and unit:

```python
sage: Psi = NonCommutativeSymmetricFunctions(QQ).Psi()

sage: Psi21 = Psi[2,1].convolution_product((Id, Id, Id))
# needs sage.combinat sage.modules
3*Psi[1, 2] + 6*Psi[2, 1] -3*Psi[1, 5] + 3*Psi[5, 1]
```

(continues on next page)
\[ [1, 3, 2] + [2, 1, 3] + 2*[2, 3, 1] + 2*[3, 1, 2] + 3*[3, 2, 1] \]

\[ 5*[1, 2, 3] + 2*[2, 3, 1] + 2*[3, 1, 2] \]

\[ 4*[1, 2, 3] + [1, 3, 2] + [2, 1, 3] + 3*[3, 2, 1] \]

\[ 9*[1, 2, 3] \]

```python
sage: x.convolution_product(Id, Id)
5*[1, 2, 3] + 2*[2, 3, 1] + 2*[3, 1, 2]

sage: x.convolution_product(Id, Id, Id)
4*[1, 2, 3] + [1, 3, 2] + [2, 1, 3] + 3*[3, 2, 1]

sage: x.convolution_product([Id] * 6)
9*[1, 2, 3]
```

class ParentMethods

Bases: object

**convolution_product** (*maps*)

Return the convolution product (a map) of the given maps.

Let \( A \) and \( B \) be bialgebras over a commutative ring \( R \). Given maps \( f_i : A \to B \) for \( 1 \leq i < n \), define the convolution product

\[
(f_1 * f_2 * \cdots * f_n) := \mu^{(n-1)} \circ (f_1 \otimes f_2 \otimes \cdots \otimes f_n) \circ \Delta^{(n-1)},
\]

where \( \Delta^{(k)} := (\Delta \otimes Id^{(k-1)}) \circ \Delta^{(k-1)} \), with \( \Delta^{(1)} = \Delta \) (the ordinary coproduct in \( A \)) and \( \Delta^{(0)} = Id \);

and with \( \mu^{(k)} := \mu \circ (\mu^{(k-1)} \otimes Id) \) and \( \mu^{(1)} = \mu \) (the ordinary product in \( B \)). See [Swe1969].

(In the literature, one finds, e.g., \( \Delta^{(2)} \) for what we denote above as \( \Delta^{(1)} \). See [KMN2012].)

**INPUT:**
- maps – any number \( n \geq 0 \) of linear maps \( f_1, f_2, \ldots, f_n \) on \( self \); or a single list or tuple of such maps

**OUTPUT:**
- the new map \( f_1 * f_2 * \cdots * f_2 \) representing their convolution product

**See also:**
- sage.categories.bialgebras.ElementMethods.convolution_product()

**AUTHORS:**
- Aaron Lauve - 12 June 2015 - Sage Days 65

**Todo:** Remove dependency on modules_with_basis methods.

**EXAMPLES:**

We construct some maps: the identity, the antipode and projection onto the homogeneous component of degree 2:

```python
sage: Id = lambda x: x
sage: Antipode = lambda x: x.antipode()

sage: Proj2 = lambda x: x.parent().sum_of_terms([[(m, c) for (m, c) in x if m.size() == 2]])
```

Compute the convolution product of the identity with itself and with the projection \( Proj2 \) on the Hopf algebra of non-commutative symmetric functions:

```python
sage: # needs sage.combinat sage.modules
sage: R = NonCommutativeSymmetricFunctions(QQ).ribbon()

sage: T = R.convolution_product([Id, Id])

sage: [4*R[1, 1, 1] + R[1, 2] + R[2, 1],
```

(continues on next page)
Compute the convolution product of no maps on the Hopf algebra of symmetric functions in non-commuting variables. This is the composition of the counit with the unit:

\[
\text{sage: } m = \text{SymmetricFunctionsNonCommutingVariables(QQ)}.m()
\]

\[
\text{sage: } T = m.\text{convolution_product}()
\]

\[
\text{sage: } [T(m(lam)) \text{ for lam in SetPartitions(0).list() + SetPartitions(2).list() }]
\]

\[
[\text{m{}}, 0, 0]
\]

Compute the convolution product of the projection \(\text{Proj2}\) with the identity on the Hopf algebra of symmetric functions in non-commuting variables:

\[
\text{sage: } T = m.\text{convolution_product}(\text{Proj2}, \text{Id})
\]

\[
\text{sage: } [T(m(lam)) \text{ for lam in SetPartitions(3)}]
\]

\[
[0, \text{m{{1, 2}, {3}}} + \text{m{{1, 2, 3}}}, \text{m{{1, 2}, {3}}} + \text{m{{1, 2, 3}}}, \text{m{{1, 2}, {3}}} + \text{m{{1, 2, 3}}}, 3*\text{m{{1}, {2}, {3}}} + 3*\text{m{{1}, {2, 3}}} + 3*\text{m{{1, 3}, {2}}}]
\]

Compute the convolution product of the antipode with itself and the identity map on group algebra of the symmetric group:

\[
\text{sage: } \# \text{ needs sage.combinat sage.groups}
\]

\[
\text{sage: } G = \text{SymmetricGroup(3)}
\]

\[
\text{sage: } QG = \text{GroupAlgebra(G, QQ)}
\]

\[
\text{sage: } x = QG.\text{sum_of_terms}()
\]

\[
\text{sage: } T = QG.\text{convolution_product}(\text{Antipode}, \text{Antipode}, \text{Id})
\]

\[
\text{sage: } T(x)
\]

\[
2*[1, 3, 2] + [2, 1, 3] + 3*[2, 3, 1] + 2*[3, 1, 2] + 3*[3, 2, 1]
\]
4.15 Bimodules

```python
class sage.categories.bimodules.Bimodules(left_base, right_base, name=None):
    Bases: CategoryWithParameters

    The category of \((R, S)\)-bimodules

    For \(R\) and \(S\) rings, a \((R, S)\)-bimodule \(X\) is a left \(R\)-module and right \(S\)-module such that the left and right actions commute: \(r \cdot (x \cdot s) = (r \cdot x) \cdot s\).
```

**EXAMPLES:**

```python
sage: Bimodules(QQ, ZZ)
Category of bimodules over Rational Field on the left and Integer Ring on the right
sage: Bimodules(QQ, ZZ).super_categories()
[Category of left modules over Rational Field, Category of right modules over Integer Ring]
```

```python
class ElementMethods
    Bases: object

class ParentMethods
    Bases: object

additional_structure()
    Return None.

    Indeed, the category of bimodules defines no additional structure: a left and right module morphism between two bimodules is a bimodule morphism.

    See also:
    Category.additional_structure()

    Todo: Should this category be a CategoryWithAxiom?
```

**EXAMPLES:**

```python
sage: Bimodules(QQ, ZZ).additional_structure()
```

```python
classmethod an_instance()
    Return an instance of this class.

    EXAMPLES:
    ```
sage: Bimodules.an_instance()
# needs sage.rings.real_mpfr
    ```
```

```python
left_base_ring()
    Return the left base ring over which elements of this category are defined.

    EXAMPLES:
    ```
sage: Bimodules(left_base_ring)
```
```
sage: Bimodules(QQ, ZZ).left_base_ring()
Rational Field

right_base_ring()
Return the right base ring over which elements of this category are defined.

EXAMPLES:

sage: Bimodules(QQ, ZZ).right_base_ring()
Integer Ring

super_categories()

EXAMPLES:

sage: Bimodules(QQ, ZZ).super_categories()
[Category of left modules over Rational Field, Category of right modules over...
 → Integer Ring]

4.16 Classical Crystals

class sage.categories.classical_crystals.ClassicalCrystals

Bases: Category_singleton

The category of classical crystals, that is crystals of finite Cartan type.

EXAMPLES:

sage: C = ClassicalCrystals()
sage: C
Category of classical crystals
sage: C.super_categories()
[Category of regular crystals,
 Category of finite crystals,
 Category of highest weight crystals]
sage: C.example()
Highest weight crystal of type A_3 of highest weight omega_1

class ElementMethods

Bases: object

lusztig_involution()
Return the Lusztig involution on the classical highest weight crystal self.

The Lusztig involution on a finite-dimensional highest weight crystal \( B(\lambda) \) of highest weight \( \lambda \) maps the highest weight vector to the lowest weight vector and the Kashiwara operator \( f_i \) to \( e_i^* \), where \( i^* \) is defined as \( \alpha_i^* = -w_0(\alpha_i) \). Here \( w_0 \) is the longest element of the Weyl group acting on the \( i \)-th simple root \( \alpha_i \).

EXAMPLES:

sage: B = crystals.Tableaux(['A',3],shape=[2,1])
sage: b = B(rows=[[1,2],[4]])
sage: b.lusztig_involution()
[[1, 4], [3]]
sage: b.to_tableau().schuetzenberger_involution(n=4)
[[1, 4], [3]]
class ParentMethods

Bases: object

cardinality()

Returns the number of elements of the crystal, using Weyl’s dimension formula on each connected component.

EXAMPLES:

sage: C = ClassicalCrystals().example(5)
sage: C.cardinality()
6

class (

character (R=None)

Returns the character of this crystal.

INPUT:

• R - a WeylCharacterRing (default: the default WeylCharacterRing for this Cartan type)

Returns the character of self as an element of R.

EXAMPLES:

sage: C = crystals.Tableaux("A2", shape=[2,1])
sage: chi = C.character(); chi
A2(2,1,0)

sage: T = crystals.TensorProduct(C,C)
sage: chiT = T.character(); chiT
A2(2,2) + 2*A2(3,2,1) + A2(3,3,0) + A2(4,1,1) + A2(4,2,0)
sage: chiT == chi^2
True

One may specify an alternate WeylCharacterRing:
It should have the same Cartan type and use the same realization of the weight lattice as self:

```
sage: R = WeylCharacterRing("A3", style="coroots")
sage: T.character(R)  
Traceback (most recent call last):
...
ValueError: Weyl character ring does not have the right Cartan type
```

demazure_character \(w, f=\text{None}\)

Return the Demazure character associated to \(w\).

**INPUT:**

- \(w\) – an element of the ambient weight lattice realization of the crystal, or a reduced word, or an
  element in the associated Weyl group

**OPTIONAL:**

- \(f\) – a function from the crystal to a module

This is currently only supported for crystals whose underlying weight space is the ambient space.

The Demazure character is obtained by applying the Demazure operator \(D_w\) (see `sage.categories.regular_crystals_REGULARCRYSTALS.ParentMethods.demazure_operator()`) to the highest weight element of the classical crystal. The simple Demazure operators \(D_i\) (see `sage.categories.regular_crystals_REGULARCRYSTALS.ElementMethods.demazure_operator_simple()`) do not braid on the level of crystals, but on the level of characters they do. That is why it makes sense to input \(w\) either as a weight, a reduced
word, or as an element of the underlying Weyl group.

**EXAMPLES:**

```
sage: T = crystals.Tableaux(['A',2], shape = [2,1])
sage: e = T.weight_lattice_realization().basis()
sage: weight = e[0] + 2*e[2]
sage: weight.reduced_word()
[2, 1]
sage: T.demazure_character(weight)
x1^2*x2 + x1*x2*x2 + x1^2*x3 + x1*x2*x3 + x1*x3*x2
sage: T = crystals.Tableaux(['A',3],shape=[2,1])
sage: T.demazure_character([1,2,3])
x1^2*x2 + x1*x2*x2 + x1^2*x3 + x1*x2*x3 + x2^2*x3
sage: W = WeylGroup(['A',3])
sage: w = W.from_reduced_word([1,2,3])
sage: T.demazure_character(w)
x1^2*x2 + x1*x2*x2 + x1^2*x3 + x1*x2*x3 + x2^2*x3
sage: T = crystals.Tableaux(['B',2], shape = [2])
sage: e = T.weight_lattice_realization().basis()
sage: weight = -2*e[1]
sage: T.demazure_character(weight)
x1^2 + x1*x2 + x2^2 + x1 + x2 + x1/x2 + 1/x2 + 1/x2^2 + 1
sage: T = crystals.Tableaux("B2",shape=[1/2,1/2])
```

(continues on next page)
REFERENCES:

- [De1974]
- [Ma2009]

```python
sage: b2=WeylCharacterRing("B2",base_ring=QQ).ambient()
sage: T.demazure_character([1,2],f=lambda x:b2(x.weight()))
b2(-1/2,1/2) + b2(1/2,-1/2) + b2(1/2,1/2)
```

class TensorProducts (category, *args)

Bases: TensorProductsCategory

The category of classical crystals constructed by tensor product of classical crystals.

extra_super_categories ()

EXAMPLES:

```python
sage: ClassicalCrystals().TensorProducts().extra_super_categories()
[Category of classical crystals]
```

additional_structure ()

Return None.

Indeed, the category of classical crystals defines no additional structure: it only states that its objects are $U_q(g)$-crystals, where $g$ is of finite type.

See also: Category.additional_structure ()

EXAMPLES:

```python
sage: ClassicalCrystals().additional_structure()
```

example (n=3)

Returns an example of highest weight crystals, as per Category.example ()

EXAMPLES:

```python
sage: B = ClassicalCrystals().example(); B
Highest weight crystal of type A_3 of highest weight omega_1
```

super_categories ()

EXAMPLES:

```python
sage: ClassicalCrystals().super_categories()
[Category of regular crystals,  
Category of finite crystals,  
Category of highest weight crystals]
```
4.17 Coalgebras

```python
class sage.categories.coalgebras.Coalgebras(base, name=None):
    Bases: [Category_over_base_ring]
    The category of coalgebras

EXAMPLES:

    sage: Coalgebras(QQ)
    Category of coalgebras over Rational Field
    sage: Coalgebras(QQ).super_categories()
    [Category of vector spaces over Rational Field]

class Cocommutative(base_category):
    Bases: [CategoryWithAxiom_over_base_ring]
    Category of cocommutative coalgebras.

class DualObjects(category, *args):
    Bases: [DualObjectsCategory]
    extra_super_categories():
        Return the dual category.

EXAMPLES:

    The category of coalgebras over the Rational Field is dual to the category of algebras over the same field:

    sage: C = Coalgebras(QQ)
    sage: C.dual()
    Category of duals of coalgebras over Rational Field
    sage: C.dual().super_categories()  # indirect doctest
    [Category of algebras over Rational Field,
     Category of duals of vector spaces over Rational Field]

Remark: This is only correct in certain cases (finite dimension, ...). See github issue #15647.

class ElementMethods:
    Bases: [object]
    coproduct():
        Return the coproduct of self.

EXAMPLES:

    sage: # needs sage.modules
    sage: A = HopfAlgebrasWithBasis(QQ).example(); A
    An example of Hopf algebra with basis:
    the group algebra of the Dihedral group of order 6 as a permutation...
    over Rational Field
    sage: [a,b] = A.algebra_generators()
    sage: a, a.coproduct()
    (B[(1,2,3)], B[(1,2,3)] # B[(1,2,3)])
    sage: b, b.coproduct()
    (B[(1,3)], B[(1,3)] # B[(1,3)])
```
counit ()

Return the counit of self.

EXAMPLES:

```sage
sage: # needs sage.modules
sage: A = HopfAlgebrasWithBasis(QQ).example(); A
An example of Hopf algebra with basis:
    the group algebra of the Dihedral group of order 6 as a permutation...
        \rightarrow group over Rational Field
sage: [a,b] = A.algebra_generators()

sage: a, a.counit()
(B[(1,2,3)], 1)
sage: b, b.counit()
(B[(1,3)], 1)
```

class Filtered(base_category)

Bases: FilteredModulesCategory

Category of filtered coalgebras.

Graded

alias of GradedCoalgebras

parentmethods

Bases: object

coproduct (x)

Return the coproduct of x.

Eventually, there will be a default implementation, delegating to the overloading mechanism and forcing the conversion back

EXAMPLES:

```sage
sage: # needs sage.modules
sage: A = HopfAlgebrasWithBasis(QQ).example(); A
An example of Hopf algebra with basis:
    the group algebra of the Dihedral group of order 6 as a permutation...
        \rightarrow group over Rational Field
sage: [a,b] = A.algebra_generators()

sage: a, A.coproduct(a)
(B[(1,2,3)], B[(1,2,3)] # B[(1,2,3)])
sage: b, A.coproduct(b)
(B[(1,3)], B[(1,3)] # B[(1,3)])
```

counit (x)

Return the counit of x.

Eventually, there will be a default implementation, delegating to the overloading mechanism and forcing the conversion back

EXAMPLES:

```sage
sage: # needs sage.modules
sage: A = HopfAlgebrasWithBasis(QQ).example(); A
An example of Hopf algebra with basis:
    the group algebra of the Dihedral group of order 6 as a permutation...
        \rightarrow group over Rational Field
```

(continues on next page)
sage: [a,b] = A.algebra_generators()
sage: a, A.counit(a)
(B[(1,2,3)], 1)
sage: b, A.counit(b)
(B[(1,3)], 1)

TODO: implements some tests of the axioms of coalgebras, bialgebras and Hopf algebras using the counit.

class Realizations (category, *args)

Bases: RealizationsCategory

class ParentMethods

Bases: object

coproduct_by_coercion (x)

Return the coproduct by coercion if coproduct_by_basis is not implemented.

EXAMPLES:

sage: # needs sage.modules
sage: Sym = SymmetricFunctions(QQ)
sage: m = Sym.monomial()
sage: f = m[2,1]
sage: f.coproduct.__module__
'sage.categories.coalgebras'
sage: m.coproduct_on_basis
NotImplemented
sage: m.coproduct == m.coproduct_by_coercion
True
sage: f.coproduct()

sage: # needs sage.modules
sage: N = NonCommutativeSymmetricFunctions(QQ)
sage: R = N.ribbon()
sage: R.coproduct_by_coercion.__module__
'sage.categories.coalgebras'
sage: R.coproduct_on_basis
NotImplemented
sage: R.coproduct == R.coproduct_by_coercion
True
sage: R[1].coproduct()
counit_by_coercion (x)

Return the counit of \( x \) if counit_by_basis is not implemented.

EXAMPLES:

sage: sp = SymmetricFunctions(QQ).sp()
... # needs sage.modules
sage: sp.an_element()
... # needs sage.modules
2*sp[] + 2*sp[1] + 3*sp[2]
sage: sp.counit(sp.an_element())
... # needs sage.modules
2

(continues on next page)
class SubcategoryMethods

    Bases: object

    Cocommutative()
    
    Return the full subcategory of the cocommutative objects of self.

    A coalgebra $C$ is said to be cocommutative if

    $\Delta(c) = \sum_{(c)} c_{(1)} \otimes c_{(2)} = \sum_{(c)} c_{(2)} \otimes c_{(1)}$

    in Sweedler’s notation for all $c \in C$.

    EXAMPLES:

    sage: C1 = Coalgebras(ZZ).Cocommutative().WithBasis(); C1
    Category of cocommutative coalgebras with basis over Integer Ring
    sage: C2 = Coalgebras(ZZ).WithBasis().Cocommutative()
    sage: C1 is C2
    True
    sage: BialgebrasWithBasis(QQ).Cocommutative()
    Category of cocommutative bialgebras with basis over Rational Field

class Super(base_category)

    Bases: SuperModulesCategory

class SubcategoryMethods

    Bases: object

    Supercocommutative()

    Return the full subcategory of the supercocommutative objects of self.

    EXAMPLES:

    sage: Coalgebras(ZZ).WithBasis().Super().Supercocommutative()
    Category of supercocommutative super coalgebras with basis over Integer Ring
    sage: BialgebrasWithBasis(QQ).Super().Supercocommutative()
    Join of Category of super algebras with basis over Rational Field
    and Category of super coalgebras with basis over Rational Field
    and Category of supercocommutative super coalgebras over Rational Field

class Supercocommutative(base_category)

    Bases: CategoryWithAxiom_over_base_ring

    Category of supercocommutative coalgebras.

4.17. Coalgebras 207
extra_super_categories()

EXAMPLES:

```
sage: Coalgebras(ZZ).Super().extra_super_categories()
[Category of graded coalgebras over Integer Ring]
sage: Coalgebras(ZZ).Super().super_categories()
[Category of graded coalgebras over Integer Ring,
 Category of super modules over Integer Ring]
```

Compare this with the situation for bialgebras:

```
sage: Bialgebras(ZZ).Super().extra_super_categories()
[]
sage: Bialgebras(ZZ).Super().super_categories()
[Category of super algebras over Integer Ring,
 Category of super coalgebras over Integer Ring]
```

The category of bialgebras does not occur in these results, since super bialgebras are not bialgebras.

class TensorProducts (category, *args)
Bases: TensorProductsCategory
class ElementMethods
Bases: object
class ParentMethods
Bases: object
extra_super_categories()

EXAMPLES:

```
sage: Coalgebras(QQ).TensorProducts().extra_super_categories()
[Category of coalgebras over Rational Field]
sage: Coalgebras(QQ).TensorProducts().super_categories()
[Category of tensor products of vector spaces over Rational Field,
 Category of coalgebras over Rational Field]
```

Meaning: a tensor product of coalgebras is a coalgebra

WithBasis
alias of CoalgebrasWithBasis
class WithRealizations (category, *args)
Bases: WithRealizationsCategory
class ParentMethods
Bases: object
coproduct (x)

Return the coproduct of x.

EXAMPLES:

```
sage: # needs sage.modules
sage: N = NonCommutativeSymmetricFunctions(QQ)
sage: S = N.complete()
sage: N.coproduct.__module__
'sage.categories.coalgebras'
```

(continues on next page)
counit(x)

Return the counit of x.

EXAMPLES:

```sage
# needs sage.modules
Sym = SymmetricFunctions(QQ)
s = Sym.schur()
f = s[2,1]
f.counit.__module__
'sage.categories.coalgebras'
f.counit()
0
```

```sage
# needs sage.modules
N = NonCommutativeSymmetricFunctions(QQ)
N.counit.__module__
'sage.categories.coalgebras'
N.counit(N.one())
1
x = N.an_element(); x
2*S[] + 2*S[1] + 3*S[1, 1]
N.counit(x)
2
```

super_categories()

EXAMPLES:

```sage
Coalgebras(QQ).super_categories()
[Category of vector spaces over Rational Field]
```

### 4.18 Coalgebras with basis

**class** `sage.categories.coalgebras_with_basis.CoalgebrasWithBasis(base_category)`

Bases: `CategoryWithAxiom_over_base_ring`

The category of coalgebras with a distinguished basis.

EXAMPLES:

```sage
CoalgebrasWithBasis(ZZ)
Category of coalgebras with basis over Integer Ring
sorted(CoalgebrasWithBasis(ZZ).super_categories(), key=str)
[Category of coalgebras over Integer Ring,
 Category of modules with basis over Integer Ring]
```

**class** `ElementMethods`

Bases: `object`
coproduct_iterated\( (n=1) \)

Apply \( n \) coproducts to \( self \).

**Todo:** Remove dependency on `modules_with_basis` methods.

EXEMPLARY:

```python
sage: Psi = NonCommutativeSymmetricFunctions(QQ).Psi()  # ...
   ~ needs sage.combinat sage.modules
sage: Psi[2,2].coproduct_iterated(0)  # ...
   ~ needs sage.combinat sage.modules
Psi[2, 2]
sage: Psi[2,2].coproduct_iterated(2)  # ...
   ~ needs sage.combinat sage.modules
```

class Filtered(base_category)

Bases: `FilteredModulesCategory`

Category of filtered coalgebras.

**Graded**

alias of `GradedCoalgebrasWithBasis`

class ParentMethods

Bases: `object`

**coproduct**

If `coproduct_on_basis()` is available, construct the coproduct morphism from `self` to `self \otimes self` by extending it by linearity. Otherwise, use `coproduct_by_coercion()`, if available.

EXEMPLARY:

```python
sage: # needs sage.groups sage.modules
sage: A = HopfAlgebrasWithBasis(QQ).example(); A
An example of Hopf algebra with basis:
   the group algebra of the Dihedral group of order 6
   as a permutation group over Rational Field
sage: a, b = A.algebra_generators()
sage: a, A.coproduct(a)  
(B[(1,2,3)], B[(1,2,3)] # B[(1,2,3)])
sage: b, A.coproduct(b)  
(B[(1,3)], B[(1,3)] # B[(1,3)])
```

coproduct_on_basis\( (i) \)

The coproduct of the algebra on the basis (optional).

**INPUT:**

- \( i \) – the indices of an element of the basis of `self`

Returns the coproduct of the corresponding basis elements If implemented, the coproduct of the algebra is defined from it by linearity.

EXEMPLARY:
An example of Hopf algebra with basis:
the group algebra of the Dihedral group of order 6
as a permutation group over Rational Field

```
sage: (a, b) = A._group.gens()
#— needs sage.groups sage.modules
sage: A.coproduct_on_basis(a)
#— needs sage.groups sage.modules
B[(1,2,3)] # B[(1,2,3)]
```

counit()

If `counit_on_basis()` is available, construct the counit morphism from `self` to `self ⊗ self`
by extending it by linearity

EXAMPLES:

```
sage: # needs sage.groups sage.modules
sage: A = HopfAlgebrasWithBasis(QQ).example(); A
An example of Hopf algebra with basis:
the group algebra of the Dihedral group of order 6
as a permutation group over Rational Field
sage: a, b = A.algebra_generators()
sage: a, A.counit(a)
(B[1,2,3], 1)
sage: b, A.counit(b)
(B[1,3], 1)
```

counit_on_basis(i)

The counit of the algebra on the basis (optional).

INPUT:
• `i` — the indices of an element of the basis of `self`

Returns the counit of the corresponding basis elements If implemented, the counit of the algebra is
defined from it by linearity.

EXAMPLES:

```
sage: # needs sage.groups sage.modules
sage: A = HopfAlgebrasWithBasis(QQ).example(); A
An example of Hopf algebra with basis:
the group algebra of the Dihedral group of order 6
as a permutation group over Rational Field
sage: a, b = A.algebra_generators()
sage: A.counit_on_basis(a)
1
```

class Super(base_category)

Bases: `SuperModulesCategory`

extra_super_categories()

EXAMPLES:

```
sage: C = Coalgebras(ZZ).WithBasis().Super()
sage: sorted(C.super_categories(), key=str)  # indirect doctest
(continues on next page)
```
[Category of graded coalgebras with basis over Integer Ring,
Category of super coalgebras over Integer Ring,
Category of super modules with basis over Integer Ring]

4.19 Commutative additive groups

class sage.categories.commutative_additive_groups.CombinativeAdditiveGroups(base_category)

Bases: CategoryWithAxiom_singleton, AbelianCategory

The category of abelian groups, i.e. additive abelian monoids where each element has an inverse.

EXAMPLES:

```
sage: C = CommutativeAdditiveGroups(); C
Category of commutative additive groups
sage: C.super_categories()
[Category of additive groups, Category of commutative additive monoids]
sage: sorted(C.axioms())
[AdditiveAssociative, AdditiveCommutative, AdditiveInverse, AdditiveUnital]
sage: C is CommutativeAdditiveMonoids().AdditiveInverse()
True
sage: from sage.categories.additive_groups import AdditiveGroups
sage: C is AdditiveGroups().AdditiveCommutative()
True
```

Note: This category is currently empty. It's left there for backward compatibility and because it is likely to grow in the future.

class Algebras(category, *args)

Bases: AlgebrasCategory

class CartesianProducts(category, *args)

Bases: CartesianProductsCategory

class ElementMethods

Bases: object

additive_order()

Return the additive order of this element.

EXAMPLES:

```
sage: G = cartesian_product([Zmod(3), Zmod(6), Zmod(5)])
sage: G((1,1,1)).additive_order()
30
sage: any((i * G((1,1,1))).is_zero() for i in range(1,30))
False
sage: 30 * G((1,1,1))
(0, 0, 0)
```

(continues on next page)
4.20 Commutative additive monoids

class sage.categories.commutative_additive_monoids.CommutativeAdditiveMonoids (base_category)

Bases: CategoryWithAxiom_singleton

The category of commutative additive monoids, that is abelian additive semigroups with a unit

EXAMPLES:

sage: C = CommutativeAdditiveMonoids(); C
Category of commutative additive monoids
sage: C.super_categories()
[Category of additive monoids, Category of commutative additive semigroups]
sage: sorted(C.axioms())
['AdditiveAssociative', 'AdditiveCommutative', 'AdditiveUnital']
sage: C is AdditiveMagmas().AdditiveAssociative().AdditiveCommutative().AdditiveUnital()
True

Note: This category is currently empty and only serves as a placeholder to make C.example() work.

4.21 Commutative additive semigroups

class sage.categories.commutative_additive_semigroups.CommutativeAdditiveSemigroups (base_category)

Bases: CategoryWithAxiom_singleton

The category of additive abelian semigroups, i.e. sets with an associative and abelian operation +.

EXAMPLES:
```python
sage: C = CommutativeAdditiveSemigroups(); C
Category of commutative additive semigroups

sage: C.example()
An example of a commutative semigroup: the free commutative semigroup generated by ('a', 'b', 'c', 'd')

sage: sorted(C.super_categories(), key=str)
[Category of additive commutative additive magmas, Category of additive semigroups]

sage: sorted(C.axioms())
['AdditiveAssociative', 'AdditiveCommutative']

sage: C is AdditiveMagmas().AdditiveAssociative().AdditiveCommutative()
True
```

**Note:** This category is currently empty and only serves as a place holder to make `C.example()` work.

### 4.22 Commutative algebra ideals

**class** sage.categories.commutative_algebra_ideals.CommutativeAlgebraIdeals(A)

Bases: Category_ideal

The category of ideals in a fixed commutative algebra $A$.

**EXAMPLES:**

```python
sage: C = CommutativeAlgebraIdeals(QQ['x'])
sage: C
Category of commutative algebra ideals in Univariate Polynomial Ring in x over Rational Field
```

**algebra()**

**EXAMPLES:**

```python
sage: CommutativeAlgebraIdeals(QQ['x']).algebra()
Univariate Polynomial Ring in x over Rational Field
```

**super_categories()**

**EXAMPLES:**

```python
sage: CommutativeAlgebraIdeals(QQ['x']).super_categories()
[Category of algebra ideals in Univariate Polynomial Ring in x over Rational Field]
```
4.23 Commutative algebras

class sage.categories.commutative_algebras.CommutativeAlgebras(base_category):
    Bases: CategoryWithAxiom_over_base_ring

    The category of commutative algebras with unit over a given base ring.

    EXAMPLES:

    sage: M = CommutativeAlgebras(GF(19))
sage: M
    Category of commutative algebras over Finite Field of size 19
    sage: CommutativeAlgebras(QQ).super_categories()
    [Category of algebras over Rational Field, Category of commutative rings]

    This is just a shortcut for:

    sage: Algebras(QQ).Commutative()
    Category of commutative algebras over Rational Field

    Todo:
    • product (= Cartesian product)
    • coproduct (= tensor product over base ring)

    class TensorProducts(category, *args):
        Bases: TensorProductsCategory

        The category of commutative algebras constructed by tensor product of commutative algebras.

        extra_super_categories()

        EXAMPLES:

        sage: Algebras(QQ).Commutative().TensorProducts().extra_super_categories()
        [Category of commutative rings]
        sage: Algebras(QQ).Commutative().TensorProducts().super_categories()
        [Category of tensor products of algebras over Rational Field, Category of commutative algebras over Rational Field]

4.24 Commutative ring ideals

class sage.categories.commutative_ring_ideals.CommutativeRingIdeals(R):
    Bases: Category_ideal

    The category of ideals in a fixed commutative ring.

    EXAMPLES:

    sage: C = CommutativeRingIdeals(IntegerRing())
sage: C
    Category of commutative ring ideals in Integer Ring
EXAMPLES:

```python
sage: CommutativeRingIdeals(ZZ).super_categories()
[Category of ring ideals in Integer Ring]
```

### 4.25 Commutative rings

**class** `sage.categories.commutative_rings.CombinativeRings` *(base_category)*

Bases: `CategoryWithAxiom_singleton`

The category of commutative rings

commutative rings with unity, i.e. rings with commutative * and a multiplicative identity

**EXAMPLES:**

```python
sage: C = CommutativeRings(); C
Category of commutative rings
sage: C.super_categories()
[Category of rings, Category of commutative monoids]
```

**class** `CartesianProducts` *(category, *args)*

Bases: `CartesianProductsCategory`

**extra_super_categories**()

Let Sage knows that Cartesian products of commutative rings is a commutative ring.

**EXAMPLES:**

```python
sage: CommutativeRings().Commutative().CartesianProducts().extra_super_categories()
[Category of commutative rings]
```

**class** `Finite` *(base_category)*

Bases: `CategoryWithAxiom_singleton`

Check that Sage knows that Cartesian products of finite commutative rings is a finite commutative ring.

**EXAMPLES:**

```python
sage: cartesian_product([Zmod(34), ....: QQ, GF(5)]) in CommutativeRings()
True
```

**class** `ParentMethods`

Bases: `object`

**class** `ElementMethods`

Bases: `object`
**cyclotomic_cosets** *(q, cosets=None)*

Return the (multiplicative) orbits of \( q \) in the ring.

Let \( R \) be a finite commutative ring. The group of invertible elements \( R^* \) in \( R \) gives rise to a group action on \( R \) by multiplication. An orbit of the subgroup generated by an invertible element \( q \) is called a *q-cyclotomic coset* (since in a finite ring, each invertible element is a root of unity).

These cosets arise in the theory of minimal polynomials of finite fields, duadic codes and combinatorial designs. Fix a primitive element \( z \) of \( GF(q^k) \). The minimal polynomial of \( z^s \) over \( GF(q) \) is given by

\[
M_s(x) = \prod_{i \in C_s} (x - z^i),
\]

where \( C_s \) is the \( q \)-cyclotomic coset mod \( n \) containing \( s \), \( n = q^k - 1 \).

**Note:** When \( R = \mathbb{Z}/n\mathbb{Z} \) the smallest element of each coset is sometimes called a *coset leader*. This function returns sorted lists so that the coset leader will always be the first element of the coset.

**INPUT:**
- \( q \) – an invertible element of the ring
- \( \text{cosets} \) – an optional list of elements of \( \text{self} \). If provided, the function only return the list of cosets that contain some element from \( \text{cosets} \).

**OUTPUT:**
A list of lists.

**EXAMPLES:**

```python
sage: Zmod(11).cyclotomic_cosets(2)
[[0], [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]]
sage: Zmod(15).cyclotomic_cosets(2)
[[0], [1, 2, 4, 8], [3, 6, 9, 12], [5, 10], [7, 11, 13, 14]]
```

Since the group of invertible elements of a finite field is cyclic, the set of squares is a particular case of cyclotomic coset:

```python
sage: # needs sage.rings.finite_rings
sage: K = GF(25, 'z')
sage: a = K.multiplicative_generator()
sage: K.cyclotomic_cosets(a**2, cosets=[1])
[[1, 2, 3, 4, z + 1, z + 3,
  2*z + 1, 2*z + 2, 3*z + 3,
  3*z + 4, 4*z + 2, 4*z + 4]]
sage: sorted(b for b in K if not b.is_zero() and b.is_square())
[1, 2, 3, 4, z + 1, z + 3,
  2*z + 1, 2*z + 2, 3*z + 3,
  3*z + 4, 4*z + 2, 4*z + 4]
```

We compute some examples of minimal polynomials:

```python
sage: # needs sage.rings.finite_rings
sage: K = GF(27, 'z')
sage: a = K.multiplicative_generator()
sage: R.<X> = PolynomialRing(K, 'X')
sage: a.minimal_polynomial('X')
X^3 + 2*X + 1
```

(continues on next page)
Cyclotomic cosets of fields are useful in combinatorial design theory to provide so-called difference families (see Wikipedia article Difference_set and difference_family). This is illustrated on the following examples:

```sage
sage: K = GF(5)
sage: a = K.multiplicative_generator() # needs sage.libs.pari
sage: H = K.cyclotomic_cosets(a**2, cosets=[1, 2]); H # needs sage.rings.finite_rings
[[1, 4], [2, 3]]
sage: sorted(x - y for D in H for x in D for y in D if x != y) # needs sage.rings.finite_rings
[1, 2, 3, 4]
```

```sage
sage: K = GF(37)
sage: a = K.multiplicative_generator() # needs sage.libs.pari
sage: H = K.cyclotomic_cosets(a**4, cosets=[1]); H # needs sage.rings.finite_rings
[[1, 7, 9, 10, 12, 16, 26, 33, 34]]
sage: sorted(x - y for D in H for x in D for y in D if x != y) # needs sage.rings.finite_rings
[1, 1, 2, 2, 3, 3, 4, 4, 5, 5, ..., 33, 34, 34, 35, 35, 36, 36]
```

The method `cyclotomic_cosets` works on any finite commutative ring:

```sage
sage: R = cartesian_product([GF(7), Zmod(14)])
sage: a = R((3,5))
sage: R.cyclotomic_cosets((3,5), [(1,1)])
[[[1, 1), (2, 1)], (3, 5), (4, 9), (5, 3), (6, 13)]]
```

```python
class ParentMethods
    Bases: object

    is_commutative()

    Return whether the ring is commutative.

    The answer is True only if the category is a sub-category of CommutativeRings.

    It is recommended to use instead `R in Rings().Commutative()`.

    EXAMPLES:
```
sage: QQ.is_commutative()
True
sage: QQ['x,y,z'].is_commutative()
True

over \((\text{base}=\text{None}, \text{gen}=\text{None}, \text{gens}=\text{None}, \text{name}=\text{None}, \text{names}=\text{None})\)

Return this ring, considered as an extension of \(\text{base}\).

INPUT:
- \text{base} – a commutative ring or a morphism or \text{None} (default: \text{None}); the base of this extension or its defining morphism
- \text{gen} – a generator of this extension (over its base) or \text{None} (default: \text{None});
- \text{gens} – a list of generators of this extension (over its base) or \text{None} (default: \text{None});
- \text{name} – a variable name or \text{None} (default: \text{None})
- \text{names} – a list or a tuple of variable names or \text{None} (default: \text{None})

EXAMPLES:

We construct an extension of finite fields:

```python
sage: # needs sage.rings.finite_rings
sage: F = GF(5^2)
```
```python
sage: k = GF(5^4)
```
```python
sage: z4 = k.gen()
```
```python
sage: K = k.over(F); K
```

Field in \(z4\) with defining polynomial \(x^2 + (4*z2 + 3)*x + z2\) over its base

If not explicitly given, the default generator of the top ring (here \(k\)) is used and the same name is kept:

```python
sage: K.gen()
```

Field in \(z4\) with defining polynomial \(x^2 + (4*z2 + 3)*x + z2\) over its base

However, it is possible to specify another generator and/or another name. For example:

```python
sage: Ka = k.over(F, name='a'); Ka
```

Field in \(a\) with defining polynomial \(x^2 + (4*z2 + 3)*x + z2\) over its base

```python
sage: Ka.gen()
```

\(a\)

```python
sage: Ka(z4)
```

\(a\)

Note that the shortcut \(K.\langle a\rangle\) is also available:
Building an extension on top of another extension is allowed:

```
sage: L = GF(5^12).over(K); L  # needs sage.modules sage.rings.finite_rings
Field in z12 with defining polynomial
x^3 + (1 + (4*z2 + 2)*z4)*x^2 + (2 + 2*z4)*x - z4 over its base
sage: L.base_ring()  # needs sage.modules sage.rings.finite_rings
Field in z4 with defining polynomial
x^2 + (4*z2 + 3)*x + z2 over its base
```

The successive bases of an extension are accessible via the method `sage.rings.
ring_extension.RingExtension_generic.bases()`:

```
sage: L.bases()  # needs sage.modules sage.rings.finite_rings
[Field in z12 with defining polynomial
  x^3 + (1 + (4*z2 + 2)*z4)*x^2 + (2 + 2*z4)*x - z4 over its base,
  Field in z4 with defining polynomial
  x^2 + (4*z2 + 3)*x + z2 over its base,
  Finite Field in z2 of size 5^2]
```

When `base` is omitted, the canonical base of the ring is used:

```
sage: S.<x> = QQ[]
sage: E = S.over(); E  # needs sage.modules
Univariate Polynomial Ring in x over Rational Field over its base
sage: E.base_ring()  # needs sage.modules
Rational Field
```

Here is an example where `base` is a defining morphism:

```
sage: # needs sage.modules sage.rings.number_field
sage: k.<a> = QQ.extension(x^2 - 2)
sage: l.<b> = QQ.extension(x^4 - 2)
sage: f = k.hom([b^2])
sage: L = l.over(f)
sage: L
Field in b with defining polynomial x^2 - a over its base
sage: L.base_ring()
Number Field in a with defining polynomial x^2 - 2
```

Similarly, one can create a tower of extensions:

```
sage: # needs sage.modules sage.rings.number_field
sage: K = k.over()
sage: L = l.over(Hom(K, l)(f)); L
Field in b with defining polynomial x^2 - a over its base
sage: L.base_ring()
```

(continues on next page)
Field in a with defining polynomial $x^2 - 2$ over its base
sage: L.bases()
[Field in b with defining polynomial $x^2 - a$ over its base, 
Field in a with defining polynomial $x^2 - 2$ over its base, 
Rational Field]

4.26 Complete Discrete Valuation Rings (CDVR) and Fields (CDVF)

class sage.categories.complete_discretevaluation.CompleteDiscreteValuationFields
    Bases: Category_singleton

The category of complete discrete valuation fields

EXAMPLES:

sage: Zp(7) in CompleteDiscreteValuationFields() 
False

sage: QQ in CompleteDiscreteValuationFields() 
False

sage: LaurentSeriesRing(QQ, 'u') in CompleteDiscreteValuationFields() 
True

sage: Qp(7) in CompleteDiscreteValuationFields() 
True

# needs sage.rings.padics
sage: TestSuite(CompleteDiscreteValuationFields()).run()

class ElementMethods
    Bases: object

denominator()

    Return the denominator of this element normalized as a power of the uniformizer

EXAMPLES:

sage: # needs sage.rings.padics
sage: K = Qp(7)
sage: x = K(1/21)
sage: x.denominator() 
7 + O(7^21)

sage: x = K(7)
sage: x.denominator() 
1 + O(7^20)

Note that the denominator lives in the ring of integers:

sage: x.denominator().parent() 
7-adic Ring with capped relative precision 20

When the denominator is indistinguishable from 0 and the precision on the input is $O(p^n)$, the return value is 1 if $n$ is nonnegative and $p^{(-n)}$ otherwise:
Category Framework, Release 10.3

```
sage: # needs sage.rings.padics
sage: x = K(0, 5); x
O(7^5)
sage: x.denominator()
1 + O(7^20)
sage: x = K(0, -5); x
O(7^-5)
sage: x.denominator()
7^-5 + O(7^-25)
```

**numerator()**

Return the numerator of this element, normalized in such a way that \( x = x.numerator() / x.denominator() \) always holds true.

**EXAMPLES:**

```
sage: # needs sage.rings.padics
sage: K = Qp(7, 5)
sage: x = K(1/21)
sage: x.numerator()
5 + 4*7 + 4*7^2 + 4*7^3 + 4*7^4 + O(7^5)
sage: x == x.numerator() / x.denominator()
True
```

Note that the numerator lives in the ring of integers:

```
sage: x.numerator().parent()  # needs sage.rings.padics
7-adic Ring with capped relative precision 5
```

**valuation()**

Return the valuation of this element.

**EXAMPLES:**

```
sage: K = Qp(7)  # needs sage.rings.padics
sage: x = K(7); x  # needs sage.rings.padics
7 + O(7^21)
sage: x.valuation()  # needs sage.rings.padics
1
```

**super_categories()**

**EXAMPLES:**

```
sage: CompleteDiscreteValuationFields().super_categories()
[Category of discrete valuation fields]
```

```
class sage.categories.complete_discrete_valuation.CompleteDiscreteValuationRings
    Bases: Category_singleton
    The category of complete discrete valuation rings
    EXAMPLES:
```
sage: Zp(7) in CompleteDiscreteValuationRings() # needs sage.rings.padics
True
sage: QQ in CompleteDiscreteValuationRings()
False
sage: QQ[['u']] in CompleteDiscreteValuationRings()
True
sage: Qp(7) in CompleteDiscreteValuationRings() # needs sage.rings.padics
False
sage: TestSuite(CompleteDiscreteValuationRings()).run()

class ElementMethods
Bases: object
denominator()

Return the denominator of this element normalized as a power of the uniformizer

EXAMPLES:

sage: # needs sage.rings.padics
sage: K = Qp(7)
sage: x = K(1/21)
sage: x.denominator()
7 + O(7^21)
sage: x = K(7)
sage: x.denominator()
1 + O(7^20)

Note that the denominator lives in the ring of integers:

sage: x.denominator().parent() # needs sage.rings.padics
7-adic Ring with capped relative precision 20

When the denominator is indistinguishable from 0 and the precision on the input is \( O(p^n) \), the return value is 1 if \( n \) is nonnegative and \( p^{(-n)} \) otherwise:

sage: # needs sage.rings.padics
sage: x = K(0, 5); x
0(7^5)
sage: x.denominator()
1 + O(7^20)
sage: x = K(0, -5); x
0(7^-5)
sage: x.denominator()
7^5 + O(7^25)

lift_to_precision(absprec=None)

Return another element of the same parent with absolute precision at least absprec, congruent to this element modulo the precision of this element.

INPUT:

- absprec – an integer or None (default: None), the absolute precision of the result. If None, lifts to the maximum precision allowed.

Note: If setting absprec that high would violate the precision cap, raises a precision error. Note that
the new digits will not necessarily be zero.

EXAMPLES:

```python
sage: # needs sage.rings.padics
sage: R = ZpCA(17)
sage: R(-1, 2).lift_to_precision(10)
16 + 16*17 + O(17^10)
sage: R(1, 15).lift_to_precision(10)
1 + O(17^15)
sage: R(1, 15).lift_to_precision(30)
Traceback (most recent call last):
..._precisionError: precision higher than allowed by the precision cap
sage: (R(-1, 2).lift_to_precision().precision_absolute())
....: == R.precision_cap())
True

numerator()

Return the numerator of this element, normalized in such a way that \( x = x.numerator() / x.denominator() \) always holds true.

EXAMPLES:

```python
sage: # needs sage.rings.padics
sage: K = Qp(7, 5)
sage: x = K(1/21)
sage: x.numerator()
5 + 4*7 + 4*7^2 + 4*7^3 + 4*7^4 + O(7^5)
sage: x == x.numerator() / x.denominator()
True
```

Note that the numerator lives in the ring of integers:

```python
sage: x.numerator().parent()
7-adic Ring with capped relative precision 5
```

valuation()

Return the valuation of this element.

EXAMPLES:

```python
sage: R = Zp(7)
sage: x = R(7)
sage: x.valuation()
1
```
**super_categories()**

**EXAMPLES:**

```python
sage: CompleteDiscreteValuationRings().super_categories()
[Category of discrete valuation rings]
```

### 4.27 Complex reflection groups

**class** `sage.categories.complex_reflection_groups.ComplexReflectionGroups`

**Bases:** `Category_singleton`

The category of complex reflection groups.

Let $V$ be a complex vector space. A *complex reflection* is an element of $\text{GL}(V)$ fixing a hyperplane pointwise and acting by multiplication by a root of unity on a complementary line.

A *complex reflection group* is a group $W$ that is (isomorphic to) a subgroup of some general linear group $\text{GL}(V)$ generated by a distinguished set of complex reflections.

The dimension of $V$ is the *rank* of $W$.

For a comprehensive treatment of complex reflection groups and many definitions and theorems used here, we refer to [LT2009]. See also Wikipedia article Reflection_group.

**See also:**

`ReflectionGroup()` for usage examples of this category.

**EXAMPLES:**

```python
sage: from sage.categories.complex_reflection_groups import ComplexReflectionGroups
sage: ComplexReflectionGroups()
Category of complex reflection groups
sage: ComplexReflectionGroups().super_categories()
[Category of complex reflection or generalized Coxeter groups]
sage: ComplexReflectionGroups().all_super_categories()
[Category of complex reflection groups,
 Category of complex reflection or generalized Coxeter groups,
 Category of groups,
 Category of monoids,
 Category of finitely generated semigroups,
 Category of semigroups,
 Category of finitely generated magmas,
 Category of inverse unital magmas,
 Category of unital magmas,
 Category of magmas,
 Category of enumerated sets,
 Category of sets,
 Category of sets with partial maps,
 Category of objects]
```

An example of a reflection group:

```python
sage: W = ComplexReflectionGroups().example(); W
#...
needs sage.combinat
5-colored permutations of size 3
```
\( W \) is in the category of complex reflection groups:

```
sage: W in ComplexReflectionGroups()  # needs sage.combinat
True
```

**Finite**

alias of `FiniteComplexReflectionGroups`

**class ParentMethods**

Bases: object

**rank()**

Return the rank of \( self \).

The rank of \( self \) is the dimension of the smallest faithful reflection representation of \( self \).

EXAMPLES:

```
sage: W = CoxeterGroups().example(); W
The symmetric group on \{0, ..., 3\}
sage: W.rank()
3
```

**additional_structure()**

Return None.

Indeed, all the structure complex reflection groups have in addition to groups (simple reflections, ...) is already defined in the super category.

See also:

`Category.additional_structure()`

EXAMPLES:

```
sage: from sage.categories.complex_reflection_groups import ComplexReflectionGroups
sage: ComplexReflectionGroups().additional_structure()
```

**example()**

Return an example of a complex reflection group.

EXAMPLES:

```
sage: from sage.categories.complex_reflection_groups import ComplexReflectionGroups
sage: ComplexReflectionGroups().example()  # needs sage.combinat
5-colored permutations of size 3
```

**super_categories()**

Return the super categories of \( self \).

EXAMPLES:

```
sage: from sage.categories.complex_reflection_groups import ComplexReflectionGroups
sage: ComplexReflectionGroups().super_categories()
[Category of complex reflection or generalized Coxeter groups]```
4.28 Common category for Generalized Coxeter Groups or Complex Reflection Groups

```
class sage.categories.complex_reflection_or_generalized_coxeter_groups.
ComplexReflectionOrGeneralizedCoxeterGroups
    Bases: Category_singleton

The category of complex reflection groups or generalized Coxeter groups.

Finite Coxeter groups can be defined equivalently as groups generated by reflections, or by presentations. Over the
last decades, the theory has been generalized in both directions, leading to the study of (finite) complex reflection
groups on the one hand, and (finite) generalized Coxeter groups on the other hand. Many of the features remain
similar, yet, in the current state of the art, there is no general theory covering both directions.

This is reflected by the name of this category which is about factoring out the common code, tests, and declarations.

A group in this category has:

- A distinguished finite set of generators \((s_i)_I\), called simple reflections. The set \(I\) is called the index set. The
  name “reflection” is somewhat of an abuse as they can have higher order; still, they are all of finite order:
  \(s_i^k = 1\) for some \(k\).
- A collection of distinguished reflections which are the conjugates of the simple reflections. For complex
  reflection groups, they are in one-to-one correspondence with the reflection hyperplanes and share the same
  index set.
- A collection of reflections which are the conjugates of all the non trivial powers of the simple reflections.

The usual notions of reduced words, length, irreducibility, etc can be canonically defined from the above.

The following methods must be implemented:

- \(\texttt{ComplexReflectionOrGeneralizedCoxeterGroups.ParentMethods.index_set()}\)
- \(\texttt{ComplexReflectionOrGeneralizedCoxeterGroups.ParentMethods.simple_reflection()}\)

Optionally one can define analog methods for distinguished reflections and reflections (see below).

At least one of the following methods must be implemented:

- \(\texttt{ComplexReflectionOrGeneralizedCoxeterGroups.ElementMethods.apply_simple_reflection()}\)
- \(\texttt{ComplexReflectionOrGeneralizedCoxeterGroups.ElementMethods.apply_simple_reflection_left()}\)
- \(\texttt{ComplexReflectionOrGeneralizedCoxeterGroups.ElementMethods.apply_simple_reflection_right()}\)
- \(\texttt{ComplexReflectionOrGeneralizedCoxeterGroups.ElementMethods._mul_()}\)

It’s recommended to implement either \_mul\_ or both apply_simple_reflection_left and apply_simple_reflection_right.

See also:

- \texttt{complex_reflection_groups.ComplexReflectionGroups}
- \texttt{generalized_coxeter_groups.GeneralizedCoxeterGroups}

EXAMPLES:
```
sage: from sage.categories.complex_reflection_or_generalized_coxeter_groups_ ˓→import ComplexReflectionOrGeneralizedCoxeterGroups
sage: C = ComplexReflectionOrGeneralizedCoxeterGroups(); C
Category of complex reflection or generalized Coxeter groups
sage: C.super_categories()
[Category of finitely generated enumerated groups]

sage: C.required_methods()
{'element': {'optional': ['reflection_length'],
                'required': []},
 'parent': {'optional': ['distinguished_reflection', 'hyperplane_index_set',
                         'irreducible_components',
                         'reflection', 'reflection_index_set'],
             'required': ['__contains__', 'index_set']}}

class ElementMethods
Bases: object

    apply_conjugation_by_simple_reflection(i)

Conjugate self by the i-th simple reflection.

EXAMPLES:

    sage: W = WeylGroup(['A',3])
    sage: w = W.from_reduced_word([3,1,2,1])
    sage: w.apply_conjugation_by_simple_reflection(1).reduced_word()
    [3, 2]

    apply_reflections (word, side='right', word_type='all')

Return the result of the (left/right) multiplication of self by word.

INPUT:
    • word – a sequence of indices of reflections
    • side – (default: 'right') indicates multiplying from left or right
    • word_type – (optional, default: 'all'): either 'simple', 'distinguished', or 'all'

EXAMPLES:

    sage: # optional - gap3
    sage: W = ReflectionGroup((1,1,3))
    sage: W.one().apply_reflections([1])
    (1,4)(2,3)(5,6)
    sage: W.one().apply_reflections([2])
    (1,3)(2,5)(4,6)
    sage: W.one().apply_reflections([2,1])
    (1,2,6)(3,4,5)

    sage: W = CoxeterGroups().example()
    sage: w = W.an_element(); w
    (1, 2, 3, 0)
    sage: w.apply_reflections([0,1], word_type='simple')
    (2, 3, 1, 0)
    sage: w
    (1, 2, 3, 0)
    sage: w.apply_reflections([0,1], side='left', word_type='simple')
    (0, 1, 3, 2)

(continues on next page)
sage: W = WeylGroup("A3", prefix='s')
sage: w = W.an_element(); w
s1*s2*s3
sage: AS = W.domain()
sage: r1 = AS.roots()[4]
sage: r1
(0, 1, 0, -1)
sage: r2 = AS.roots()[5]
sage: r2
(0, 0, 1, -1)
sage: w.apply_reflections([r1, r2], word_type='all')
s1

sage: # optional - gap3
sage: W = ReflectionGroup((1,1,3))
sage: W.one().apply_reflections([1], word_type='distinguished')
(1,4)(2,3)(5,6)
sage: W.one().apply_reflections([2], word_type='distinguished')
(1,3)(2,5)(4,6)
sage: W.one().apply_reflections([3], word_type='distinguished')
(1,5)(2,4)(3,6)
sage: W.one().apply_reflections([2,1], word_type='distinguished')
(1,2,6)(3,4,5)

sage: W = ReflectionGroup((1,1,3), hyperplane_index_set=['A','B','C']); W
Irreducible real reflection group of rank 2 and type A2
sage: W.one().apply_reflections(['A'], word_type='distinguished') # optional - gap3
(1,4)(2,3)(5,6)

apply_simple_reflection(i, side='right')

Return self multiplied by the simple reflection s[i].

INPUT:

- i – an element of the index set
- side – (default: "right") "left" or "right"

This default implementation simply calls apply_simple_reflection_left() or apply_simple_reflection_right().

EXAMPLES:

sage: W = CoxeterGroups().example()
sage: w = W.an_element(); w
(1, 2, 3, 0)
sage: w.apply_simple_reflection(0, side = "left")
(0, 2, 3, 1)
sage: w.apply_simple_reflection(1, side = "left")
(2, 1, 3, 0)
sage: w.apply_simple_reflection(2, side = "left")
(1, 3, 2, 0)
sage: w.apply_simple_reflection(0, side = "right")
(2, 1, 3, 0)
sage: w.apply_simple_reflection(1, side = "right")
By default, side is "right":

```
sage: w.apply_simple_reflection(0)
(2, 1, 3, 0)
```

Some tests with a complex reflection group:

```
sage: from sage.categories.complex_reflection_groups import...
˓→ComplexReflectionGroups
sage: W = ComplexReflectionGroups().example(); W
5-colored permutations of size 3
sage: w = W.an_element(); w
[[1, 0, 0], [3, 1, 2]]
```

```
sage: w.apply_simple_reflection(1, side="left")
[[0, 1, 0], [1, 3, 2]]
```

```
sage: w.apply_simple_reflection(2, side="left")
[[1, 0, 0], [3, 2, 1]]
```

```
sage: w.apply_simple_reflection(3, side="left")
[[1, 0, 1], [3, 1, 2]]
```

```
sage: w.apply_simple_reflection(1, side="right")
[[1, 0, 0], [3, 2, 1]]
```

```
sage: w.apply_simple_reflection(2, side="right")
[[1, 0, 0], [2, 1, 3]]
```

```
sage: w.apply_simple_reflection(3, side="right")
[[2, 0, 0], [3, 1, 2]]
```

```
apply_simple_reflection_left(i)
Return self multiplied by the simple reflection s[i] on the left.

This low level method is used intensively. Coxeter groups are encouraged to override this straightforward implementation whenever a faster approach exists.

EXAMPLES:

```
sage: W = CoxeterGroups().example()
sage: w = W.an_element(); w
(1, 2, 3, 0)
```

```
sage: w.apply_simple_reflection_left(0)
(0, 2, 3, 1)
```

```
sage: w.apply_simple_reflection_left(1)
(2, 1, 3, 0)
```

```
sage: w.apply_simple_reflection_left(2)
(1, 3, 2, 0)
```

EXAMPLES:

```
sage: from sage.categories.complex_reflection_groups import...
˓→ComplexReflectionGroups
sage: W = ComplexReflectionGroups().example()
sage: w = W.an_element(); w
[[1, 0, 0], [3, 1, 2]]
```

```
sage: w.apply_simple_reflection_left(1)
```
apply_simple_reflection_right \( (i) \)

Return \( \text{self} \) multiplied by the simple reflection \( s[i] \) on the right.

This low level method is used intensively. Coxeter groups are encouraged to override this straightforward implementation whenever a faster approach exists.

EXAMPLES:

```
sage: \W = \text{CoxeterGroups().example()}
sage: w = \W.an_element(); w
(1, 2, 3, 0)
sage: w.apply_simple_reflection_right(0)
(2, 1, 3, 0)
sage: w.apply_simple_reflection_right(1)
(1, 3, 2, 0)
sage: w.apply_simple_reflection_right(2)
(1, 2, 0, 3)
sage: from \text{sage.categories.complex_reflection_groups import...}
\rightarrow \text{ComplexReflectionGroups}
sage: \W = \text{ComplexReflectionGroups().example()}
sage: w = \W.an_element(); w
[[1, 0, 0], [3, 1, 2]]
sage: w.apply_simple_reflection_right(1)
[[1, 0, 0], [3, 2, 1]]
sage: w.apply_simple_reflection_right(2)
[[1, 0, 0], [2, 1, 3]]
sage: w.apply_simple_reflection_right(3)
[[2, 0, 0], [3, 1, 2]]
```
(continued from previous page)

```plaintext
(1, 2, 3, 0)
sage: w.apply_simple_reflections([0,1], side='left')
(0, 1, 3, 2)
```

**is** **reflection** 

Return whether self is a reflection.

**EXAMPLES:**

```plaintext
sage: W = ReflectionGroup((1,1,4))  # optional - gap3
sage: [t.is_reflection() for t in W.reflections()]  # optional - gap3
[True, True, True, True, True, True]
```

```plaintext
sage: len([t for t in W.reflections() if t.is_reflection()])  # optional - gap3
6
```

```plaintext
sage: W = ReflectionGroup((2,1,3))  # optional - gap3
sage: [t.is_reflection() for t in W.reflections()]  # optional - gap3
[True, True, True, True, True, True, True, True, True]
```

```plaintext
sage: len([t for t in W.reflections() if t.is_reflection()])  # optional - gap3
9
```

**reflection_length**

Return the reflection length of self.

This is the minimal length of a factorization of self into reflections.

**EXAMPLES:**

```plaintext
sage: W = ReflectionGroup((1,1,2))  # optional - gap3
sage: sorted([t.reflection_length() for t in W])  # optional - gap3
[0, 1]
```

```plaintext
sage: W = ReflectionGroup((2,1,2))  # optional - gap3
sage: sorted([t.reflection_length() for t in W])  # optional - gap3
[0, 1, 1, 1, 1, 2, 2, 2]
```

```plaintext
sage: W = ReflectionGroup((3,1,2))  # optional - gap3
sage: sorted([t.reflection_length() for t in W])  # optional - gap3
[0, 1, 1, 1, 1, 1, 1, 1, 1, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2]
```

```plaintext
sage: W = ReflectionGroup((2,2,2))  # optional - gap3
sage: sorted([t.reflection_length() for t in W])  # optional - gap3
[0, 1, 1, 2]
```

**class** **Irreducible**(base_category)

**Bases:** CategoryWithAxiom

**class** **ParentMethods**

**Bases:** object

**irreducible_components**

Return a list containing all irreducible components of self as finite reflection groups.

**EXAMPLES:**
sage: W = ColoredPermutations(4, 3)
sage: W.irreducible_components()
[4-colored permutations of size 3]

class ParentMethods

Bases: object

distinguished_reflection(i)

Return the i-th distinguished reflection of self.

INPUT:
• i - an element of the index set of the distinguished reflections.

See also:
• distinguished_reflections()
• hyperplane_index_set()

EXAMPLES:

sage: W = ReflectionGroup((1,1,4), hyperplane_index_set=('a','b','c','d',
˓→'e','f'))  # optional - gap3
sage: for i in W.hyperplane_index_set():                # optional - gap3
    ....: print('%s %s' % (i, W.distinguished_reflection(i)))
a (1,7)(2,4)(5,6)(8,10)(11,12)
b (1,4)(2,8)(3,5)(7,10)(9,11)
c (2,5)(3,9)(4,6)(8,11)(10,12)
d (1,8)(2,7)(3,6)(4,10)(9,12)
e (1,6)(2,9)(3,8)(5,11)(7,12)
f (1,11)(3,10)(4,9)(5,7)(6,12)
distinguished_reflections()

Return a finite family containing the distinguished reflections of self, indexed by hyperplane_index_set().

A distinguished reflection is a conjugate of a simple reflection. For a Coxeter group, reflections and distinguished reflections coincide. For a Complex reflection groups this is a reflection acting on the complement of the fixed hyperplane $H$ as $\exp(2\pi i/n)$, where $n$ is the order of the reflection subgroup fixing $H$.

See also:
• distinguished_reflection()
• hyperplane_index_set()

EXAMPLES:

sage: W = ReflectionGroup((1,1,3))  # optional - gap3
sage: distinguished_reflections = W.distinguished_reflections()  # optional - gap3
sage: for index in sorted(distinguished_reflections.keys()):  # optional - gap3
    ....: print('%s %s' % (index, distinguished_reflections[index]))
1 (1,4)(2,3)(5,6)
2 (1,3)(2,5)(4,6)
3 (1,5)(2,4)(3,6)

(continues on next page)
from_reduced_word(word, word_type='simple')

Return an element of self from its (reduced) word.

INPUT:

- `word` - a list (or iterable) of elements of the index set of self (resp. of the distinguished or of all reflections)
- `word_type` - (optional, default: 'simple'): either 'simple', 'distinguished', or 'all'

If `word` is \([i_1, i_2, \ldots, i_k]\), then this returns the corresponding product of simple reflections \(s_{i_1} s_{i_2} \cdots s_{i_k}\).

If `word_type` is 'distinguished' (resp. 'all'), then the product of the distinguished reflections (resp. all reflections) is returned.

**Note:** The main use case is for constructing elements from reduced words, hence the name of this method. However, the input word need not be reduced.

See also:

- `index_set()`
- `reflection_index_set()`
- `hyperplane_index_set()`
- `apply_simple_reflections()`
- `reduced_word()`
- `_test_reduced_word()`

**EXAMPLES:**

```python
sage: W = CoxeterGroups().example()
sage: W
The symmetric group on {0, ..., 3}
sage: s = W.simple_reflections()
sage: W.from_reduced_word([0,2,0,1])
(0, 3, 1, 2)
sage: W.from_reduced_word((0,2,0,1))
(0, 3, 1, 2)
sage: s[0]*s[2]*s[0]*s[1]
(0, 3, 1, 2)
```

We now experiment with the different values for `word_type` for the colored symmetric group:

```python
sage: W = ColoredPermutations(1,4)
sage: W.from_reduced_word([1,2,1,2,1,2])
[[0, 0, 0, 0], [1, 2, 3, 4]]
sage: W.from_reduced_word([1, 2, 3]).reduced_word()
[1, 2, 3]
sage: W = WeylGroup("A3", prefix='s')
sage: AS = W.domain()
sage: r1 = AS.roots()[4]
sage: r2 = AS.roots()[5]
sage: W.from_reduced_word([r1, r2], word_type='all')
s3*s2
sage: W = WeylGroup("G2", prefix='s')
sage: W.from_reduced_word(W.domain().positive_roots(), word_type='all')
s1*s2
sage: W = ReflectionGroup((1,1,4)) # optional - gap3
sage: W.from_reduced_word([1,2,3], word_type='all').reduced_word_in_reflections() # optional - gap3
[1, 2, 3]
sage: W.from_reduced_word([1,2,3]).reduced_word_in_reflections() # optional - gap3
[1, 2, 3]
```

**group_generators()**

Return the simple reflections of `self`, as distinguished group generators.

See also:
• `simple_reflections()`
• `Groups.ParentMethods.group_generators()`
• `Semigroups.ParentMethods.semigroup_generators()`

**EXAMPLES:**

```python
sage: D10 = FiniteCoxeterGroups().example(10)
sage: D10.group_generators()
Finite family {1: (1,), 2: (2,)}
sage: SymmetricGroup(5).group_generators()
Finite family {1: (1,2), 2: (2,3), 3: (3,4), 4: (4,5)}

sage: W = ColoredPermutations(3,2)
sage: W.group_generators()
Finite family {1: [0, 0],
              2: [0, 1],
              [1, 2]}

The simple reflections are also semigroup generators, even for an infinite group:

```python
sage: W = WeylGroup(['A',2,1])
sage: W.semigroup_generators()
Finite family {0: [-1  1  1]
              [ 0  1  0],
              [ 0  0  1],
              1: [ 1  0  0]
              [ 1 -1  1],
              [ 0  0  1],
              2: [ 1  0  0]
              [ 0  1  0]
              [ 1  1 -1]}
```

**hyperplane_index_set()**

Return the index set of the distinguished reflections of `self`.

This is also the index set of the reflection hyperplanes of `self`, hence the name. This name is slightly abusive since the concept of reflection hyperplanes is not defined for all generalized Coxeter groups. However for all practical purposes this is only used for complex reflection groups, and there this is the desirable name.

**See also:**

• `distinguished_reflection()`
• `distinguished_reflections()`

**EXAMPLES:**

```python
sage: # optional - gap3
sage: W = ReflectionGroup((1,1,4))
sage: W.hyperplane_index_set()  
(1, 2, 3, 4, 5, 6)
sage: W = ReflectionGroup((1,1,4), hyperplane_index_set=[1,3,'asdf',7,9,
˓→11])
sage: W.hyperplane_index_set()  
(1, 3, 'asdf', 7, 9, 11)
sage: W = ReflectionGroup((1,1,4), hyperplane_index_set=('a','b','c','d',
˓→'e','f'))
```

(continues on next page)
index_set()

Return the index set of (the simple reflections of) self, as a list (or iterable).

See also:

- simple_reflection()
- simple_reflections()

EXAMPLES:

```sage
sage: W = CoxeterGroups().Finite().example(); W
The 5-th dihedral group of order 10
sage: W.index_set()
(1, 2)
sage: W = ColoredPermutations(1, 4)
sage: W.index_set()
(1, 2, 3)
sage: W = ReflectionGroup((1,1,4), index_set=[1,3,'asdf'])  # optional - gap3
sage: W.index_set()                                         # optional - gap3
(1, 3, 'asdf')
sage: W = ReflectionGroup((1,1,4), index_set=('a','b','c'))  # optional - gap3
sage: W.index_set()                                          # optional - gap3
('a', 'b', 'c')
```

irreducible_component_index_sets()

Return a list containing the index sets of the irreducible components of self as finite reflection groups.

EXAMPLES:

```sage
sage: W = ReflectionGroup([1,1,3], [3,1,3], 4); W  # optional - gap3
Reducible complex reflection group of rank 7 and type A2 x G(3,1,3) x ST4
sage: sorted(W.irreducible_component_index_sets())  # optional - gap3
[[[1, 2], [3, 4, 5], [6, 7]]]
```

ALGORITHM:

Take the connected components of the graph on the index set with edges (i,j), where s[i] and s[j] do not commute.

irreducible_components()

Return the irreducible components of self as finite reflection groups.

EXAMPLES:

```sage
sage: W = ReflectionGroup([1,1,3], [3,1,3], 4)  # optional - gap3
sage: W.irreducible_components()                  # optional - gap3
[Irreducible real reflection group of rank 2 and type A2,
 Irreducible complex reflection group of rank 3 and type G(3,1,3),
 Irreducible complex reflection group of rank 2 and type ST4]
```

is_irreducible()

Return True if self is irreducible.
EXAMPLES:

```python
sage: W = ColoredPermutations(1,3); W
1-colored permutations of size 3
sage: W.is_irreducible()
True

sage: W = ReflectionGroup((1,1,3),(2,1,3)); W  # optional - gap3
Reducible real reflection group of rank 5 and type A2 x B3
sage: W.is_irreducible()  # optional - gap3
False
```

`is_reducible()`

Return True if self is not irreducible.

EXAMPLES:

```python
sage: W = ColoredPermutations(1,3); W
1-colored permutations of size 3
sage: W.is_reducible()
False

sage: W = ReflectionGroup((1,1,3), (2,1,3)); W  # optional - gap3
Reducible real reflection group of rank 5 and type A2 x B3
sage: W.is_reducible()  # optional - gap3
True
```

`number_of_irreducible_components()`

Return the number of irreducible components of self.

EXAMPLES:

```python
sage: SymmetricGroup(3).number_of_irreducible_components()
1

sage: ColoredPermutations(1,3).number_of_irreducible_components()
1

sage: ReflectionGroup((1,1,3), (2,1,3)).number_of_irreducible_components()  # optional - gap3
2
```

`number_of_simple_reflections()`

Return the number of simple reflections of self.

EXAMPLES:

```python
sage: W = ColoredPermutations(1,3)
sage: W.number_of_simple_reflections()
2

sage: W = ColoredPermutations(2,3)
sage: W.number_of_simple_reflections()
3

sage: W = ColoredPermutations(4,3)
sage: W.number_of_simple_reflections()
3

sage: W = ReflectionGroup((4,2,3))  # optional - gap3
sage: W.number_of_simple_reflections()  # optional - gap3
4
```
reflection\((i)\)
Return the \(i\)-th reflection of \(self\).

For \(i \in 1, \ldots, N\), this gives the \(i\)-th reflection of \(self\).

See also:

• reflections_index_set()
• reflections()

EXAMPLES:

```
sage: W = ReflectionGroup((1,1,4))  # optional - gap3
sage: for i in W.reflection_index_set():  # optional - gap3
      ....:   print(''.join('%s %s' % (i, W.reflection(i))))
1 1 (1,7)(2,4)(5,6)(8,10)(11,12)
2 1 2 (1,4)(2,8)(3,5)(7,10)(9,11)
3 1 2 3 (2,5)(3,9)(4,6)(8,11)(10,12)
4 1 2 3 4 (1,8)(2,7)(3,6)(4,10)(9,12)
5 1 2 3 4 5 (1,6)(2,9)(3,8)(5,11)(7,12)
6 1 2 3 4 5 6 (1,11)(3,10)(4,9)(5,7)(6,12)
```

reflection_index_set()
Return the index set of the reflections of \(self\).

See also:

• reflection()
• reflections()

EXAMPLES:

```
sage: # optional - gap3
sage: W = ReflectionGroup((1,1,4))
sage: W.reflection_index_set()
(1, 2, 3, 4, 5, 6)
sage: W = ReflectionGroup((1,1,4), reflection_index_set=[1,3,'asdf',7,9,→11])
sage: W.reflection_index_set()
(1, 3, 'asdf', 7, 9, 11)
sage: W = ReflectionGroup((1,1,4), reflection_index_set=('a','b','c','d',→'e','f'))
sage: W.reflection_index_set()
('a', 'b', 'c', 'd', 'e', 'f')
```

reflections()
Return a finite family containing the reflections of \(self\), indexed by \(reflection_index_set()\).

See also:

• reflection()
• reflection_index_set()

EXAMPLES:

```
sage: # optional - gap3
sage: W = ReflectionGroup((1,1,3))  # optional - gap3
sage: reflections = W.reflections()
sage: for index in sorted(reflections.keys()):  # optional - gap3
      ....:     print(''.join('%s %s' % (index, reflections[index])))
1 (1,4)(2,3)(5,6)
```
2 (1,3) (2,5) (4,6)
3 (1,5) (2,4) (3,6)

\begin{verbatim}
sage: W = ReflectionGroup((1,1,3), reflection_index_set=['a', 'b', 'c'])    # optional - gap3
sage: reflections = W.reflections()  # optional - gap3
sage: for index in sorted(reflections.keys()):  # optional - gap3
....:
    print('%.2s %.2s' % (index, reflections[index]))
a (1,4) (2,3) (5,6)
b (1,3) (2,5) (4,6)
c (1,5) (2,4) (3,6)
\end{verbatim}

\begin{verbatim}
sage: W = ReflectionGroup((3,1,1))  # optional - gap3
sage: reflections = W.reflections()  # optional - gap3
sage: for index in sorted(reflections.keys()):  # optional - gap3
....:
    print('%.2s %.2s' % (index, reflections[index]))
1 (1,2,3)
2 (1,3,2)
\end{verbatim}

\begin{verbatim}
sage: W = ReflectionGroup((1,1,3), (3,1,2))  # optional - gap3
sage: reflections = W.reflections()  # optional - gap3
sage: for index in sorted(reflections.keys()):  # optional - gap3
....:
    print('%.2s %.2s' % (index, reflections[index]))
1 (1,6) (2,5) (7,8)
2 (1,5) (2,7) (6,8)
3 (3,9,15) (4,10,16) (12,17,23) (14,18,24) (20,25,29) (21,22,26) (27,28,30)
5 (1,7) (2,6) (5,8)
7 (4,21,27) (10,22,28) (11,13,19) (12,14,20) (16,26,30) (17,18,25) (23,24,29)
8 (3,13) (4,24) (9,19) (10,29) (11,15) (12,26) (14,21) (16,23) (17,30) (18,27) (20,22,23) (24,26)
9 (3,15,9) (4,16,10) (12,23,17) (14,24,18) (20,29,25) (21,26,22) (27,30,28)
10 (4,27,21) (10,28,22) (11,19,13) (12,20,14) (16,30,26) (17,25,18) (23,29,24)
\end{verbatim}

\textbf{semigroup\_generators}()

Return the simple reflections of \texttt{self}, as distinguished group generators.

See also:

- \texttt{simple\_reflections()}  
- \texttt{Groups.ParentMethods.group\_generators()}  
- \texttt{Semigroups.ParentMethods.semigroup\_generators()}

\textbf{EXAMPLES:}

\begin{verbatim}
sage: D10 = FiniteCoxeterGroups().example(10)
sage: D10.group\_generators()
Finite family {1: (1,), 2: (2,)}
sage: SymmetricGroup(5).group\_generators()
Finite family {1: (1,2), 2: (2,3), 3: (3,4), 4: (4,5)}

sage: W = ColoredPermutations(3,2)
sage: W.group\_generators()
Finite family {1: [[0, 0],

\end{verbatim}
The simple reflections are also semigroup generators, even for an infinite group:

```
sage: W = WeylGroup(["A",2,1])
sage: W.semigroup_generators()  
Finite family {0: [-1 1 1]
[ 0 1 0]
[ 0 0 1],
1: [ 1 0 0]
[ 1 -1 1]
[ 0 0 1],
2: [ 1 0 0]
[ 0 1 0]
[ 1 1 -1]}
```

**simple_reflection** *(i)*  
Return the *i*-th simple reflection $s_i$ of self.

**INPUT:**  
• *i* — an element from the index set

**See also:**  
• `index_set()`  
• `simple_reflections()`

**EXAMPLES:**

```
sage: W = CoxeterGroups().example()  
sage: W  
The symmetric group on {0, ..., 3}
sage: W.simple_reflection(1)  
(0, 2, 1, 3)
sage: s = W.simple_reflections()  
sage: s[1]  
(0, 2, 1, 3)
sage: W = ReflectionGroup((1,1,4), index_set=[1,3,'asdf'])  
# optional - gap3
sage: for i in W.index_set():  
  # optional - gap3
  print('%s %s' %(i, W.simple_reflection(i)))
1 (1,7)(2,4)(5,6)(8,10)(11,12)
3 (1,4)(2,8)(3,5)(7,10)(9,11)
asdf (2,5)(3,9)(4,6)(8,11)(10,12)
```

**simple_reflection_orders()**  
Return the orders of the simple reflections.

**EXAMPLES:**

```
sage: W = WeylGroup(["B",3])  
sage: W.simple_reflection_orders()  
[2, 2, 2]
sage: W = CoxeterGroup(["C",4])  
sage: W.simple_reflection_orders()  
[2, 2, 2]
sage: W = CoxeterGroup(["D",4])  
sage: W.simple_reflection_orders()  
[2, 2, 2]
sage: W = CoxeterGroup(["E",6])  
sage: W.simple_reflection_orders()  
[2, 2, 2]
sage: W = CoxeterGroup(["E",7])  
sage: W.simple_reflection_orders()  
[2, 2, 2]
sage: W = CoxeterGroup(["E",8])  
sage: W.simple_reflection_orders()  
[2, 2, 2]
sage: W = CoxeterGroup(["F",4])  
sage: W.simple_reflection_orders()  
[2, 2, 2]
sage: W = CoxeterGroup(["G",2])  
sage: W.simple_reflection_orders()  
[2, 2, 2]
sage: W = CoxeterGroup(["H",3])  
sage: W.simple_reflection_orders()  
[2, 2, 2]
sage: W = CoxeterGroup(["I",4])  
sage: W.simple_reflection_orders()  
[2, 2, 2]
```

(continues on next page)
simple_reflections()

Return the simple reflections \((s_i)_{i \in I}\) of \(\text{self}\) as a family indexed by \(\text{index_set()}\).

See also:
• simple_reflection()
• index_set()

EXAMPLES:

For the symmetric group, we recognize the simple transpositions:

```python
sage: W = SymmetricGroup(4); W
Symmetric group of order 4! as a permutation group
sage: s = W.simple_reflections()
sage: s
Finite family {1: (1,2), 2: (2,3), 3: (3,4)}
```

```
sage: W = ColoredPermutations(1,3)
sage: W.simple_reflections()
Finite family {1: [[0, 0, 0], [2, 1, 3]], 2: [[0, 0, 0], [1, 3, 2]]}
```

```
sage: W = ReflectionGroup((1,1,3), index_set=['a','b']) # optional - gap3
sage: W.simple_reflections()  # optional - gap3
Finite family {'a': (1,4)(2,3)(5,6), 'b': (1,3)(2,5)(4,6)}
```

This default implementation uses \(\text{index_set()}\) and \(\text{simple_reflection()}\).

some_elements()

Implement \(\text{Sets.ParentMethods.some_elements()}\) by returning some typical elements of \(\text{self}\).

The result is currently composed of the simple reflections together with the unit and the result of \(\text{an_element()}\).

EXAMPLES:

```python
sage: W = WeylGroup(['A',3])
sage: W.some_elements()
[ [0 1 0 0] [1 0 0 0] [1 0 0 0] [1 0 0 0] [0 0 0 1] [1 0 0 0] [0 0 1 0] [0 1 0 0] [0 1 0 0] [1 0 0 0] [0 0 1 0] [0 1 0 0] [0 0 1 0] [0 1 0 0]]
```

(continues on next page)
class SubcategoryMethods

Bases: object

Irreducible()

Return the full subcategory of irreducible objects of self.

A complex reflection group, or generalized Coxeter group is reducible if its simple reflections can be split in two sets $X$ and $Y$ such that the elements of $X$ commute with that of $Y$. In particular, the group is then direct product of $\langle X \rangle$ and $\langle Y \rangle$. It’s irreducible otherwise.

EXAMPLES:

```python
sage: from sage.categories.complex_reflection_groups import ComplexReflectionGroups
sage: ComplexReflectionGroups().Irreducible()
Category of irreducible complex reflection groups
sage: CoxeterGroups().Irreducible()
Category of irreducible Coxeter groups
```

super_categories()

Return the super categories of self.

EXAMPLES:

```python
sage: from sage.categories.complex_reflection_groups import ComplexReflectionGroups
sage: ComplexReflectionGroups().super_categories()
[Category of complex reflection or generalized Coxeter groups]
```

### 4.29 Coxeter Group Algebras

class sage.categories.coxeter_group_algebras.CoxeterGroupAlgebras (category, *args)

Bases: AlgebrasCategory

class ParentMethods

Bases: object

demazure_lusztig_eigenvectors(q1, q2)

Return the family of eigenvectors for the Cherednik operators.

INPUT:

- **self** – a finite Coxeter group $W$
- **q1, q2** – two elements of the ground ring $K$
The affine Hecke algebra $H_{q_1,q_2}(\tilde{W})$ acts on the group algebra of $W$ through the Demazure-Lusztig operators $T_i$. Its Cherednik operators $Y^\lambda$ can be simultaneously diagonalized as long as $q_1/q_2$ is not a small root of unity [HST2008].

This method returns the family of joint eigenvectors, indexed by $W$.

See also:

- `demazure_lusztig_operators()`
- `sage.combinat.root_system.hecke_algebra_representation.CherednikOperatorsEigenvectors`

**EXAMPLES:**

```python
sage: W = WeylGroup(['B',2])
sage: W.element_class._repr_ = lambda x: ''.join(str(i) for i in x.reduced_word())
sage: K = QQ['q1,q2'].fraction_field()
sage: q1, q2 = K.gens()
sage: KW = W.algebra(K)
sage: E = KW.demazure_lusztig_eigenvectors(q1,q2)
sage: E.keys()  # needs sage.rings.number_field
Weyl Group of type ['B', 2] (as a matrix group acting on the ambient space)
sage: w = W.an_element()
sage: E[w]  # needs sage.rings.number_field
(q2/(-q1+q2))*2121 + ((-q2)/(-q1+q2))*121 - 212 + 12
```

demazure_lusztig_operator_on_basis($w$, $i$, $q_1$, $q_2$, $side='right'$)

Return the result of applying the $i$-th Demazure Lusztig operator on $w$.

**INPUT:**

- $w$ - an element of the Coxeter group
- $i$ - an element of the index set
- $q_1, q_2$ - two elements of the ground ring
- $bar$ - a boolean (default False)

See `demazure_lusztig_operators()` for details.

**EXAMPLES:**

```python
sage: W = WeylGroup(['B',3])
sage: W.element_class._repr_ = lambda x: ''.join(str(i) for i in x.reduced_word())
sage: K = QQ['q1,q2']
sage: q1, q2 = K.gens()
sage: KW = W.algebra(K)
sage: w = W.an_element()
sage: KW.demazure_lusztig_operator_on_basis(w, 0, q1, q2)
(-q2)*323123 + (q1+q2)*123
sage: KW.demazure_lusztig_operator_on_basis(w, 1, q1, q2)
q1*1231
sage: KW.demazure_lusztig_operator_on_basis(w, 2, q1, q2)
q1*1232
sage: KW.demazure_lusztig_operator_on_basis(w, 3, q1, q2)
(q1+q2)*123 + (-q2)*12
```

At $q_1 = 1$ and $q_2 = 0$ we recover the action of the isobaric divided differences $\pi_i$: 

```python
```
At $q_1 = 1$ and $q_2 = -1$ we recover the action of the simple reflection $s_i$:

\[
\begin{align*}
sage: &KW.demazure_lusztig_operator_on_basis(w, 0, 1, -1) \\
&323123 \\
sage: &KW.demazure_lusztig_operator_on_basis(w, 1, 1, -1) \\
&1231 \\
sage: &KW.demazure_lusztig_operator_on_basis(w, 2, 1, -1) \\
&1232 \\
sage: &KW.demazure_lusztig_operator_on_basis(w, 3, 1, -1) \\
&12
\end{align*}
\]

\[\text{demazure_lusztig_operators} (q1, q2, side='right', affine=True)\]

Return the Demazure Lusztig operators acting on self.

INPUT:
- $q_1, q_2$ – two elements of the ground ring $K$
- side = "left" or "right" (default: "right"); which side to act upon
- affine – a boolean (default: True)

The Demazure-Lusztig operator $T_i$ is the linear map $R \to R$ obtained by interpolating between the simple projection $\pi_i$ (see CoxeterGroups.ElementMethods.simple_projection()) and the simple reflection $s_i$ so that $T_i$ has eigenvalues $q_1$ and $q_2$:

\[(q_1 + q_2)\pi_i - q_2 s_i.\]

The Demazure-Lusztig operators give the usual representation of the operators $T_i$ of the $q_1, q_2$ Hecke algebra associated to the Coxeter group.

For a finite Coxeter group, and if affine=True, the Demazure-Lusztig operators $T_1, \ldots, T_n$ are completed by $T_0$ to implement the level 0 action of the affine Hecke algebra.

EXAMPLES:

\[
\begin{align*}
sage: &W = WeylGroup(["B",3]) \\
sage: &W.element_class._repr_ = lambda x: ":"\ join(str(i) for i in x.reduced_ \rightarrow word()) \\
sage: &K = QQ[\"q1,q2\"] \\
sage: &q1, q2 = K.gens() \\
sage: &KW = W.algebra(K) \\
sage: &T = KW.demazure_lusztig_operators(q1, q2, affine=True) \\
sage: &x = KW.monomial(W.an_element()); x \\
&123 \\
sage: &T[0](x) \\
&(-q2)*323123 + (q1+q2)*123 \\
sage: &T[1](x) \\
&q1*1231 \\
sage: &T[2](x) \\
&q1*1232 \\
sage: &T[3](x) \\
\end{align*}
\]

(continues on next page)
4.30 Coxeter Groups

class sage.categories.coxeter_groups.CoxeterGroups

Bases: Category_singleton

The category of Coxeter groups.

A Coxeter group is a group $W$ with a distinguished (finite) family of involutions $(s_i)_{i \in I}$, called the simple reflections, subject to relations of the form $(s_is_j)^{m_{i,j}} = 1$.

$I$ is the index set of $W$ and $|I|$ is the rank of $W$.

See Wikipedia article Coxeter_group for details.

EXAMPLES:

sage: C = CoxeterGroups(); C
Category of Coxeter groups
sage: C.super_categories()
[Category of generalized Coxeter groups]

sage: W = C.example(); W
The symmetric group on {0, ..., 3}

sage: W.simple_reflections()
Finite family {0: (1, 0, 2, 3), 1: (0, 2, 1, 3), 2: (0, 1, 3, 2)}

Here are some further examples:

sage: FiniteCoxeterGroups().example()
The 5-th dihedral group of order 10
sage: FiniteWeylGroups().example()
The symmetric group on (0, ..., 3)

Weyl Group of type ['B', 3] (as a matrix group acting on the ambient space)

sage: S4 = SymmetricGroup(4); S4
Symmetric group of order 4! as a permutation group
sage: S4 in CoxeterGroups().Finite()
True

Those will eventually be also in this category:
Todo: add a demo of usual computations on Coxeter groups.

See also:

- `sage.combinat.root_system`
- `WeylGroups`
- `GeneralizedCoxeterGroups`

Warning: It is assumed that morphisms in this category preserve the distinguished choice of simple reflections. In particular, subobjects in this category are parabolic subgroups. In this sense, this category might be better named `Coxeter Systems`. In the long run we might want to have two distinct categories, one for Coxeter groups (with morphisms being just group morphisms) and one for Coxeter systems:

```python
sage: CoxeterGroups().is_full_subcategory(Groups())
False
sage: from sage.categories.generalized_coxeter_groups import GeneralizedCoxeterGroups
sage: CoxeterGroups().is_full_subcategory(GeneralizedCoxeterGroups())
True
```

Algebras

alias of `CoxeterGroupAlgebras`

class `ElementMethods`

Bases: `object`

``absolute_chain()``

Return a (saturated) chain in absolute order from 1 to `self`.

See also:

``absolute_chain_reflections()``

EXAMPLES:

```python
sage: W = CoxeterGroup(['A', 2, 1])
sage: (r, s, t) = W.simple_reflections()
sage: (r * s * r * t).absolute_chain()
[1 0 0] [0 -1 2] [2 1 -2]
[0 1 0] [-1 0 2] [1 2 -2]
[0 0 1], [0 0 1], [1 1 -1]
```

``absolute_chain_reflections()``

Return a list of reflection which, when (left) multiplied in order, give `self`.  

4.30. Coxeter Groups
This method is based on Theorem 1.1 in [Dy2001], combined with the strong exchange condition. As an example, if $W$ is a type $A_2$ Coxeter group with simple reflections $a, b$, then the absolute chain reflections for the element $w = ab$ is the list $[a, aba]$ as $w = (aba)a = ab$.

See also:

*absolute_length*, *absolute_chain*

**EXAMPLES:**

```python
sage: W = CoxeterGroup("A", 2)

sage: W.one().absolute_chain_reflections()
[]

sage: (r, s, t) = W.simple_reflections()

sage: r.absolute_chain_reflections()
[-1 1 1]
[0 1 0]
[0 0 1]

sage: (r * s).absolute_chain_reflections()
[-1 1 1]
[0 1 0]
[0 0 1]

sage: (r * s * r * t).absolute_chain_reflections()
[0 -1 2]
[-1 0 2]
[0 0 1]

sage: W = CoxeterGroup(['A', 3, 1])

sage: (r, s, t, u) = W.simple_reflections()

sage: (r * s * t * u).absolute_chain_reflections()
[-1 1 0 1]
[0 0 -1 2]
[0 1 0 0]
[0 0 1 0]

sage: (r * s * t * u * s).absolute_chain_reflections()
[-1 1 0 1]
[0 0 -1 2]
[0 1 0 0]
[0 0 1 0]
```

**absolute_covers()**

Return the list of covers of self in absolute order.

See also:

*absolute_length*

**EXAMPLES:**

```python
sage: # needs sage.combinat sage.groups

sage: W = WeylGroup(['A', 3])
```

(continues on next page)
sage: s = \text{W}.simple_reflections()
sage: w0 = s[1]
sage: w1 = s[1]*s[2]*s[3]
sage: list(w0.absolute_covers())

\[
\begin{array}{cccccccc}
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0
\end{array}
\]

\textbf{absolute\_le}(\text{other})

Return whether \text{self} is smaller than \text{other} in the absolute order.

A general reflection is an element of the form \(w s_i w^{-1}\), where \(s_i\) is a simple reflection. The absolute order is defined analogously to the weak order but using general reflections rather than just simple reflections.

This partial order can be used to define noncrossing partitions associated with this Coxeter group.

\textbf{See also:}

\texttt{absolute\_length()}

\textbf{EXAMPLES:}

sage: \# needs \texttt{sage.combinat sage.groups}

sage: \text{W} = \text{WeylGroup}(\text{"A", 3})
sage: \text{s} = \text{W}.simple_reflections()
sage: \text{w0} = \text{s}[1]
sage: \text{w1} = \text{s}[1]*\text{s}[2]*\text{s}[3]
sage: \text{w0.absolute\_le(w1)}

True

sage: \text{w1.absolute\_le(w0)}

False

sage: \text{w1.absolute\_le(w1)}

True

\textbf{absolute\_length()}

Return the absolute length of \text{self}.

The absolute length is the length of the shortest expression of the element as a product of reflections. In general, we use Theorem 1.1 in [Dy2001].

\textbf{See also:}

\texttt{absolute\_le()}, \texttt{absolute\_chain()}

\textbf{EXAMPLES:}

sage: \# needs \texttt{sage.combinat sage.groups}

sage: \text{W} = \text{WeylGroup}(\text{"A", 3})

\texttt{SymmetricGroup(4)}

sage: \text{W} = \text{SymmetricGroup}(4)
apply_demazure_product (element, side='right', length_increasing=True)

Return the Demazure or 0-Hecke product of self with another Coxeter group element.

See CoxeterGroups.ParentMethods.simple_projections().

INPUT:

• **element** – either an element of the same Coxeter group as self or a tuple or a list (such as a reduced word) of elements from the index set of the Coxeter group.

• **side** – ‘left’ or ‘right’ (default: ‘right’); the side of self on which the element should be applied. If side is ‘left’ then the operation is applied on the left.

• **length_increasing** – a boolean (default True) whether to act length increasingly or decreasingly

EXAMPLES:

```
sage: v = W.from_reduced_word([1,3,4,3,3])
sage: v.apply_demazure_product([1,3,4,3])
s4*s1*s2*s3*s4*s3*s1
sage: v.apply_demazure_product([1,3,4,3], side='left')
s3*s4*s1*s2*s3*s4*s2*s3*s1
```

apply_simple_projection (i, side='right', length_increasing=True)

Return the result of the application of the simple projection \( \pi_i \) (resp. \( \overline{\pi}_i \)) on self.

INPUT:
• i - an element of the index set of the Coxeter group
• side - 'left' or 'right' (default: 'right')
• length_increasing - a boolean (default: True) specifying the direction of the projection

See `CoxeterGroups.ParentMethods.simple_projections()` for the definition of the simple projections.

**EXAMPLES:**

```python
sage: W = CoxeterGroups().example()
sage: w = W.an_element()
sage: w
(1, 2, 3, 0)
sage: w.apply_simple_projection(2)
(1, 2, 3, 0)
sage: w.apply_simple_projection(2, length_increasing=False)
(1, 2, 0, 3)
sage: # needs sage.combinat sage.groups
sage: W = WeylGroup(['C', 4], prefix="s")
sage: v = W.from_reduced_word([1,2,3,4,3,1])
sage: v
s1*s2*s3*s4*s3*s1
sage: v.apply_simple_projection(2)
s1*s2*s3*s4*s3*s1*s2
sage: v.apply_simple_projection(2, side='left')
s1*s2*s3*s4*s3*s1
sage: v.apply_simple_projection(1, length_increasing=False)
s1*s2*s3*s4*s3
```

**binary_factorizations** *(predicate=The constant function (...) -> True)*

Return the set of all the factorizations \( s = uv \) such that \( l(s) = l(u) + l(v) \).

Iterating through this set is Constant Amortized Time (counting arithmetic operations in the Coxeter group as constant time) complexity, and memory linear in the length of \( s \).

One can pass as optional argument a predicate \( p \) such that \( p(u) \) implies \( p(u') \) for any \( u \) left factor of \( s \) and \( u' \) left factor of \( u \). Then this returns only the factorizations \( s = uv \) such \( p(u) \) holds.

**EXAMPLES:**

We construct the set of all factorizations of the maximal element of the group:

```python
sage: # needs sage.combinat sage.groups
sage: W = WeylGroup(['A', 3])
sage: s = W.simple_reflections()
sage: w0 = W.from_reduced_word([1,2,3,1,2,1])
sage: w0.binary_factorizations().cardinality()
24
```

The same number of factorizations, by bounded length:

```python
sage: [w0.binary_factorizations()
..... : lambda u: u.length() <= 1
..... : ).cardinality()]
[0, 1, 4, 9, 15, 20, 23, 24]
```

The number of factorizations of the elements just below the maximal element:
sage: [(s[i]*w0).binary_factorizations().cardinality() #→
˓→needs sage.combinat sage.groups
[12, 12, 12]
sage: w0.binary_factorizations(lambda u: False).cardinality() #→
˓→needs sage.combinat sage.groups
0

bruhat_le(other)

Return whether self <= other in the Bruhat order.

INPUT:
• other -- an element of the same Coxeter group

OUTPUT: a boolean

EXAMPLES:

sage: # needs sage.combinat sage.groups
sage: W = WeylGroup("A", 3)
sage: u = W.from_reduced_word([1, 2, 1])
sage: v = W.from_reduced_word([1, 2, 3, 2, 1])
sage: u.bruhat_le(u)
True
sage: u.bruhat_le(v)
True
sage: v.bruhat_le(u)
False
sage: v.bruhat_le(v)
True
sage: s = W.simple_reflections()
sage: s[1].bruhat_le(W.one())
False

The implementation uses the equivalent condition that any reduced word for other contains a reduced word for self as subword. See Stembridge, A short derivation of the Möbius function for the Bruhat order. J. Algebraic Combin. 25 (2007), no. 2, 141–148, Proposition 1.1.

Complexity: $O(l * c)$, where $l$ is the minimum of the lengths of $u$ and of $v$, and $c$ is the cost of the low level methods first_descent(), has_descent(), apply_simple_reflection(), etc. Those are typically $O(n)$, where $n$ is the rank of the Coxeter group.

bruhat_lower_covers()

Return all elements that self covers in (strong) Bruhat order.

If $w = self$ has a descent at $i$, then the elements that $w$ covers are exactly $\{ws_i, u_1s_i, u_2s_i, ..., u_js_i\}$, where the $u_k$ are elements that $ws_i$ covers that also do not have a descent at $i$.

EXAMPLES:

sage: W = WeylGroup("A", 3) #...
˓→needs sage.combinat sage.groups
sage: w = W.from_reduced_word([3, 2, 3]) #...
˓→needs sage.combinat sage.groups
sage: print([v.reduced_word() for v in w.bruhat_lower_covers()]) #...
˓→needs sage.combinat sage.groups
[[3, 2], [2, 3]]
sage: # needs sage.combinat sage.groups

(continues on next page)
We now show how to construct the Bruhat poset:

```
sage: # needs sage.combinat.sage.groups
sage: W = WeylGroup(["A", 3])
sage: covers = tuple([u, v]
    ....:     for v in W.simple_reflection(1).bruhat_lower_covers())
sage: P = Poset((W, covers), cover_relations=True)
    # needs sage.graphs
sage: P.show()  # needs sage.graphs sage.plot
```

Alternatively, one can just use:

```
sage: P = W.bruhat_poset()
    # needs sage.combinat.sage.graphs.sage.groups
```

The algorithm is taken from Stembridge’s ‘coxeter/weyl’ package for Maple.

### bruhat_lower_covers_reflections()

Return all 2-tuples of lower_covers and reflections \((v, r)\) where \(v\) is covered by \(self\) and \(r\) is the reflection such that \(self = vr\).

**ALGORITHM:**

See bruhat_lower_covers()

**EXAMPLES:**

```
sage: W = WeylGroup(["A", 3], prefix="s")
    # needs sage.combinat.sage.groups
sage: w = W.from_reduced_word([3,1,2,1])
    # needs sage.combinat.sage.groups
sage: w.bruhat_lower_covers_reflections()
    # needs sage.combinat.sage.groups
[(s1*s2*s1, s1*s2*s3*s2*s1), (s3*s2*s1, s2), (s3*s1*s2, s1)]
```

### bruhat_upper_covers()

Return all elements that cover \(self\) in (strong) Bruhat order.

The algorithm works recursively, using the ‘inverse’ of the method described for lower covers bruhat_lower_covers(). Namely, it runs through all \(i\) in the index set. Let \(w\) equal \(self\).
If \( w \) has no right descent \( i \), then \( ws_i \) is a cover; if \( w \) has a decent at \( i \), then \( u_j s_i \) is a cover of \( w \) where \( u_j \) is a cover of \( ws_i \).

**EXAMPLES:**

```python
sage: W = WeylGroup(['A', 3, 1], prefix="s")
# needs sage.combinat, sage.groups
sage: w = W.from_reduced_word([1,2,1])  # needs sage.combinat, sage.groups
sage: w.bruhat_upper_covers()  # needs sage.combinat, sage.groups
[s1*s2*s1*s0, s1*s2*s0*s1, s0*s1*s2*s1, s3*s1*s2*s1, s2*s3*s1*s2, #
 s1*s2*s3*s1]
sage: W = WeylGroup(['A', 3])  # needs sage.combinat, sage.groups
sage: w = W.long_element()  # needs sage.combinat, sage.groups
sage: w.bruhat_upper_covers()  # needs sage.combinat, sage.groups
[]
sage: # needs sage.combinat, sage.groups
sage: W = WeylGroup(['A', 3])
sage: w = W.from_reduced_word([1,2,1])
sage: S = [v for v in W if w in v.bruhat_lower_covers()]
sage: C = w.bruhat_upper_covers()
sage: set(S) == set(C)
True
```

**bruhat_upper_covers_reflections()**

Return all 2-tuples of covers and reflections \((v, r)\) where \( v \) covers \( self \) and \( r \) is the reflection such that \( self = vr \).

**ALGORITHM:**

See \texttt{bruhat_upper_covers()}

**EXAMPLES:**

```python
sage: W = WeylGroup(['A', 4], prefix="s")  # needs sage.combinat, sage.groups
sage: w = W.from_reduced_word([3,1,2,1])  # needs sage.combinat, sage.groups
sage: w.bruhat_upper_covers_reflections()  # needs sage.combinat, sage.groups
[(s1*s2*s3*s2*s1, s3), (s2*s3*s1*s2*s1, s2*s3*s2), (s3*s4*s1*s2*s1, s4), (s4*s3*s1*s2*s1, s1*s2*s3*s4*s2*s1)]
```

**canonical_matrix()**

Return the matrix of \( self \) in the canonical faithful representation.

This is an \( n \)-dimension real faithful essential representation, where \( n \) is the number of generators of the Coxeter group. Note that this is not always the most natural matrix representation, for instance in type \( A_n \).

**EXAMPLES:**
```python
sage: W = WeylGroup(['A', 3])
#-- needs sage.combinat sage.groups
sage: s = W.simple_reflections()
#-- needs sage.combinat sage.groups
sage: (s[1]*s[2]*s[3]).canonical_matrix()
#-- needs sage.combinat sage.groups
[ 0 0 -1]
[ 1 0 -1]
[ 0 1 -1]
```

**coset_representative** *(index_set, side='right')*

Return the unique shortest element of the Coxeter group \( W \) which is in the same left (resp. right) coset as \( self \), with respect to the parabolic subgroup \( W_I \).

**INPUT:**
- \( \text{index_set} \) - a subset (or iterable) of the nodes of the Dynkin diagram
- \( \text{side} \) - ‘left’ or ‘right’

**EXAMPLES:**

```python
sage: W = CoxeterGroups().example(5)
sage: s = W.simple_reflections()
sage: w = s[2]*s[1]*s[3]
sage: w.coset_representative([]).reduced_word()
[2, 3, 1]
sage: w.coset_representative([1]).reduced_word()
[2, 3]
sage: w.coset_representative([1,2]).reduced_word()
[2, 3]
sage: w.coset_representative([1,3]).reduced_word()
[3]
sage: w.coset_representative([2,3]).reduced_word()
[1]
sage: w.coset_representative([1,2,3]).reduced_word()
[
]
```

**cover_reflections** *(side='right')*

Return the set of reflections \( t \) such that \( self \ t \) covers \( self \).

If \( \text{side} \) is ‘left’, \( t \ self \) covers \( self \).

**EXAMPLES:**

```python
sage: # needs sage.combinat sage.groups
sage: W = WeylGroup(['A', 4], prefix='s')
sage: w = W.from_reduced_word([3,1,2,1])
(continues on next page)
```

---

4.30. Coxeter Groups 255
sage: w.cover_reflections()
[\text{s}3, \text{s}2\text{s}3\text{s}2, \text{s}4, \text{s}1\text{s}2\text{s}3\text{s}4\text{s}3\text{s}2\text{s}1]
sage: w.cover_reflections(side='left')
[\text{s}4, \text{s}2, \text{s}1\text{s}2\text{s}1, \text{s}3\text{s}4\text{s}3]

\textbf{coxeter\_sorting\_word}(c)

Return the c-sorting word of self.

For a Coxeter element c and an element w, the c-sorting word of w is the lexicographic minimal reduced expression of w in the infinite word c^\infty.

\textbf{INPUT:}

- c - a Coxeter element.

\textbf{OUTPUT:}

the c-sorting word of self as a list of integers.

\textbf{EXAMPLES:}

sage: \text{W = CoxeterGroups().example()}
sage: c = \text{W.from_reduced_word([0,2,1])}
sage: w = \text{W.from_reduced_word([1,2,1,0,1])}
sage: w.coxeter\_sorting\_word(c)
[2, 1, 2, 0, 1]

deodhar\_factor\_element\( (w, \text{index\_set})\)

Return Deodhar's Bruhat order factoring element.

\textbf{INPUT:}

- w is an element of the same Coxeter group W as self
- index\_set is a subset of Dynkin nodes defining a parabolic subgroup W' of W

It is assumed that v = self and w are minimum length coset representatives for \(W/W'\) such that \(v \leq w\) in Bruhat order.

\textbf{OUTPUT:}

Deodhar's element \(f(v, w)\) is the unique element of \(W'\) such that, for all \(v'\) and \(w'\) in \(W\), \(vv' \leq ww'\) in \(W\) if and only if \(v' \leq f(v, w) \ast w'\) in \(W'\) where \(\ast\) is the Demazure product.

\textbf{EXAMPLES:}

sage: \text{# needs sage.combinat sage.groups}
sage: \text{W = WeylGroup(['A', 5], prefix="s")}
sage: v = \text{W.from_reduced_word([5])}
sage: w = \text{W.from_reduced_word([4,5,2,3,1,2])}
sage: v.deodhar\_factor\_element(w, [1,3,4])
s3*s1
sage: \text{W = WeylGroup(['C', 2])}
sage: w = \text{W.from_reduced_word([2,1])}
sage: \text{W.deodhar\_factor\_element(W.from_reduced_word([2]),[1])}
Traceback (most recent call last):
... ValueError: [2, 1] is not of minimum length in its coset for the parabolic subgroup with index set [1]

\textbf{REFERENCES:}

- [Deo1987a]
\textbf{deodhar\_lift\_down}(w, index\_set)

Letting $v = \text{self}$, given a Bruhat relation $v W \geq w W'$ among cosets with respect to the subgroup $W'$ given by the Dynkin node subset index\_set, returns the Bruhat-maximum lift $x$ of $wW'$ such that $v \geq x$.

**INPUT:**
- $w$ is an element of the same Coxeter group $W$ as $\text{self}$.
- index\_set is a subset of Dynkin nodes defining a parabolic subgroup $W'$.

**OUTPUT:**
The unique Bruhat-maximum element $x$ in $W$ such that $x W' = w W'$ and $v \geq x$.

**See also:**
sage.categories.coxeter_groups.CoxeterGroups.ElementMethods.deodhar\_lift\_up()

**EXAMPLES:**

```
sage: # needs sage.combinat sage.groups
sage: W = WeylGroup(['A', 3], prefix="s")
sage: v = W.from_reduced_word([1,2,3,2])
sage: w = W.from_reduced_word([3,2])
sage: v.deodhar\_lift\_down(w, [3])
s2*s3*s2
```

\textbf{deodhar\_lift\_up}(w, index\_set)

Letting $v = \text{self}$, given a Bruhat relation $v W \leq w W'$ among cosets with respect to the subgroup $W'$ given by the Dynkin node subset index\_set, returns the Bruhat-minimum lift $x$ of $wW'$ such that $v \leq x$.

**INPUT:**
- $w$ is an element of the same Coxeter group $W$ as $\text{self}$.
- index\_set is a subset of Dynkin nodes defining a parabolic subgroup $W'$.

**OUTPUT:**
The unique Bruhat-minimum element $x$ in $W$ such that $x W' = w W'$ and $v \leq x$.

**See also:**
sage.categories.coxeter_groups.CoxeterGroups.ElementMethods.deodhar\_lift\_down()

**EXAMPLES:**

```
sage: # needs sage.combinat sage.groups
sage: W = WeylGroup(['A', 3], prefix="s")
sage: v = W.from_reduced_word([1,2,3])
sage: w = W.from_reduced_word([1,3,2])
sage: v.deodhar\_lift\_up(w, [3])
s1*s2*s3*s2
```

\textbf{descents}(side='right', index\_set=None, positive=False)

Return the descents of self, as a list of elements of the index\_set.

**INPUT:**
- index\_set - a subset (as a list or iterable) of the nodes of the Dynkin diagram; (default: all of them)
- side - ‘left’ or ‘right’ (default: ‘right’)
- positive - a boolean (default: False)
The `index_set` option can be used to restrict to the parabolic subgroup indexed by `index_set`. If positive is `True`, then returns the non-descents instead

**Todo:** find a better name for `positive`: complement? non_descent?

Caveat: the return type may change to some other iterable (tuple, …) in the future. Please use keyword arguments also, as the order of the arguments may change as well.

**EXAMPLES:**

```python
sage: W = CoxeterGroups().example()
sage: s = W.simple_reflections()
sage: w = s[0]*s[1]
sage: w.descents()
[1]
sage: w = s[0]*s[2]
sage: w.descents()
[0, 2]
```

**Todo:** side, index_set, positive

```python
first_descent (side='right', index_set=None, positive=False)
```
Return the first left (resp. right) descent of self, as an element of `index_set`, or `None` if there is none.

See `descents()` for a description of the options.

**EXAMPLES:**

```python
sage: W = CoxeterGroups().example()
sage: s = W.simple_reflections()
sage: w = s[2]*s[0]
sage: w.first_descent()
0
sage: w = s[0]*s[2]
sage: w.first_descent()
0
sage: w = s[0]*s[1]
sage: w.first_descent()
1
```

```python
has_descent (i, side='right', positive=False)
```
Return whether `i` is a (left/right) descent of self.

See `descents()` for a description of the options.

**EXAMPLES:**

```python
sage: W = CoxeterGroups().example()
sage: s = W.simple_reflections()
sage: w = s[0] * s[1] * s[2]
sage: w.has_descent(2) # True
sage: [ w.has_descent(i) for i in [0,1,2] ] # [False, False, True]
sage: [ w.has_descent(i, side='left') for i in [0,1,2] ] # [False, False, False]
```
This default implementation delegates the work to `has_left_descent()` and `has_right_descent()`.

### has_full_support()

Return whether `self` has full support.

An element is said to have full support if its support contains all simple reflections.

**EXAMPLES:**

```python
sage: W = CoxeterGroups().example()
sage: w = W.from_reduced_word([1,2,1])
sage: w.has_full_support()  # False
sage: w = W.from_reduced_word([1,2,1,0,1])
sage: w.has_full_support()  # True
```

### has_left_descent(i)

Return whether `i` is a left descent of `self`.

This default implementation uses that a left descent of `w` is a right descent of `w^{-1}`.

**EXAMPLES:**

```python
sage: W = CoxeterGroups().example(); W
The symmetric group on {0, ..., 3}
sage: w = W.an_element(); w
(1, 2, 3, 0)
sage: w.has_left_descent(0)  # True
sage: w.has_left_descent(1)  # False
sage: w.has_left_descent(2)  # False
```

### has_right_descent(i)

Return whether `i` is a right descent of `self`.

**EXAMPLES:**

```python
sage: W = CoxeterGroups().example(); W
The symmetric group on {0, ..., 3}
sage: w = W.an_element(); w
(1, 2, 3, 0)
sage: w.has_right_descent(0)  # False
sage: w.has_right_descent(1)  # False
sage: w.has_right_descent(2)  # True
```

### inversions_as_reflections()

Return the set of reflections `r` such that `self r < self`.

4.30. Coxeter Groups
EXAMPLES:

```python
sage: W = WeylGroup(['A', 3], prefix="s")
# needs sage.combinat sage.groups
sage: w = W.from_reduced_word([3,1,2,1])
# needs sage.combinat sage.groups
sage: w.inversions_as_reflections()
# needs sage.combinat sage.groups
[s1, s1*s2*s1, s2, s1*s2*s3*s2*s1]
```

**is_coxeter_sortable** (c, sorting_word=None)

Return whether self is c-sortable.

Given a Coxeter element c, an element w is c-sortable if its c-sorting word decomposes into a sequence of weakly decreasing subwords of c.

**INPUT:**

- c – a Coxeter element.
- sorting_word – sorting word (default: None) used to not recompute the c-sorting word if already computed.

**OUTPUT:**

is self c-sortable

**EXAMPLES:**

```python
sage: W = CoxeterGroups().example()
sage: c = W.from_reduced_word([0,2,1])
sage: w = W.from_reduced_word([1,2,1,0,1])
sage: w.coxeter_sorting_word(c)
[2, 1, 2, 0, 1]
sage: w.is_coxeter_sortable(c)
False
sage: w = W.from_reduced_word([0,2,1,0,2])
sage: w.coxeter_sorting_word(c)
[2, 0, 1, 2, 0]
sage: w.is_coxeter_sortable(c)
True
```

Number of c-sortable elements in A₃ (Catalan number):

```python
sage: len([w for w in W if w.is_coxeter_sortable(c)])
14
```

**is_fully_commutative**()

Check if self is a fully-commutative element.

We use the characterization that an element w in a Coxeter system (W, S) is fully-commutative if and only if for every pair of generators s, t ∈ S for which m(s, t) > 2, no reduced word of w contains the ‘braid’ word sts... of length m(s, t) as a contiguous subword. See [Ste1996].

**EXAMPLES:**

```
sage: # needs sage.combinat sage.groups
sage: W = CoxeterGroup(['A', 3])
14
sage: W = CoxeterGroup(['B', 3])
24

is_grassmannian (side='right')

Return whether self is Grassmannian.

INPUT:
  • side = “left” or “right” (default: “right”)

An element is Grassmannian if it has at most one descent on the right (resp. on the left).

EXAMPLES:

```
sage: W = CoxeterGroups().example(); W
The symmetric group on {0, ..., 3}
sage: s = W.simple_reflections()
sage: W.one().is_grassmannian()
True
sage: s[1].is_grassmannian()
True
sage: (s[1]*s[2]).is_grassmannian()
True
sage: (s[0]*s[1]).is_grassmannian()
True
sage: (s[1]*s[2]*s[1]).is_grassmannian()
False
sage: (s[0]*s[2]*s[1]).is_grassmannian(side="left")
False
sage: (s[0]*s[2]*s[1]).is_grassmannian(side="right")
True
sage: (s[0]*s[2]*s[1]).is_grassmannian()
True
```

kazhdan_lusztig_cell (side='left')

Compute the left, right, or two-sided Kazhdan-Lusztig cell containing the element self depending on the specified side.

Let $C'$ denote the Kazhdan-Lusztig $C'$-basis of the Iwahori-Hecke algebra $H$ of a Coxeter system $(W, S)$. Two elements $x, y$ of the Coxeter group $W$ are said to lie in the same left Kazhdan-Lusztig cell if there exist sequences $x = w_1, w_2, \ldots, w_k = y$ and $y = u_1, u_2, \ldots, u_l = x$ such that for all $1 \leq i < k$ and all $1 \leq j < l$, there exist some Coxeter generators $s, t \in S$ for which $C'_{w_{i+1}}$ appears in $C'_{s}C'_{w_i}$, and $C'_{u_{j+1}}$ appears in $C'_{s}C'_{u_j}$ in $H$. Right and two-sided Kazhdan-Lusztig cells of $W$ are defined similarly; see [Lus2013].

In this function, we compute products in the $C'$ basis by using IwahoriHeckeAlgebra.Cp. As mentioned in that class, installing the optional package coxeter3 is recommended (though not required) before using this function because the package speeds up product computations that are sometimes computationally infeasible without it.

INPUT:
  • w - an element of self
  • side = (default: 'left') the kind of cell to compute; must be either 'left', 'right', or 'two-sided'

4.30. Coxeter Groups
EXAMPLES:

We compute the left cell of the generator $s_1$ in type $A_3$ in three different implementations of the Coxeter group. Note that the choice of implementation affects the representation of elements in the output cell but not the method used for the cell computation:

```python
sage: W = CoxeterGroup('A3', implementation='permutation')  # needs sage.combinat sage.groups
sage: s1, s2, s3 = W.simple_reflections()  # needs sage.combinat sage.groups
sage: s1.kazhdan_lusztig_cell()  # needs sage.combinat sage.groups
{(1,2,3,12)(4,5,10,11)(6,7,8,9),
 (1,2,10)(3,6,5)(4,7,8)(9,12,11),
 (1,7)(2,4)(5,6)(8,10)(11,12)}
```

The cell computation uses the optional package `coxeter3` in the background if available to speed up the computation, even in the different implementations:

```python
sage: W = CoxeterGroup('A3', implementation='coxeter3')  # needs sage.combinat sage.groups sage.modules
sage: s1, s2, s3 = W.simple_reflections()

sage: s1.kazhdan_lusztig_cell()  # needs sage.combinat sage.groups
{(1,2,3,12)(4,5,10,11)(6,7,8,9),
 (1,2,10)(3,6,5)(4,7,8)(9,12,11),
 (1,7)(2,4)(5,6)(8,10)(11,12)}
```

Next, we compute a right cell and a two-sided cell in $A_3$:

```python
sage: W = CoxeterGroup('A3', implementation='coxeter3')  # needs sage.combinat sage.groups sage.modules
sage: s1, s2, s3 = W.simple_reflections()

sage: w = s1 * s3

sage: w.kazhdan_lusztig_cell(side='right')  # long time (4 seconds)
{(1,2,3,12)(4,5,10,11)(6,7,8,9),
 (1,2,10)(3,6,5)(4,7,8)(9,12,11),
 (1,7)(2,4)(5,6)(8,10)(11,12)}

sage: w.kazhdan_lusztig_cell(side='two-sided')  # long time (8 seconds)
{(1,2,3,12)(4,5,10,11)(6,7,8,9),
 (1,2,10)(3,6,5)(4,7,8)(9,12,11),
 (1,7)(2,4)(5,6)(8,10)(11,12)}
```

Some slightly longer computations in $B_4$:

```python
sage: W = CoxeterGroup('B4', implementation='coxeter3')  # needs sage.combinat sage.groups sage.modules
sage: s1, s2, s3, s4 = W.simple_reflections()

sage: s1.kazhdan_lusztig_cell(side='right')  # long time (4 seconds)
{(1,2),
 [1, 2],
 [1, 2, 3],
 [1, 2, 3, 4],
 [1, 2, 3, 4, 3],
 [1, 2, 3, 4, 3, 2],
 [1, 2, 3, 4, 3, 2, 1]}

sage: (s4*s2*s3*s4).kazhdan_lusztig_cell(side='two-sided')  # long time (8 seconds)
{(2, 3, 1),
 [2, 3, 1, 2],
 [2, 3, 4, 1],
 [2, 3, 4, 1, 2],
 [2, 3, 4, 1, 2, 3],
 [2, 3, 4, 1, 2, 3, 4]}
```

(continues on next page)
\[ [2, 3, 4, 1, 2], \\
[2, 3, 4, 1, 2, 3], \\
[2, 3, 4, 1, 2, 3, 4], \\
[2, 3, 4, 3, 1], \\
[2, 3, 4, 3, 1, 2], \\
\ldots \\
[4, 3, 4, 2, 3, 4, 1, 2, 3, 4] \]

**left_inversions_as_reflections()**

Return the set of reflections \( r \) such that \( r \self < \self \).

**EXAMPLES:**

```python
sage: W = WeylGroup(['A', 3], prefix="s")
# needs sage.combinat sage.groups
sage: w = W.from_reduced_word([3,1,2,1])
# needs sage.combinat sage.groups
sage: w.left_inversions_as_reflections()
# needs sage.combinat sage.groups
[s1, s3, s1*s2*s3*s2*s1, s2*s3*s2]
```

**length()**

Return the length of \( \self \).

This is the minimal length of a product of simple reflections giving \( \self \).

**EXAMPLES:**

```python
sage: W = CoxeterGroups().example()
sage: s1 = W.simple_reflection(1)
sage: s2 = W.simple_reflection(2)
sage: s1.length()
1
sage: (s1*s2).length()
2
sage: W = CoxeterGroups().example()
sage: s = W.simple_reflections()
sage: w = s[0]*s[1]*s[0]
sage: w.length()
3
sage: W = CoxeterGroups().example()
sage: R.<x> = ZZ[]
sage: s = sum(x^w.length() for w in W)
sage: p = prod(sum(x^i for i in range(j)) for j in range(1, 5))
sage: s - p
0
```

**See also:**

`reduced_word()`

**Todo:** Should use reduced_word_iterator (or reverse_iterator)

**lower_cover_reflections(side='right')**

Return the reflections \( t \) such that \( \self \) covers \( \self t \).

If `side` is 'left', \( \self \) covers \( t \) \( \self \).
EXAMPLES:

```
sage: # needs sage.combinat sage.groups
sage: W = WeylGroup([['A', 3],prefix="s")
sage: w = W.from_reduced_word([3,1,2,1])
sage: w.lower_cover_reflections()
[s1*s2*s3*s2*s1, s2, s1]
sage: w.lower_cover_reflections(side='left')
[s2*s3*s2, s3, s1]
```

`lower_covers(side='right', index_set=None)`

Return all elements that self covers in weak order.

INPUT:
- `side` - 'left' or 'right' (default: 'right')
- `index_set` - a list of indices or None

OUTPUT: a list

EXAMPLES:

```
sage: W = WeylGroup([['A', 3]])  # needs sage.combinat sage.groups
sage: w = W.from_reduced_word([3,2,1])  # needs sage.combinat sage.groups
sage: [x.reduced_word() for x in w.lower_covers()]
[[3, 2]]
sage: [x.reduced_word() for x in w.lower_covers(side='left')]
[[2, 1]]
```

To obtain covers for left weak order, set the option side to 'left':

```
sage: [x.reduced_word() for x in w.lower_covers(side='left')]
[[2, 1]]
sage: w = W.from_reduced_word([3,2,3,1])  # needs sage.combinat sage.groups
sage: [x.reduced_word() for x in w.lower_covers()]  # needs sage.combinat sage.groups
[[2, 3, 2], [3, 2, 1]]
sage: [x.reduced_word() for x in w.lower_covers(side=left)]]
[[3, 2, 1], [2, 3, 1]]
```

Covers w.r.t. a parabolic subgroup are obtained with the option `index_set`:

```
sage: [x.reduced_word() for x in w.lower_covers(index_set=[1,2])]  # needs sage.combinat sage.groups
[[2, 3, 2]]
sage: [x.reduced_word() for x in w.lower_covers(side='left')]  # needs sage.combinat sage.groups
[[3, 2, 1], [2, 3, 1]]
```

`min_demazure_product_greater(element)`

Find the unique Bruhat-minimum element $u$ such that $v \leq w * u$ where $v$ is `self`, $w$ is `element` and $*$ is the Demazure product.

INPUT:
- `element` is either an element of the same Coxeter group as `self` or a list (such as a reduced word) of elements from the index set of the Coxeter group.

EXAMPLES:
### reduced_word()

Return a reduced word for self.

This is a word $[i_1, i_2, \ldots, i_k]$ of minimal length such that $s_{i_1}s_{i_2}\cdots s_{i_k} = \text{self}$, where the $s_i$ are the simple reflections.

**EXAMPLES:**

```python
sage: W = CoxeterGroups().example()
sage: s = W.simple_reflections()
sage: w = s[0]*s[1]*s[2]
sage: w.reduced_word()
[0, 1, 2]
sage: w = s[0]*s[2]
sage: w.reduced_word()
[2, 0]
```

See also:
- `reduced_words()`, `reduced_word_reverse_iterator()`,
- `length()`, `reduced_word_graph()`

### reduced_word_graph()

Return the reduced word graph of self.

The reduced word graph of an element $w$ in a Coxeter group is the graph whose vertices are the reduced words for $w$ (see `reduced_word()` for a definition of this term), and which has an $m$-colored edge between two reduced words $x$ and $y$ whenever $x$ and $y$ differ by exactly one length-$m$ braid move (with $m \geq 2$).

This graph is always connected (a theorem due to Tits) and has no multiple edges.

**EXAMPLES:**

```python
sage: W = WeylGroup(['A', 3], prefix='s')
sage: w0 = W.long_element()
sage: G = w0.reduced_word_graph()
sage: G.num_verts()
16
sage: len(w0.reduced_words())
16
sage: G.num_edges()
18
sage: len([e for e in G.edges(sort=False) if e[2] == 2])
10
sage: len([e for e in G.edges(sort=False) if e[2] == 3])
8
```
See also:

reduced_words(), reduced_word_reverse_iterator(), length(), reduced_word()

reduced_word_reverse_iterator()

Return a reverse iterator on a reduced word for self.

EXAMPLES:

```python
sage: W = CoxeterGroups().example()
sage: s = W.simple_reflections()
sage: sigma = s[0]*s[1]*s[2]
sage: rI=sigma.reduced_word_reverse_iterator()
sage: [i for i in rI]
[2, 1, 0]
sage: s[0]*s[1]*s[2]==sigma
True
sage: sigma.length()
3
```

See also:

reduced_word()

Default implementation: recursively remove the first right descent until the identity is reached (see first_descent() and apply_simple_reflection()).

reduced_words()

Return all reduced words for self.

See reduced_word() for the definition of a reduced word.

The algorithm uses the Matsumoto property that any two reduced expressions are related by braid relations, see Theorem 3.3.1(ii) in [BB2005].

See also:

braid_orbit()

EXAMPLES:

```python
sage: W = CoxeterGroups().example()
sage: s = W.simple_reflections()
sage: w = s[0] * s[2]
sage: sorted(w.reduced_words())
[[0, 2], [2, 0]]
```

(continues on next page)
Todo: The result should be full featured finite enumerated set (e.g., counting can be done much faster than iterating).

See also:

- `reduced_word()`, `reduced_word_reverse_iterator()`, `length()`, `reduced_word_graph()`
- `reflection_length()`

Iterate over all reduced words for `self`.

See `reduced_word()` for the definition of a reduced word.

The algorithm uses the Matsumoto property that any two reduced expressions are related by braid relations, see Theorem 3.3.1(ii) in [BB2005].

See also:

- `braid_orbit_iter()`

**EXAMPLES:**

```python
sage: w = CoxeterGroups().example()
sage: s = W.simple_reflections()
sage: w = s[0] * s[2]
sage: sorted(w.reduced_words_iter())
```

```
[0, 2]
```

Return the reflection length of `self`.

The reflection length is the length of the shortest expression of the element as a product of reflections.

See also:

- `absolute_length()`

**EXAMPLES:**
```python
sage: W = WeylGroup(['A', 3])  #--
needs sage.combinat sage.groups
sage: s = W.simple_reflections()  #--
needs sage.combinat sage.groups
sage: (s[1]*s[2]*s[3]).reflection_length()  #--
needs sage.combinat sage.groups
3

sage: W = SymmetricGroup(4)  #--
needs sage.groups
sage: s = W.simple_reflections()  #--
needs sage.groups
sage: (s[3]*s[2]*s[3]).reflection_length()  #--
needs sage.combinat sage.groups
1

support()

Return the support of self, that is the simple reflections that appear in the reduced expressions of self.

OUTPUT:
The support of self as a set of integers

EXAMPLES:

```python
sage: W = CoxeterGroups().example()
sage: w = W.from_reduced_word([1,2,1])
sage: w.support()
{1, 2}
```

```python
upper_covers(side='right', index_set=None)

Return all elements that cover self in weak order.

INPUT:
• side: 'left' or 'right' (default: 'right')
• index_set – a list of indices or None

OUTPUT: a list

EXAMPLES:

```python
sage: W = WeylGroup(['A', 3])

```

weak_covers \( \text{(side='right', index_set=None, positive=False)} \)

Return all elements that self covers in weak order.

INPUT:
• side – ‘left’ or ‘right’ (default: ‘right’)
• positive – a boolean (default: False)
• index_set – a list of indices or None

OUTPUT: a list

EXAMPLES:

```
sage: W = WeylGroup(['A', 3])

sage: w = W.from_reduced_word([3,2,1])

sage: [x.reduced_word() for x in w.weak_covers()]
[[3, 2], [3, 1, 2, 1], [2, 3, 2, 1]]
```

To obtain instead elements that cover self, set positive=True:

```
sage: [x.reduced_word() for x in w.weak_covers(positive=True)]
[[3, 1, 2, 1], [2, 3, 2, 1]]
```

To obtain covers for left weak order, set the option side to ‘left’:

```
sage: w = W.from_reduced_word([3,2,3,1])

sage: [x.reduced_word() for x in w.weak_covers(side='left')]  # needs sage.combinat sage.groups
[[2, 3, 1], [3, 2, 1]]
```

Covers w.r.t. a parabolic subgroup are obtained with the option index_set:

```
sage: [x.reduced_word() for x in w.weak_covers(index_set=[1,2])]
[[2, 3, 2]]
```

weak_le \( \text{(other, side='right')} \)

Comparison in weak order.

INPUT:
• other – an element of the same Coxeter group
• side – ‘left’ or ‘right’ (default: ‘right’)

OUTPUT: a boolean
This returns whether \texttt{self $\leq$ other} in left (resp. right) weak order, that is if ‘\texttt{v}’ can be obtained from ‘\texttt{v}’ by length increasing multiplication by simple reflections on the left (resp. right).

**EXAMPLES:**

```python
sage: # needs sage.combinat sage.groups
sage: W = WeylGroup(["A", 3])
sage: u = W.from_reduced_word([1,2])
sage: v = W.from_reduced_word([1,2,3,2])
sage: u.weak_le(u) # True
sage: u.weak_le(v) # True
sage: v.weak_le(u) # False
sage: v.weak_le(v) # True
```

Comparison for left weak order is achieved with the option \texttt{side}:

```python
sage: u.weak_le(v, side='left') # needs sage.combinat sage.groups
False
```

The implementation uses the equivalent condition that any reduced word for \texttt{u} is a right (resp. left) prefix of some reduced word for \texttt{v}.

Complexity: $O(l \ast c)$, where \texttt{l} is the minimum of the lengths of \texttt{u} and of \texttt{v}, and \texttt{c} is the cost of the low level methods \texttt{first_descent()}, \texttt{has_descent()}, \texttt{apply_simple_reflection()}, etc. Those are typically $O(n)$, where \texttt{n} is the rank of the Coxeter group.

We now run consistency tests with permutations:

```python
sage: W = WeylGroup(["A", 3]) # needs sage.combinat sage.groups
sage: P4 = Permutations(4)
sage: def P4toW(w): return W.from_reduced_word(w.reduced_word())
sage: for u in P4: # long time (5s on sage.math, 2011), ...
    for v in P4:
        assert u.permutahedron_lequal(v) == P4toW(u).weak_le(P4toW(v))
        assert u.permutahedron_lequal(v, side='left') == P4toW(u).weak_le(P4toW(v), side='left')
```

**Finite**

alias of \texttt{FiniteCoxeterGroups}

**class ParentMethods**

Bases: \texttt{object}

\texttt{braid_group_as_finitely_presented_group()}

Return the associated braid group.

**EXAMPLES:**

```python
sage: W = CoxeterGroup(["A", 2]) # needs sage.combinat sage.groups
sage: W.braid_group_as_finitely_presented_group() #...
```
braid_orbit (word)

Return the braid orbit of a word word of indices.

The input word does not need to be a reduced expression of an element.

INPUT:

• word: a list (or iterable) of indices in self.index_set()

OUTPUT:

a list of all lists that can be obtained from word by replacements of braid relations

See braid_relations() for the definition of braid relations.

EXAMPLES:

sage: W = CoxeterGroups().example()
sage: s = W.simple_reflections()
sage: word = w.reduced_word(); word
[0, 1, 2, 1]
sage: sorted(W.braid_orbit(word))
[[0, 1, 2, 1], [0, 2, 1, 2], [2, 0, 1, 2]]
sage: sorted(W.braid_orbit([2,1,1,2,1]))
[[1, 2, 1, 1, 2], [2, 1, 1, 2, 1], [2, 1, 2, 1, 2], [2, 2, 1, 2, 2]]
sage: # optional - gap3
sage: W = ReflectionGroup(["A",3], index_set=["AA","BB","5"])
sage: w = W.long_element()
sage: W.braid_orbit(w.reduced_word())
[["BB","5","AA","BB","5","AA"],
 ["5","BB","5","AA","BB","5"],
 ["BB","AA","BB","5","BB","AA"],
 ["AA","5","BB","AA","5","BB"],
 ["5","AA","BB","AA","5","BB"],
 ["AA","BB","5","AA","BB","AA"],
 ["AA","BB","AA","5","BB","AA"],
 ["AA","BB","5","BB","AA","BB"],
 ["AA","BB","AA","5","BB","AA"],
 ["AA","BB","5","BB","AA","BB"],
 ["AA","BB","AA","5","BB","AA"],
 ["AA","BB","5","BB","AA","BB"],
 ["AA","BB","AA","5","BB","AA"],
 ["AA","BB","5","BB","AA","BB"],
 ["AA","BB","AA","5","BB","AA"],
 ["AA","BB","5","BB","AA","BB"],
 ["AA","BB","AA","5","BB","AA"]]
Todo: The result should be full featured finite enumerated set (e.g., counting can be done much faster than iterating).

See also:

reduced_words()

braid_orbit_iter(word)
Iterate over the braid orbit of a word word of indices.
The input word does not need to be a reduced expression of an element.

INPUT:
• word – a list (or iterable) of indices in self.index_set()

OUTPUT:
all lists that can be obtained from word by replacements of braid relations

EXAMPLES:

```
sage: W = CoxeterGroups().example()
sage: sorted(W.braid_orbit_iter([0, 1, 2, 1]))
# needs sage.combinat sage.graphs
[[0, 1, 2, 1], [0, 2, 1, 2], [2, 0, 1, 2]]
```

braid_relations()
Return the braid relations of self as a list of reduced words of the braid relations.

EXAMPLES:

```
sage: W = WeylGroup(['A', 2])  # needs sage.combinat sage.groups
sage: W.braid_relations()  # needs sage.combinat sage.groups
[[[1, 2, 1], [2, 1, 2]]]
sage: W = WeylGroup(['B', 3])  # needs sage.combinat sage.groups
sage: W.braid_relations()  # needs sage.combinat sage.groups
[[[1, 2, 1], [2, 1, 2]], [[1, 3], [3, 1]], [[2, 3, 2, 3], [3, 2, 3, 2]]]
```

bruhat_graph (x=None, y=None, edge_labels=False)
Return the Bruhat graph as a directed graph, with an edge \( u \rightarrow v \) if and only if \( u < v \) in the Bruhat order, and \( u = r \cdot v \).
The Bruhat graph \( \Gamma(x, y) \), defined if \( x \leq y \) in the Bruhat order, has as its vertices the Bruhat interval \( \{ t \mid x \leq t \leq y \} \), and as its edges are the pairs \( (u, v) \) such that \( u = r \cdot v \) where \( r \) is a reflection, that is, a
conjugate of a simple reflection.

REFERENCES:


EXAMPLES:

```python
sage: W = CoxeterGroup(['H', 3])
# needs sage.combinat sage.graphs sage.groups
sage: G = W.bruhat_graph(); G
# needs sage.combinat sage.graphs sage.groups
Digraph on 120 vertices

sage: # needs sage.combinat sage.graphs sage.groups
sage: W = CoxeterGroup(['A', 2, 1])
sage: s1, s2, s3 = W.simple_reflections()
sage: W.bruhat_graph(s1, s1*s3*s2*s3)
Digraph on 6 vertices
sage: W.bruhat_graph(s1, s3*s2*s3)
Digraph on 0 vertices

sage: W = WeylGroup("A3", prefix="s")
# needs sage.combinat sage.groups
sage: s1, s2, s3 = W.simple_reflections()
# needs sage.combinat sage.groups
sage: G = W.bruhat_graph(s1*s3, s1*s2*s3*s2*s1); G
# needs sage.combinat sage.graphs sage.groups
Digraph on 10 vertices

Check that the graph has the correct number of edges (see github issue #17744):

```python
sage: len(G.edges(sort=False))
# needs sage.combinat sage.graphs sage.groups
16
```

**bruhat_interval** (*x*, *y*)

Return the list of *t* such that *x* <= *t* <= *y*.

EXAMPLES:

```python
sage: W = WeylGroup("A3", prefix="s")
# needs sage.combinat sage.groups
sage: s1, s2, s3 = W.simple_reflections()
# needs sage.combinat sage.groups
sage: W.bruhat_interval(s2, s1*s3*s2*s1*s3)
# needs sage.combinat sage.graphs sage.groups
[s1*s2*s3*s2*s1, s2*s3*s2*s1, s3*s1*s2*s1, s1*s2*s3*s1, s1*s2*s3*s2, s3*s2*s1, s2*s3*s1, s2*s3*s2, s1*s2*s1, s3*s1*s2, s1*s2*s3*s1, s2*s3*s1, s3*s1]*2, s1*s2, s2*s3, s1*s2, s2]

sage: W = WeylGroup(['A', 2, 1], prefix="s")
# needs sage.combinat sage.groups
sage: s0, s1, s2 = W.simple_reflections()
# needs sage.combinat sage.groups
sage: W.bruhat_interval(1, s0*s1*s2)
# needs sage.combinat sage.graphs sage.groups
(continues on next page)
```
needs sage.combinat sage.groups

\[s_0*s_1*s_2, s_1*s_2, s_0*s_2, s_0*s_1, s_2, s_1, s_0, 1\]

\textbf{bruhat_interval_poset}(x, y, \textit{facade}=False)

Return the poset of the Bruhat interval between \(x\) and \(y\) in Bruhat order.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: W = WeylGroup("A3", prefix="s")
sage: s1, s2, s3 = W.simple_reflections() sage: W.bruhat_interval_poset(s2, s1*s3*s2*s1*s3) Finite poset containing 16 elements
\end{verbatim}

\begin{verbatim}
sage: W = WeylGroup(['A', 2, 1], prefix="s") sage: s0, s1, s2 = W.simple_reflections() sage: W.bruhat_interval_poset(1, s0*s1*s2) Finite poset containing 8 elements
\end{verbatim}

\textbf{canonical_representation}()

Return the canonical faithful representation of \textit{self}.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: W = WeylGroup("A3") sage: W.canonical_representation() Finite Coxeter group over Integer Ring with Coxeter matrix:
[1 3 2]
[3 1 3]
[2 3 1]
\end{verbatim}

\textbf{coxeter_diagram}()

Return the Coxeter diagram of \textit{self}.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: # needs sage.combinat sage.graphs sage.groups
sage: W = CoxeterGroup(['H', 3], implementation="reflection")
sage: G = W.coxeter_diagram(); G
Graph on 3 vertices
\end{verbatim}
**coxeter_element()**

Return a Coxeter element.

The result is the product of the simple reflections, in some order.

**Note:** This implementation is shared with well generated complex reflection groups. It would be nicer to put it in some joint super category; however, in the current state of the art, there is none where it is clear that this is the right construction for obtaining a Coxeter element.

In this context, this is an element having a regular eigenvector (a vector not contained in any reflection hyperplane of self).

**EXAMPLES:**

```sage
# needs sage.combinat sage.groups
CoxeterGroup(['A', 4]).coxeter_element().reduced_word()
[1, 2, 3, 4]
CoxeterGroup(['B', 4]).coxeter_element().reduced_word()
[1, 2, 3, 4]
CoxeterGroup(['D', 4]).coxeter_element().reduced_word()
[1, 2, 4, 3]
CoxeterGroup(['F', 4]).coxeter_element().reduced_word()
[1, 2, 3, 4]
CoxeterGroup(['E', 8]).coxeter_element().reduced_word()
[1, 3, 2, 4, 5, 6, 7, 8]
CoxeterGroup(['H', 3]).coxeter_element().reduced_word()
[1, 2, 3]
```

This method is also used for well generated finite complex reflection groups:

```sage
W = ReflectionGroup((1,1,4))  # optional - gap3
W.coxeter_element().reduced_word()
[1, 2, 3]
W = ReflectionGroup((2,1,4))  # optional - gap3
W.coxeter_element().reduced_word()
[1, 2, 3, 4]
W = ReflectionGroup((4,1,4))  # optional - gap3
W.coxeter_element().reduced_word()
[1, 2, 3, 4]
W = ReflectionGroup((4,4,4))  # optional - gap3
W.coxeter_element().reduced_word()
[1, 2, 3, 4]
```

**coxeter_matrix()**

Return the Coxeter matrix associated to self.

**EXAMPLES:**

```sage
G = WeylGroup(['A', 3])  # needs sage.combinat sage.groups
G.coxeter_matrix()
[1 3 2]
```
coxeter_type()
Return the Coxeter type of self.

EXAMPLES:

```sage
sage: W = CoxeterGroup(["H", 3])
sage: W.coxeter_type()
```

```sage
Coxeter type of ["H", 3]
```

demazure_product (Q)
Return the Demazure product of the list Q in self.

INPUT:
• Q is a list of elements from the index set of self.
This returns the Coxeter group element that represents the composition of 0-Hecke or Demazure operators.


EXAMPLES:

```sage
sage: A = AffinePermutationGroup(['A', 2, 1])
sage: [len(list(A.elements_of_length(i))) for i in [0..5]]
```

```sage
[1, 3, 6, 9, 12, 15]
```

```sage
W = CoxeterGroup(["H", 3])
sage: [len(list(W.elements_of_length(i))) for i in range(4)]
```

(continues on next page)
fully_commutative_elements()

Return the set of fully commutative elements in this Coxeter group.

See also:

FullyCommutativeElements

EXAMPLES:

```python
sage: W = CoxeterGroup(['A', 2])
# needs sage.combinat sage.groups
sage: [len(list(W.elements_of_length(i))) for i in range(6)]
# needs sage.combinat sage.groups
[1, 2, 2, 1, 0, 0]
```

grassmannian_elements(side='right')

Return the left or right Grassmannian elements of self as an enumerated set.

INPUT:

- side -- (default: "right") "left" or "right"

EXAMPLES:

```python
sage: S = CoxeterGroups().example()
sage: G = S.grassmannian_elements()
sage: G.cardinality()
12
sage: G.list()
[(0, 1, 2, 3), (1, 0, 2, 3), (0, 2, 1, 3), (0, 1, 3, 2),
 (2, 0, 1, 3), (1, 2, 0, 3), (0, 3, 1, 2), (0, 2, 3, 1),
 (3, 0, 1, 2), (1, 3, 0, 2), (1, 2, 3, 0), (2, 3, 0, 1)]
sage: sorted(tuple(w.descents()) for w in G)
[(), (0,), (0,), (0,), (1,), (1,), (1,), (1,), (1,), (2,), (2,), (2,)]
sage: G = S.grassmannian_elements(side = "left")
sage: G.cardinality()
12
sage: sorted(tuple(w.descents(side = "left")) for w in G)
[(), (0,), (0,), (0,), (1,), (1,), (1,), (1,), (1,), (1,), (1,), (2,), (2,), (2,)]
```

index_set()

Return the index set of self.

EXAMPLES:

```python
sage: index_set()
```

(continues on next page)
sage: W = CoxeterGroup([[1, 3], [3, 1]], index_set=['x', 'y'])
sage: W.index_set()
('x', 'y')
sage: W = CoxeterGroup(['H', 3])
sage: W.index_set()
(1, 2, 3)

\texttt{\texttt{kazhdan\_lusztig\_cells}} (\texttt{\texttt{side='left'}})

Compute the left, right, or two-sided Kazhdan-Lusztig cells of \texttt{\texttt{self}} if \texttt{\texttt{self}} is finite.

The cells are computed by using \texttt{\texttt{kazhdan\_lusztig\_cell()}}.

As detailed there, installation of the optional package \texttt{coxeter3} is recommended (though not required) before using this function as it speeds up the computation.

INPUT:
\begin{itemize}
\item \texttt{side} – (default: \texttt{'left'}) either \texttt{'left'}, \texttt{'right'}, or \texttt{'two-sided'}
\end{itemize}

EXAMPLES:

We compute the right cells in the Coxeter group of type $A_2$ below. Note that each Coxeter group may be created with multiple implementations, namely, ‘reflection’ (default), ‘permutation’, ‘matrix’, or ‘coxeter3’. The choice of implementation affects the representation of elements in the output cells but not the method used for the cell computation:

\begin{verbatim}
sage: # needs sage.combinat sage.groups
sage: W = CoxeterGroup('A2')
sage: KL_cells = W.kazhdan_lusztig_cells(side='right')
sage: set([tuple(sorted(C, key=lambda w: w.reduced_word())) for C in KL_cells])
{(1, -1), (1, 1), (0, -1), (0, 1), (-1, 0), (-1, 1)}
sage: len(KL_cells)
4

sage: W = CoxeterGroup('A2', implementation='permutation') # needs sage.combinat sage.groups
sage: len(W.kazhdan_lusztig_cells(side='right'))
4
\end{verbatim}

We compute the left cells in the Coxeter group of type $A_3$ below. If the optional package \texttt{coxeter3} is installed, it runs in the background even if the group is not created with the \texttt{\texttt{'coxeter3'}} implementation:
sage: # optional - coxeter3, needs sage.combinat sage.groups sage.libs.
# gap sage.modules sage.rings.number_field
sage: W = CoxeterGroup('A3', implementation='coxeter3')
sage: KL_cells = W.kazhdan_lusztig_cells()
sage: set([tuple(sorted(C)) for C in KL_cells])
{([],),
 ([1, 2, 1], [3, 2, 1]),
 ([1, 2], [2], [3, 2]),
 ([1, 2, 1], [1, 3, 2, 1], [2, 1, 3, 2, 1]),
 ([1, 2, 1, 3], [1, 2, 3, 2, 1], [2, 3, 2, 1]),
 ([1, 2, 1, 3, 2], [1, 2, 3, 2], [2, 3, 2]),
 ([1, 2, 1, 3, 2, 1],),
 ([1, 2, 3], [2, 3], [3]),
 ([1, 3], [2, 1, 3]),
 ([1, 3, 2], [2, 1, 3, 2])}
sage: len(KL_cells)
10
sage: W = CoxeterGroup('A3', implementation='permutation')
sage: len(W.kazhdan_lusztig_cells())
10
Computing the two sided cells in $B_3$:

sage: # optional - coxeter3, needs sage.combinat sage.groups sage.libs.
# gap sage.modules sage.rings.number_field
sage: W = CoxeterGroup('B3', implementation='coxeter3')
sage: b3_cells = W.kazhdan_lusztig_cells('two-sided')
sage: len(b3_cells)
6
sage: set([tuple(sorted(C))
....:     for C in W.kazhdan_lusztig_cells()])
{([],),
 ([1], [2, 3, 2, 1]),
 ([1, 2], [2], [3, 2]),
 ([1, 2, 3], [2], [3, 2]),
 ([1, 2, 3], [3], [3, 2]),
 ([1, 2, 3], [3, 2, 1], [3, 2, 3]),
 ([1, 2, 3, 2], [3, 2, 1, 2], [3, 2, 3]),
 ([1, 2, 3, 2, 1], [3, 2, 3, 2], [3, 2, 3, 2, 1]),
 ([1, 2, 3, 2, 1], [3, 2, 3, 2, 1], [3, 2, 3, 2, 1, 2]),
 ([2, 1, 2, 3, 2, 1, 2, 3, 2, 1, 2, 3, 2], [3, 2, 3, 2, 1, 2, 3, 2, 1], [3, 2, 3, 2, 1, 2, 3])}}
Return a random element of length \( n \) in \( \text{self} \).

Starts at the identity, then chooses an upper cover at random.

Not very uniform: actually constructs a uniformly random reduced word of length \( n \). Thus we most likely get elements with lots of reduced words!

EXAMPLES:

```python
sage: # needs sage.combinat sage.groups
sage: A = AffinePermutationGroup(['A', 7, 1])
sage: p = A.random_element_of_length(10)
sage: p in A
True
sage: p.length() == 10
True

sage: # needs sage.combinat sage.groups
sage: W = CoxeterGroup(['A', 4])
sage: p = W.random_element_of_length(5)
sage: p in W
True
sage: p.length() == 5
True
```

**sign_representation** \((base\_ring=None, side='twosided')\)

Return the sign representation of \( \text{self} \) over \( base\_ring \).

**INPUT:**
- \( base\_ring \) – (optional) the base ring; the default is \( \mathbb{Z} \)
- \( side \) – ignored

**EXAMPLES:**

```python
sage: W = WeylGroup(['A', 1, 1])  # needs sage.combinat sage.groups
sage: W.sign_representation()  # needs sage.combinat sage.groups
Sign representation of Weyl Group of type ['A', 1, 1] (as a matrix group acting on the root space) over Integer Ring
```

**simple_projection** \((i, side='right', length\_increasing=True)\)

Return the simple projection \( \pi_i \) (or \( \pi_i \) if \( length\_increasing \) is False).

**INPUT:**
- \( i \) – an element of the index set of \( \text{self} \)

See **simple_projections()** for the options and for the definition of the simple projections.

**EXAMPLES:**

```python
sage: W = CoxeterGroups().example()
sage: W
The symmetric group on {0, ..., 3}
sage: s = W.simple_reflections()
sage: sigma = W.an_element()
sage: sigma
(1, 2, 3, 0)
sage: u0 = W.simple_projection(0)
```
simple_projections \( (side='right', \text{length\_increasing}=\text{True} ) \)

Return the family of simple projections, also known as 0-Hecke or Demazure operators.

**INPUT:**
- **self** – a Coxeter group \( W \)
- **side** – ‘left’ or ‘right’ (default: ‘right’)
- **length\_increasing** – a boolean (default: True) specifying whether the operator increases or decreases length

This returns the simple projections of \( W \), as a family.

To each simple reflection \( s_i \) of \( W \), corresponds a simple projection \( \pi_i \) from \( W \) to \( W \) defined by:
\[
\pi_i(w) = \begin{cases} 
  ws_i & \text{if } i \text{ is not a descent of } w \\
  w & \text{otherwise.}
\end{cases}
\]

The simple projections \( (\pi_i)_{i \in I} \) move elements down the right permutohedron, toward the maximal element. They satisfy the same braid relations as the simple reflections, but are idempotents \( \pi_i^2 = \pi \) not involutions \( s_i^2 = 1 \). As such, the simple projections generate the 0-Hecke monoid.

By symmetry, one can also define the projections \( (\pi_i)_{i \in I} \) (when the option **length\_increasing** is False):
\[
\pi_i(w) = \begin{cases} 
  ws_i & \text{if } i \text{ is a descent of } w \\
  w & \text{otherwise.}
\end{cases}
\]
as well as the analogues acting on the left (when the option **side** is ‘left’).

**EXAMPLES:**

```
sage: W = CoxeterGroups().example(); W
The symmetric group on \{0, ..., 3\}
sage: s = W.simple_reflections()
sage: sigma = W.an_element(); sigma
\(1, 2, 3, 0\)
sage: pi = W.simple_projections(); pi
Finite family \{0: <function ...<lambda> at ...>, 
  1: <function ...<lambda> at ...>, 
  2: <function ...<lambda> ...>\}
sage: pi[1](sigma)
\(1, 3, 2, 0\)
sage: W.simple_projection(1)(sigma)
\(1, 3, 2, 0\)
```

standard_coxeter_elements()

Return all standard Coxeter elements in self.

This is the set of all elements in self obtained from any product of the simple reflections in self.
Note:

- `self` is assumed to be well-generated.
- This works even beyond real reflection groups, but the conjugacy class is not unique and we only obtain one such class.

**EXAMPLES:**

```python
sage: W = ReflectionGroup(4) # optional - gap3
sage: sorted(W.standard_coxeter_elements()) # optional - gap3
[(1,7,6,12,23,20)(2,8,17,24,9,5) (3,16,10,19,15,21) (4,14,11,22,18,13),
 (1,10,4,12,21,22) (2,11,19,24,13,3) (5,15,7,17,16,23) (6,18,8,20,14,9)]
```

**weak_order_ideal** (*predicate*, *side*='right', *category*=`None`)

Return a weak order ideal defined by a predicate

**INPUT:**

- `predicate`: a predicate on the elements of `self` defining an weak order ideal in `self`
- `side`: “left” or “right” (default: “right”)

**OUTPUT:** an enumerated set

**EXAMPLES:**

```python
sage: D6 = FiniteCoxeterGroups().example(5)
sage: I = D6.weak_order_ideal(predicate=lambda w: w.length() <= 3)
sage: I.cardinality()
7
sage: list(I)
[(), (1,), (2,), (1, 2), (2, 1), (1, 2, 1), (2, 1, 2)]
```

We now consider an infinite Coxeter group:

```python
sage: W = WeylGroup(["A",1,1]) # needs sage.groups sage.rings.number_field
sage: I = W.weak_order_ideal(predicate=lambda w: w.length() <= 2) # needs sage.groups sage.rings.number_field
sage: list(iter(I)) # needs sage.groups sage.rings.number_field
[[1 0] [-1 2] [ 1 0] [ 3 -2] [-1 2]
 [0 1], [ 0 1], [ 2 -1], [ 2 -1], [-2 3]
]
```

Even when the result is finite, some features of `FiniteEnumeratedSets` are not available:

```python
sage: I.cardinality() # todo: not implemented
5
sage: list(I) # todo: not implemented
```

unless this finiteness is explicitly specified:

```python
sage: I = W.weak_order_ideal(predicate=lambda w: w.length() <= 2, # needs sage.groups sage.rings.number_field
...: category=FiniteEnumeratedSets())
sage: I.cardinality() # needs sage.groups sage.rings.number_field
5
```

(continues on next page)
Background

The weak order is returned as a \texttt{RecursivelyEnumeratedSet\_forest}. This is achieved by assigning to each element $u_1$ of the ideal a single ancestor $u = u_1 s_i$, where $i$ is the smallest descent of $u$.

This allows for iterating through the elements in roughly Constant Amortized Time and constant memory (taking the operations and size of the generated objects as constants).

\texttt{additional\_structure()}\n
Return \texttt{None}.

Indeed, all the structure Coxeter groups have in addition to groups (simple reflections, …) is already defined in the super category.

See also:

\texttt{Category\_additional\_structure()}\n
EXAMPLES:

\texttt{sage: CoxeterGroups().additional\_structure()}

\texttt{super\_categories()}\n
EXAMPLES:

\texttt{sage: CoxeterGroups().super\_categories()}

[\texttt{Category of generalized Coxeter groups}]

4.31 Crystals

\texttt{class sage\_categories\_crystals.CrystalHomset (X, Y, category=None)}\n
Bases: \texttt{Homset}

The set of crystal morphisms from one crystal to another. An $U_q(g)$ $I$-crystal morphism $\Psi : B \rightarrow C$ is a map $\Psi : B \cup \{0\} \rightarrow C \cup \{0\}$ such that:

- $\Psi(0) = 0$.
- If $b \in B$ and $\Psi(b) \in C$, then $\text{wt}(\Psi(b)) = \text{wt}(b)$, $\varepsilon_i(\Psi(b)) = \varepsilon_i(b)$, and $\varphi_i(\Psi(b)) = \varphi_i(b)$ for all $i \in I$.
- If $b, b' \in B$, $\Psi(b), \Psi(b') \in C$ and $f_i b = b'$, then $f_i \Psi(b) = \Psi(b')$ and $\Psi(b) = e_i \Psi(b')$ for all $i \in I$.

If the Cartan type is unambiguous, it is suppressed from the notation.

We can also generalize the definition of a crystal morphism by considering a map of $\sigma$ of the (now possibly different) Dynkin diagrams corresponding to $B$ and $C$ along with scaling factors $\gamma_i \in \mathbb{Z}$ for $i \in I$. Let $\sigma_i$ denote the orbit of
We write objects for $B$ as $X$ with corresponding objects of $C$ as $\bar{X}$. Then a virtual crystal morphism $\Psi$ is a map such that the following holds:

- $\Psi(0) = 0$.
- If $b \in B$ and $\Psi(b) \in C$, then for all $j \in \sigma_i$:
  $$
  \varepsilon_i(b) = \frac{1}{\gamma_j} \varepsilon_j(\Psi(b)), \quad \varphi_i(b) = \frac{1}{\gamma_j} \varphi_j(\Psi(b)), \quad \text{wt}(\Psi(b)) = \sum_i c_i \sum_j \gamma_j \bar{A}_j,
  $$

where $\text{wt}(b) = \sum_i c_i A_i$.

- If $b, b' \in B$, $\Psi(b), \Psi(b') \in C$ and $f_i b = b'$, then independent of the ordering of $\sigma_i$ we have:
  $$
  \Psi(b') = e_i \Psi(b) = \prod_{j \in \sigma_i} e_j^i \Psi(b), \quad \Psi(b') = f_i \Psi(b) = \prod_{j \in \sigma_i} f_j^i \Psi(b).
  $$

If $\gamma_i = 1$ for all $i \in I$ and the Dynkin diagrams are the same, then we call $\Psi$ a twisted crystal morphism.

INPUT:
- $X$ – the domain
- $Y$ – the codomain
- category – (optional) the category of the crystal morphisms

See also:
For the construction of an element of the homset, see $\text{CrystalMorphismByGenerators}$ and $\text{cystal_morphism()}$.

EXAMPLES:
We begin with the natural embedding of $B(2\Lambda_1)$ into $B(\Lambda_1) \otimes B(\Lambda_1)$ in type $A_1$:

```
sage: B = crystals.Tableaux(['A', 1], shape=[2])
sage: F = crystals.Tableaux(['A', 1], shape=[1])
sage: T = crystals.TensorProduct(F, F)
sage: v = T.highest_weight_vectors()[0]; v
[[[1]], [[1]]]
sage: H = Hom(B, T)
sage: psi = H([v])
sage: psi(b)
[[[1]], [[1]]]
sage: b.f(1)
[[[1]], [[2]]]
sage: psi(b.f(1))
[[[1]], [[2]]]
```

We now look at the decomposition of $B(\Lambda_1) \otimes B(\Lambda_1)$ into $B(2\Lambda_1) \oplus B(0)$:

```
sage: B0 = crystals.Tableaux(['A', 1], shape=[])
sage: D = crystals.DirectSum([B, B0])
sage: H = Hom(T, D)
sage: psi = H([D.module_generators])
sage: psi
['A', 1] Crystal morphism:
  From: Full tensor product of the crystals
  [The crystal of tableaux of type ['A', 1] and shape(s) [[1]],
(continues on next page)
The crystal of tableaux of type ['A', 1] and shape(s) [[1]]
To: Direct sum of the crystals Family
(The crystal of tableaux of type ['A', 1] and shape(s) [[2]],
The crystal of tableaux of type ['A', 1] and shape(s) [[3]])
Defn: [[1]], [[1]] |--> [[1, 1]]
[[2]], [[1]] |--> []
sage: psi.is_isomorphism()
True

We can always construct the trivial morphism which sends everything to 0:

```python
sage: Binf = crystals.infinity.Tableaux(['B', 2])
sage: B = crystals.Tableaux(['B', 2], shape=[1])
sage: H = Hom(Binf, B)
sage: psi = H(lambda x: None)
sage: psi(Binf.highest_weight_vector())
```

For Kirillov-Reshetikhin crystals, we consider the map to the corresponding classical crystal:

```python
sage: K = crystals.KirillovReshetikhin(['D', 4, 1], 2,1)
sage: B = K.classical_decomposition()
sage: H = Hom(K, B)
sage: psi = H(lambda x: x.lift(), cartan_type=['D', 4])
sage: L = [psi(mg) for mg in K.module_generators]; L
[[], [[1], [2]]]
sage: all(x.parent() == B for x in L)
True
```

Next we consider a type $D_4$ crystal morphism where we twist by $3 \leftrightarrow 4$:

```python
sage: B = crystals.Tableaux(['D', 4], shape=[1])
sage: H = Hom(B, B)
sage: d = {1:1, 2:2, 3:4, 4:3}
sage: psi = H(B.module_generators, automorphism=d)
sage: b = B.highest_weight_vector()
sage: b.f_string([1,2,3])
[[4]]
sage: b.f_string([1,2,4])
[[4]]
sage: psi(b.f_string([1,2,3]))
[[4]]
sage: psi(b.f_string([1,2,4]))
[[4]]
```

We construct the natural virtual embedding of a type $B_3$ into a type $D_4$ crystal:

```python
sage: B = crystals.Tableaux(['B', 3], shape=[1])
sage: C = crystals.Tableaux(['D', 4], shape=[2])
sage: H = Hom(B, C)
sage: psi = H(C.module_generators)
From: The crystal of tableaux of type ['B', 3] and shape(s) [[1]]
To: The crystal of tableaux of type ['D', 4] and shape(s) [[2]]
Defn: [[1]] |--> [[1, 1]]
sage: for b in B: print("/ |--> /\).format(b, psi(b))
[[1]] |--> [[1, 1]]
```

(continues on next page)
Element

alias of CrystalMorphismByGenerators

class sage.categories.crystals.CrystalMorphism(parent, cartan_type=None, virtualization=None, scaling_factors=None)

Bases: Morphism

A crystal morphism.

INPUT:

• parent – a homset
• cartan_type – (optional) a Cartan type; the default is the Cartan type of the domain
• virtualization – (optional) a dictionary whose keys are in the index set of the domain and whose values are lists of entries in the index set of the codomain
• scaling_factors – (optional) a dictionary whose keys are in the index set of the domain and whose values are scaling factors for the weight, $\varepsilon$ and $\varphi$

cartan_type()

Return the Cartan type of self.

EXAMPLES:

```
sage: B = crystals.Tableaux(['A',2], shape=[2,1])
sage: psi = Hom(B, B).an_element()
sage: psi.cartan_type()
['A', 2]
```

is_injective()

Return if self is an injective crystal morphism.

EXAMPLES:

```
sage: B = crystals.Tableaux(['A',2], shape=[2,1])
sage: psi = Hom(B, B).an_element()
sage: psi.is_injective()
False
```

is_surjective()

Check if self is a surjective crystal morphism.

EXAMPLES:

```
sage: B = crystals.Tableaux(['C',2], shape=[1,1])
sage: C = crystals.Tableaux(['C',2], ([2,1], [1,1]))
sage: psi = B.crystal_morphism(C.module_generators[1:], codomain=C)
sage: psi.is_surjective()
False
```
sage: im_gens = [None, B.module_generators[0]]
sage: psi = C.crystal_morphism(im_gens, codomain=B)
sage: psi.is_surjective()
True

sage: C = crystals.Tableaux(['A',2], shape=[2,1])
sage: B = crystals.infinity.Tableaux(['A',2])
sage: La = RootSystem(['A',2]).weight_lattice().fundamental_weights()
sage: W = crystals.elementary.T(['A',2], La[1]+La[2])
sage: T = W.tensor(B)
sage: mg = T.module_generators[0], B.module_generators[0])
sage: psi = Hom(C,T)([mg])
sage: psi.is_surjective()
False

scaling_factors()
Return the scaling factors \( \gamma_i \).

EXAMPLES:

sage: B = crystals.Tableaux(['B',3], shape=[1])
sage: C = crystals.Tableaux(['D',4], shape=[2])
sage: psi = B.crystal_morphism(C.module_generators)
sage: psi.scaling_factors()
Finite family {1: 2, 2: 2, 3: 1}

virtualization()
Return the virtualization sets \( \sigma_i \).

EXAMPLES:

sage: B = crystals.Tableaux(['B',3], shape=[1])
sage: C = crystals.Tableaux(['D',4], shape=[2])
sage: psi = B.crystal_morphism(C.module_generators)
sage: psi.virtualization()
Finite family {1: (1,), 2: (2,), 3: (3, 4)}

class sage.categories.crystals.CrystalMorphismByGenerators (parent, on_gens, cartan_type=None, virtualization=None, scaling_factors=None, gens=None, check=True)

Bases: CrystalMorphism

A crystal morphism defined by a set of generators which create a virtual crystal inside the codomain.

INPUT:

- parent – a homset
- on_gens – a function or list that determines the image of the generators (if given a list, then this uses the order of the generators of the domain) of the domain under self
- cartan_type – (optional) a Cartan type; the default is the Cartan type of the domain
- virtualization – (optional) a dictionary whose keys are in the index set of the domain and whose values are lists of entries in the index set of the codomain
- **scaling_factors** – (optional) a dictionary whose keys are in the index set of the domain and whose values are scaling factors for the weight, $\varepsilon$ and $\varphi$

- **gens** – (optional) a finite list of generators to define the morphism; the default is to use the highest weight vectors of the crystal

- **check** – (default: True) check if the crystal morphism is valid

See also:

`sage.categories.crystals.Crystals.ParentMethods.crystal_morphism()`

**im_gens()**

Return the image of the generators of self as a tuple.

**EXAMPLES:**

```python
sage: B = crystals.Tableaux(['A',2], shape=[2,1])
sage: F = crystals.Tableaux(['A',2], shape=[1])
sage: T = crystals.TensorProduct(F, F, F)
sage: H = Hom(T, B)
sage: b = B.highest_weight_vector()
sage: psi = H((None, b, b, None), generators=T.highest_weight_vectors())
sage: psi.im_gens()
((), ([1, 1], [2]), ([1, 1], [2]), None)
```

**image()**

Return the image of self in the codomain as a Subcrystal.

**Warning:** This assumes that self is a strict crystal morphism.

**EXAMPLES:**

```python
sage: B = crystals.Tableaux(['B',3], shape=[1])
sage: C = crystals.Tableaux(['D',4], shape=[2])
sage: H = Hom(B, C)
sage: psi = H(C.module_generators)
sage: psi.image()
Virtual crystal of The crystal of tableaux of type ['D', 4] and shape(s)...
˓→([2]) of type ['B', 3]
```

**to_module_generator(x)**

Return a generator mg and a path of $e_i$ and $f_i$ operations to mg.

**OUTPUT:**

A tuple consisting of:

- a module generator,
- a list of 'e' and 'f' to denote which operation, and
- a list of matching indices.

**EXAMPLES:**

```python
sage: B = crystals.elementary.Elementary(['A',2], 2)
sage: psi = B.crystal_morphism(B.module_generators)
sage: psi.to_module_generator(B(4))
```
class sage.categories.crystals.Crystals

Bases: Category_singleton

The category of crystals.

See sage.combinat.crystals.crystals for an introduction to crystals.

EXAMPLES:

    sage: C = Crystals()
    sage: C
    Category of crystals
    sage: C.super_categories()
    [Category of... enumerated sets]
    sage: C.example()
    Highest weight crystal of type A_3 of highest weight omega_1

Parents in this category should implement the following methods:

- either an attribute _cartan_type or a method cartan_type
- module_generators: a list (or container) of distinct elements which generate the crystal using \( f_i \)

Furthermore, their elements \( x \) should implement the following methods:

- \( x.e(i) \) (returning \( e_i(x) \))
- \( x.f(i) \) (returning \( f_i(x) \))
- \( x.epsilon(i) \) (returning \( \epsilon_i(x) \))
- \( x.phi(i) \) (returning \( \varphi_i(x) \))

EXAMPLES:

    sage: from sage.misc.abstract_method import abstract_methods_of_class
    sage: abstract_methods_of_class(Crystals().element_class)
    {'optional': [], 'required': ['e', 'epsilon', 'f', 'phi', 'weight']}

class ElementMethods

    Bases: object

    Epsilon()

    EXAMPLES:

        sage: C = crystals.Letters(['A',5])
        sage: C(0).Epsilon()
        (0, 0, 0, 0, 0, 0)
        sage: C(1).Epsilon()
        (0, 0, 0, 0, 0, 0)
        sage: C(2).Epsilon()
        (1, 0, 0, 0, 0, 0)

    Phi()

    EXAMPLES:
all_paths_to_highest_weight (index_set=None)

Iterate over all paths to the highest weight from self with respect to index_set.

INPUT:
• index_set – (optional) a subset of the index set of self

EXAMPLES:

```python
sage: B = crystals.infinity.Tableaux("A2")
sage: b0 = B.highest_weight_vector()
sage: b = b0.f_string([1, 2, 1, 2])
sage: L = b.all_paths_to_highest_weight()
sage: list(L)
[[2, 1, 2, 1], [2, 2, 1, 1]]
```

```python
sage: Y = crystals.infinity.GeneralizedYoungWalls(3)
sage: y0 = Y.highest_weight_vector()
sage: y = y0.f_string([0, 1, 2, 3, 2, 1, 0])
sage: list(y.all_paths_to_highest_weight())
[[0, 1, 2, 3, 2, 1, 0],
 [0, 1, 3, 2, 2, 1, 0],
 [0, 3, 1, 2, 2, 1, 0],
 [0, 3, 2, 1, 1, 0, 2],
 [0, 3, 2, 1, 1, 2, 0]]
```

```python
sage: B = crystals.Tableaux("A3", shape=[4,2,1])
sage: b0 = B.highest_weight_vector()
sage: b = b0.f_string([1, 1, 2, 3])
sage: list(b.all_paths_to_highest_weight())
[[1, 3, 2, 1], [3, 1, 2, 1], [3, 2, 1, 1]]
```

cartan_type()

Returns the Cartan type associated to self

EXAMPLES:

```python
sage: C = crystals.Letters(['A', 5])
sage: C(1).cartan_type()
['A', 5]
```

e(i)

Return \(e_i\) of self if it exists or None otherwise.

This method should be implemented by the element class of the crystal.

EXAMPLES:

```python
sage: C = Crystals().example(5)
sage: x = C[2]; x
3
```
(continued from previous page)

\begin{Verbatim}
  sage: x.e(1), x.e(2), x.e(3)
  (None, 2, None)
\end{Verbatim}

**e_string** (list)
Applies $e_{i_r} \cdots e_{i_1}$ to \texttt{self} for list as $[i_1, \ldots, i_r]$

**EXAMPLES:**

\begin{Verbatim}
  sage: C = crystals.Letters(['A', 3])
  sage: b = C(3)
  sage: b.e_string([2, 1])
  1
  sage: b.e_string([1, 2])
\end{Verbatim}

**epsilon** ($i$)

**EXAMPLES:**

\begin{Verbatim}
  sage: C = crystals.Letters(['A', 5])
  sage: C(1).epsilon(1)
  0
  sage: C(2).epsilon(1)
  1
\end{Verbatim}

**f** ($i$)
Return $f_i$ of \texttt{self} if it exists or \texttt{None} otherwise.

This method should be implemented by the element class of the crystal.

**EXAMPLES:**

\begin{Verbatim}
  sage: C = Crystals().example(5)
  sage: x = C[1]; x
  2
  sage: x.f(1), x.f(2), x.f(3)
  (None, 3, None)
\end{Verbatim}

**f_string** (list)
Applies $f_{i_r} \cdots f_{i_1}$ to \texttt{self} for list as $[i_1, \ldots, i_r]$

**EXAMPLES:**

\begin{Verbatim}
  sage: C = crystals.Letters(['A', 3])
  sage: b = C(1)
  sage: b.f_string([1, 2])
  3
  sage: b.f_string([2, 1])
\end{Verbatim}

**index_set** ()

**EXAMPLES:**

\begin{Verbatim}
  sage: C = crystals.Letters(['A', 5])
  sage: C(1).index_set()
  (1, 2, 3, 4, 5)
\end{Verbatim}

**is_highest_weight** (index_set=None)
Return \texttt{True} if \texttt{self} is a highest weight.
Specifying the option `index_set` to be a subset \( I \) of the index set of the underlying crystal, finds all highest weight vectors for arrows in \( I \).

**EXAMPLES:**

```
sage: C = crystals.Letters(['A', 5])
sage: C(1).is_highest_weight()
True
sage: C(2).is_highest_weight()
False
sage: C(2).is_highest_weight(index_set = [2, 3, 4, 5])
True
```

**is_lowest_weight** (`index_set=None`)

Returns True if \( \text{self} \) is a lowest weight. Specifying the option `index_set` to be a subset \( I \) of the index set of the underlying crystal, finds all lowest weight vectors for arrows in \( I \).

**EXAMPLES:**

```
sage: C = crystals.Letters(['A', 5])
sage: C(1).is_lowest_weight()
False
sage: C(6).is_lowest_weight()
True
sage: C(4).is_lowest_weight(index_set = [1, 3])
True
```

**\( \phi(i) \)**

**EXAMPLES:**

```
sage: C = crystals.Letters(['A', 5])
sage: C(1).phi(1)
1
sage: C(2).phi(1)
0
```

**\( \phi_{-\epsilon}(i) \)**

Return \( \phi_i - \epsilon_i \) of \( \text{self} \).

There are sometimes better implementations using the weight for this. It is used for reflections along a string.

**EXAMPLES:**

```
sage: C = crystals.Letters(['A', 5])
sage: C(1).phi_minus_epsilon(1)
1
```

**\( s(i) \)**

Return the reflection of \( \text{self} \) along its \( i \)-string.

**EXAMPLES:**

```
sage: C = crystals.Tableaux(['A', 2], shape=[2, 1])
sage: b = C(rows=[[1,1],[3]])
sage: b.s(1)
[[2, 2], [3]]
sage: b = C(rows=[[1,2],[3]])
sage: b.s(1)
[[2, 2], [3]]
```

(continues on next page)
sage: b.s(2)
[[1, 2], [3]]
sage: T = crystals.Tableaux(['A',2],shape=[4])
sage: t = T(rows=[[1,2,2,2]])
sage: t.s(1)
[[1, 1, 1, 2]]

**subcrystal** *(index_set=None, max_depth=inf, direction='both', contained=None, cartan_type=None, category=None)*

Construct the subcrystal generated by self using $e_i$ and/or $f_i$ for all $i$ in index_set.

**INPUT:**
- index_set – (default: None) the index set; if None then use the index set of the crystal
- max_depth – (default: infinity) the maximum depth to build
- direction – (default: 'both') the direction to build the subcrystal; it can be one of the following:
  - 'both' - using both $e_i$ and $f_i$
  - 'upper' - using $e_i$
  - 'lower' - using $f_i$
- contained – (optional) a set (or function) defining the containment in the subcrystal
- cartan_type – (optional) specify the Cartan type of the subcrystal
- category – (optional) specify the category of the subcrystal

**See also:**
- `Crystals.ParentMethods.subcrystal()`

**EXAMPLES:**

```python
sage: C = crystals.KirillovReshetikhin(['A', 3,1], 1, 2)
sage: elt = C(1,4)
sage: list(elt.subcrystal(index_set=[1,3]))
[[[1, 4]], [[2, 4]], [[1, 3]], [[2, 3]]]
sage: list(elt.subcrystal(index_set=[1,3], max_depth=1))
[[[1, 4]], [[2, 4]], [[1, 3]]]
sage: list(elt.subcrystal(index_set=[1,3], direction='upper'))
[[[1, 4]], [[1, 3]]]
sage: list(elt.subcrystal(index_set=[1,3], direction='lower'))
[[[1, 4]], [[2, 3]]]
```

**tensor** *(elts)*

Return the tensor product of self with the crystal elements elts.

**EXAMPLES:**

```python
sage: C = crystals.Letters(['A', 3])
sage: B = crystals.infinity.Tableaux(['A', 3])
sage: c = C[0]
sage: b = B.highest_weight_vector()
sage: t = c.tensor(c, b)
sage: ascii_art(t)
1 1 1
1 # 1 # 2 2
3
sage: tensor([c, c, b]) == t
True
sage: ascii_art(tensor([b, b, c]))
```

(continues on next page)
to\_highest\_weight (index\_set=\text{None})

Return the highest weight element $u$ and a list $[i_1, ..., i_k]$ such that $\text{self} = f_{i_1} ... f_{i_k} u$, where $i_1, ..., i_k$ are elements in index\_set.

By default the index\_set is assumed to be the full index set of self.

EXAMPLES:

```
sage: T = crystals.Tableaux(['A',3], shape = [1])
sage: t = T(rows = [[3]])
sage: t.to\_highest\_weight()
[[[1]], [2, 1]]
```

```
sage: T = crystals.Tableaux(['A',3], shape = [2,1])
sage: t = T(rows = [[1,2],[4]])
sage: t.to\_highest\_weight()
[[[1, 1], [2]], [1, 3, 2]]
```

```
sage: T = crystals.Tableaux(['A',3], shape = [2,1])
sage: t = T(rows = [[1,2],[4]])
sage: t.to\_highest\_weight(index\_set = [3])
[[[1, 2], [3]], [3]]
```

```
sage: K = crystals.KirillovReshetikhin(['A',3,1],2,1)
sage: t = K(rows=[[2],[3]]); t.to\_highest\_weight(index\_set=[1])
[[[1], [3]], [1]]
```

```
sage: t.to\_highest\_weight()
Traceback (most recent call last):
... ValueError: this is not a highest weight crystal
```

to\_lowest\_weight (index\_set=\text{None})

Return the lowest weight element $u$ and a list $[i_1, ..., i_k]$ such that $\text{self} = e_{i_1} ... e_{i_k} u$, where $i_1, ..., i_k$ are elements in index\_set.

By default the index\_set is assumed to be the full index set of self.

EXAMPLES:

```
sage: T = crystals.Tableaux(['A',3], shape = [1])
sage: t = T(rows = [[3]])
sage: t.to\_lowest\_weight()
[[[4]], [3]]
```

```
sage: T = crystals.Tableaux(['A',3], shape = [2,1])
sage: t = T(rows = [[1,2],[4]])
sage: t.to\_lowest\_weight()
[[[3, 4], [4]], [1, 2, 2, 3]]
```

```
sage: T = crystals.Tableaux(['A',3], shape = [2,1])
sage: t = T(rows = [[1,2],[4]])
sage: t.to\_lowest\_weight(index\_set = [3])
[[[1, 2], [4]], [1]]
```

```
sage: K = crystals.KirillovReshetikhin(['A',3,1],2,1)
sage: t = K.module\_generator(); t
[[[1], [2]]]
sage: t.to\_lowest\_weight(index\_set=[1,2])
[[[3], [4]], [2, 1, 3, 2]]
```

```
sage: T = crystals.Tableaux(['A',3], shape = [2,1])
sage: t = T(rows = [[3],[4]])
sage: t.to\_lowest\_weight()
Traceback (most recent call last):
... ValueError: this is not a highest weight crystal
```
**weight** ()

Return the weight of this crystal element.

This method should be implemented by the element class of the crystal.

EXAMPLES:

```
sage: C = crystals.Letters(['A',5])
sage: C(1).weight()
(1, 0, 0, 0, 0)
```

**Finite**

alias of *FiniteCrystals*

class *MorphismMethods*

Bases: object

**is_embedding** ()

Check if `self` is an injective crystal morphism.

EXAMPLES:

```
sage: B = crystals.Tableaux(['C',2], shape=[1,1])
sage: C = crystals.Tableaux(['C',2], ([2,1], [1,1]))
sage: psi = B.crystal_morphism(C.module_generators[1:], codomain=C)
sage: psi.is_embedding()
True
```

**is_isomorphism** ()

Check if `self` is a crystal isomorphism.

EXAMPLES:

```
sage: B = crystals.Tableaux(['C',2], shape=[1,1])
sage: C = crystals.Tableaux(['C',2], ([2,1], [1,1]))
sage: psi = B.crystal_morphism(C.module_generators[1:], codomain=C)
sage: psi.is_isomorphism()
False
```

**is_strict** ()

Check if `self` is a strict crystal morphism.

EXAMPLES:

```
sage: B = crystals.Tableaux(['C',2], shape=[1,1])
sage: C = crystals.Tableaux(['C',2], ([2,1], [1,1]))
sage: psi = B.crystal_morphism(C.module_generators[1:], codomain=C)
sage: psi.is_strict()
True
```
class ParentMethods
    Bases: object

    Lambda ()
    Returns the fundamental weights in the weight lattice realization for the root system associated with the crystal
    EXAMPLES:

    sage: C = crystals.Letters(['A', 5])
sage: C.Lambda()  # doctest: +NORMALIZE_WHITESPACE
    Finite family {1: (1, 0, 0, 0, 0), 2: (1, 1, 0, 0, 0), 3: (1, 1, 1, 0, 0), 4: (1, 1, 1, 1, 0), 5: (1, 1, 1, 1, 1)}

    an_element ()
    Returns an element of self
    sage: C = crystals.Letters(['A', 5])
sage: C.an_element()  # doctest: +NORMALIZE_WHITESPACE
    1

    cartan_type ()
    Returns the Cartan type of the crystal
    EXAMPLES:

    sage: C = crystals.Letters(['A', 2])
sage: C.cartan_type()  # doctest: +NORMALIZE_WHITESPACE
    ['A', 2]

    connected_components ()
    Return the connected components of self as subcrystals.
    EXAMPLES:

    sage: B = crystals.Tableaux(['A', 2], shape=[2,1])
sage: C = crystals.Letters(['A', 2])
sage: T = crystals.TensorProduct(B, C)
sage: T.connected_components()  # doctest: +NORMALIZE_WHITESPACE
    [Subcrystal of Full tensor product of the crystals
     [The crystal of tableaux of type ['A', 2] and shape(s) [[2, 1]],
      The crystal of letters for type ['A', 2]],
     Subcrystal of Full tensor product of the crystals
     [The crystal of tableaux of type ['A', 2] and shape(s) [[2, 1]],
      The crystal of letters for type ['A', 2]],
     Subcrystal of Full tensor product of the crystals
     [The crystal of tableaux of type ['A', 2] and shape(s) [[2, 1]],
      The crystal of letters for type ['A', 2]]]

    connected_components_generators ()
    Return a tuple of generators for each of the connected components of self.
    EXAMPLES:

    sage: B = crystals.Tableaux(['A', 2], shape=[2,1])
sage: C = crystals.Letters(['A', 2])
sage: T = crystals.TensorProduct(B, C)
sage: T.connected_components_generators()  # doctest: +NORMALIZE_WHITESPACE
    ([(1, 0), 1], [(2, 0), 1], [(1, 0), 1])
crystal_morphism(on_gens, codomain=None, cartan_type=None, index_set=None, 
generators=None, automorphism=None, virtualization=None, 
scaling_factors=None, category=None, check=True)

Construct a crystal morphism from self to another crystal codomain.

INPUT:
- on_gens – a function or list that determines the image of the generators (if given a list, then this
  uses the order of the generators of the domain) of self under the crystal morphism
- codomain – (default: self) the codomain of the morphism
- cartan_type – (optional) the Cartan type of the morphism; the default is the Cartan type of
  self
- index_set – (optional) the index set of the morphism; the default is the index set of the Cartan
  type
- generators – (optional) the generators to define the morphism; the default is the generators of
  self
- automorphism – (optional) the automorphism to perform the twisting
- virtualization – (optional) a dictionary whose keys are in the index set of the domain and
  whose values are lists of entries in the index set of the codomain; the default is the identity dictionary
- scaling_factors – (optional) a dictionary whose keys are in the index set of the domain and
  whose values are scaling factors for the weight, $\varepsilon$ and $\varphi$; the default are all scaling factors to be one
- category – (optional) the category for the crystal morphism; the default is the category of Crystals.
- check – (default: True) check if the crystal morphism is valid

See also:

For more examples, see sage.categories.crystals.CrystalHomset.

EXAMPLES:

We construct the natural embedding of a crystal using tableaux into the tensor product of single boxes
via the reading word:

```
sage: B = crystals.Tableaux(['A',2], shape=[2,1])
sage: F = crystals.Tableaux(['A',2], shape=[1])
sage: T = crystals.TensorProduct(F, F, F)
sage: mg = T.highest_weight_vectors()[2]; mg
[[[1]], [[2]], [[1]]]
sage: psi = B.crystal_morphism([mg], codomain=T); psi
['A', 2] Crystal morphism:
  From: The crystal of tableaux of type ['A', 2] and shape(s) [[2, 1]]
  To:  Full tensor product of the crystals
        [The crystal of tableaux of type ['A', 2] and shape(s) [[1]],
        The crystal of tableaux of type ['A', 2] and shape(s) [[1]],
        The crystal of tableaux of type ['A', 2] and shape(s) [[1]]]
  Defn: [[1, 1], [2]] |--> [[[1]], [[2]], [[1]]]
sage: b = B.module_generators[0]
sage: b.pp()
  1 1
  2
sage: psi(b)
[[[1]], [[2]], [[1]]]
sage: psi(b.f(2))
[[[1]], [[3]], [[1]]]
sage: psi(b.f_string([2,1,1]))
[[[2]], [[3]], [[2]]]
sage: lw = b.to_lowest_weight()[0]
sage: lw.pp()
```
We now take the other isomorphic highest weight component in the tensor product:

\[
\text{sage: } mg = T.highest_weight_vectors()[1]; mg
\]

\[
\text{[[[2]], [[1]], [[1]]]}
\]

\[
\text{sage: } psi = B.crystal_morphism([mg], codomain=T)
\]

\[
\text{sage: } psi(lw)
\]

\[
\text{[[[3]], [[2]], [[3]]]}
\]

We construct a crystal morphism of classical crystals using a Kirillov-Reshetikhin crystal:

\[
\text{sage: } B = crystals.Tableaux(['D', 4], shape=[1,1])
\]

\[
\text{sage: } K = crystals.KirillovReshetikhin(['D',4,1], 2,2)
\]

\[
\text{sage: } v = K.module_generators
\]

\[
\text{[[], [1, 2], [2, 2]]}
\]

\[
\text{sage: } psi = B.crystal_morphism([v], codomain=K, category=FiniteCrystals())
\]

\[
\text{sage: } psi
\]

\[
\text{[D, 4] -> [D, 4, 1] Virtual Crystal morphism:}
\]

\[
\text{From: The crystal of tableaux of type [D, 4] and shape(s) [[1, 1]]}
\]

\[
\text{To: Kirillov-Reshetikhin crystal of type [D, 4, 1] with (r,s)=(2,2)}
\]

\[
\text{Defn: [1, 2] |--> [1, 2]}
\]

\[
\text{sage: } b = B.module_generators[0]
\]

\[
\text{sage: } psi(b)
\]

\[
\text{[[1], [2]]}
\]

\[
\text{sage: } psi(b.to_lowest_weight()[0])
\]

\[
\text{[[-2], [-1]]}
\]

We can define crystal morphisms using a different set of generators. For example, we construct an example using the lowest weight vector:

\[
\text{sage: } B = crystals.Tableaux(['A',2], shape=[1])
\]

\[
\text{sage: } La = RootSystem(['A',2]).weight_lattice().fundamental_weights()
\]

\[
\text{sage: } T = crystals.elementary.T(['A',2], La[2])
\]

\[
\text{sage: } Bp = T.tensor(B)
\]

\[
\text{sage: } C = crystals.Tableaux(['A',2], shape=[2,1])
\]

\[
\text{sage: } x = C.module_generators[0].f_string([1,2])
\]

\[
\text{sage: } psi = Bp.crystal_morphism([x], generators=Bp.lowest_weight_vectors())
\]

\[
\text{sage: } psi(Bp.highest_weight_vector())
\]

\[
\text{[[1, 1], [2]]}
\]

We can also use a dictionary to specify the generators and their images:

\[
\text{sage: } psi = Bp.crystal_morphism({Bp.lowest_weight_vectors()[0]: x})
\]

\[
\text{sage: } psi(Bp.highest_weight_vector())
\]

\[
\text{[[1, 1], [2]]}
\]

We construct a twisted crystal morphism induced from the diagram automorphism of type $A_{3}^{(1)}$: 

We construct a virtual crystal morphism from type $G_2$ into type $D_4$:

```python
sage: D = crystals.Tableaux(['D',4], shape=[1,1])
sage: G = crystals.Tableaux(['G',2], shape=[1])
sage: psi = G.crystal_morphism(D.module_generators,
            virtualization={1:[2],2:[1,3,4]},
            scaling_factors={1:1, 2:1})
sage: for x in G:
            ascii_art(x, psi(x), sep=' |--> ')
```

```
1 |-->  2
  1 |-->  3
  2 |-->  3
  3 |--> -3
  3 |--> -3
  0 |--> -3
  3 |--> -2
  3 |--> -2
-2 |--> -1
-1 |--> -1
```
sage: C = Crystals().example(5)
sage: C.digraph()
Digraph on 6 vertices

The edges of the crystal graph are by default colored using blue for edge 1, red for edge 2, and green for edge 3:

sage: C = Crystals().example(3)
sage: G = C.digraph()
sage: view(G)  # optional - dot2tex graphviz, not tested (opens external...window)

One may also overwrite the colors:

sage: C = Crystals().example(3)
sage: G = C.digraph()
sage: G.set_latex_options(color_by_label = {1:"red", 2:"purple", 3:"blue"})
sage: view(G)  # optional - dot2tex graphviz, not tested (opens external...window)

Or one may add colors to yet unspecified edges:

sage: C = Crystals().example(4)
sage: G = C.digraph()
sage: C.cartan_type()._index_set_coloring[4]="purple"
sage: view(G)  # optional - dot2tex graphviz, not tested (opens external...window)

Here is an example of how to take the top part up to a given depth of an infinite dimensional crystal:

sage: C = CartanType(['C',2,1])
sage: La = C.root_system().weight_lattice().fundamental_weights()
sage: T = crystals.HighestWeight(La[0])
sage: S = T.subcrystal(max_depth=3)
sage: G = T.digraph(subset=S); G
Digraph on 5 vertices

sage: G.vertices(sort=True, key=str)
[(-Lambda[0] + 2*Lambda[1] - delta,),
 (Lambda[0],)]

Here is a way to construct a picture of a Demazure crystal using the subset option:

sage: B = crystals.Tableaux(['A',2], shape=[2,1])
sage: t = B.highest_weight_vector()
sage: D = B.demazure_subcrystal(t, [2,1])
sage: list(D)
[[[1, 1], [2]], [[1, 2], [2]], [[1, 1], [3]], [[1, 3], [2]], [[1, 3], [3]]]
sage: view(D)  # optional - dot2tex graphviz, not tested (opens external...window)

We can also choose to display particular arrows using the index_set option:
sage: C = crystals.KirillovReshetikhin(['D',4,1], 2, 1)
sage: G = C.digraph(index_set=[1,3])
sage: len(G.edges(sort=False))
20
sage: view(G)  # optional - dot2tex graphviz, not tested (opens external_window)

Todo: Add more tests.

direct_sum(X)
Return the direct sum of self with X.

EXAMPLES:
sage: B = crystals.Tableaux(['A',2], shape=[2,1])
sage: C = crystals.Letters(['A',2])
sage: B.direct_sum(C)
Direct sum of the crystals Family
(The crystal of tableaux of type ['A', 2] and shape(s) [[2, 1]],
The crystal of letters for type ['A', 2])

As a shorthand, we can use +:

sage: B + C
Direct sum of the crystals Family
(The crystal of tableaux of type ['A', 2] and shape(s) [[2, 1]],
The crystal of letters for type ['A', 2])

dot_tex()
Return a dot_tex string representation of self.

EXAMPLES:
sage: C = crystals.Letters(['A',2])
sage: C.dot_tex()
'digraph G {
 node [ shape=plaintext ];
 N_0 [ label = "", texlbl = \"$1$\"
 ];
 N_1 [ label = "", texlbl = \"$2$\"
 ];
 N_2 [ label = "", texlbl = \"$3$\"
 ];
 N_0 -> N_1 [ label = "", texlbl = \"$1$\"
 ];
 N_1 -> N_2 [ label = "", texlbl = \"$2$\"
 ];
}

index_set()
Returns the index set of the Dynkin diagram underlying the crystal

EXAMPLES:
sage: C = crystals.Letters(['A', 5])
sage: C.index_set()
(1, 2, 3, 4, 5)

is_connected()
Return True if self is a connected crystal.

EXAMPLES:
sage: B = crystals.Tableaux(['A',2], shape=[2,1])
sage: C = crystals.Letters(['A',2])
sage: T = crystals.TensorProduct(B,C)
sage: B.is_connected()
True
sage: T.is_connected()
False

latex(**options)

Returns the crystal graph as a latex string. This can be exported to a file with self.latex_file('filename').

EXAMPLES:

```python
sage: T = crystals.Tableaux(['A',2],shape=[1])
sage: T._latex_()
'\ldots\text{tikzpicture...}'
sage: view(T) # optional - dot2tex graphviz, not tested (opens external...)
```

One can for example also color the edges using the following options:

```python
sage: T = crystals.Tableaux(['A',2],shape=[1])
sage: T._latex_(color_by_label={0:"black", 1:"red", 2:"blue"})
'\ldots\text{tikzpicture...}'
```

latex_file(filename)

Export a file, suitable for pdflatex, to filename.

This requires a proper installation of dot2tex in sage-python. For more information see the documentation for self.latex().

EXAMPLES:

```python
sage: C = crystals.Letters(['A', 5])
sage: fn = tmp_filename(ext='.tex')
sage: C.latex_file(fn)
```

metapost (filename, thicklines=False, labels=True, scaling_factor=1.0, tallness=1.0)

Export a file, suitable for MetaPost, to filename.

Root operators $e(1)$ or $f(1)$ move along red lines, $e(2)$ or $f(2)$ along green. The highest weight is in the lower left. Vertices with the same weight are kept close together. The concise labels on the nodes are strings introduced by Berenstein and Zelevinsky and Littelmann; see Littelmann’s paper Cones, Crystals, Patterns, sections 5 and 6.

For Cartan types B2 or C2, the pattern has the form

$$a_2 a_3 a_4 a_1$$

where $e(1) a_2 = a_4 = 2 * a_4 = 0$ and $a_1 = 0$, with $c = 2$ for B2, $c = 1$ for C2. Applying $e(2) a_1$ times, $e(1) a_2$ times, $e(2) a_3$ times, $e(1) a_4$ times returns to the highest weight. (Observe that Littelmann writes the roots in opposite of the usual order, so our $e(1)$ is his $e(2)$ for these Cartan types.) For type A2, the pattern has the form

$$a_3 a_2 a_1$$

where applying $e(1) a_3$ times, $e(2) a_2$ times then $e(1) a_1$ times returns to the highest weight. These data determine the vertex and may be translated into a Gelfand-Tsetlin pattern or tableau.
INPUT:
- `filename` – name of the output file, e.g., 'filename.mp'
- `thicklines` – (default: True) for thicker edges
- `labels` – (default: False) to suppress labeling of the vertices
- `scaling_factor` – (default: 1.0) Increasing or decreasing the scaling factor changes the size of the image
- `tallness` – (default: 1.0) Increasing makes the image taller without increasing the width

EXAMPLES:
```
sage: C = crystals.Letters(['A', 2])
sage: C.metapost(tmp_filename())
```
```
sage: C = crystals.Letters(['A', 5])
sage: C.metapost(tmp_filename())
Traceback (most recent call last):
  ... 
NotImplementedError
```

`number_of_connected_components()`
Return the number of connected components of self.

EXAMPLES:
```
sage: B = crystals.Tableaux(['A',2], shape=[2,1])
sage: C = crystals.Letters(['A',2])
sage: T = crystals.TensorProduct(B,C)
sage: T.number_of_connected_components()
3
```

`plot(**options)`
Return the plot of self as a directed graph.

EXAMPLES:
```
sage: C = crystals.Letters(['A', 5])
sage: print(C.plot())
Graphics object consisting of 17 graphics primitives
```

`plot3d(**options)`
Return the 3-dimensional plot of self as a directed graph.

EXAMPLES:
```
sage: C = crystals.KirillovReshetikhin(['A',3,1],2,1)
sage: print(C.plot3d())
Graphics3d Object
```

`subcrystal(index_set=None, generators=None, max_depth=inf, direction='both', contained=None, virtualization=None, scaling_factors=None, cartan_type=None, category=None)`
Construct the subcrystal from generators using $e_i$ and/or $f_i$ for all $i$ in index_set.

INPUT:
- `index_set` – (default: None) the index set; if None then use the index set of the crystal
- `generators` – (default: None) the list of generators; if None then use the module generators of the crystal
- `max_depth` – (default: infinity) the maximum depth to build
• **direction** — (default: 'both') the direction to build the subcrystal; it can be one of the following:
  - 'both' - using both $e_i$ and $f_i$
  - 'upper' - using $e_i$
  - 'lower' - using $f_i$

• **contained** — (optional) a set or function defining the containment in the subcrystal

• **virtualization**, **scaling_factors** — (optional) dictionaries whose key $i$ corresponds to the sets $\sigma_i$ and $\gamma_i$ respectively used to define virtual crystals; see VirtualCrystal

• **cartan_type** — (optional) specify the Cartan type of the subcrystal

• **category** — (optional) specify the category of the subcrystal

EXAMPLES:

```python
sage: C = crystals.KirillovReshetikhin(['A',3,1], 1, 2)
sage: S = list(C.subcrystal(index_set=[1,2])); S
[[[1, 1]], [[1, 2]], [[2, 2]], [[1, 3]], [[2, 3]], [[3, 3]]]  
sage: len(S)  
6
sage: list(C.subcrystal(index_set=[1,3], generators=[C(1,4)]))
[[[1, 4]], [[2, 4]], [[1, 3]], [[2, 3]]]
```

We construct the subcrystal which contains the necessary data to construct the corresponding dual equivalence graph:

```python
sage: C = crystals.Tableaux(['A',5], shape=[3,3])
sage: is_wt0 = lambda x: all(x.epsilon(i) == x.phi(i) for i in x.parent().index_set())

sage: def check(x):
....:     if is_wt0(x):
....:         return True
....:     for i in x.parent().index_set()[:-1]:
....:         L = [x.e(i), x.e_string([i,i+1]), x.f(i), x.f_string([i,i+1])]
....:         if any(y is not None and is_wt0(y) for y in L):
....:             return True
....:     return False

sage: wt0 = [x for x in C if is_wt0(x)]
sage: S = C.subcrystal(contained=check, generators=wt0)
```
An example of a type $B_2$ virtual crystal inside of a type $A_3$ ambient crystal:

```python
sage: A = crystals.Tableaux(['A',3], shape=[2,1,1])
sage: S = A.subcrystal(virtualization={1:[1,3], 2:[2]},
....: scaling_factors={1:1,2:1}, cartan_type=['B',2])
sage: B = crystals.Tableaux(['B',2], shape=[1])
sage: S.digraph().is_isomorphic(B.digraph(), edge_labels=True)
True
```

tensor (*crystals, **options)

Return the tensor product of self with the crystals B.

EXAMPLES:

```python
sage: C = crystals.Letters(['A', 3])
sage: B = crystals.infinity.Tableaux(['A', 3])
sage: T = C.tensor(C, B); T
Full tensor product of the crystals [The crystal of letters for type ['A', 3],
The crystal of letters for type ['A', 3],
The infinity crystal of tableaux of type ['A', 3]]
sage: tensor([C, C, B]) is T
True
```

weight_lattice_realization()

Return the weight lattice realization used to express weights in self.

This default implementation uses the ambient space of the root system for (non relabelled) finite types and the weight lattice otherwise. This is a legacy from when ambient spaces were partially implemented, and may be changed in the future.

For affine types, this returns the extended weight lattice by default.

EXAMPLES:

```python
sage: C = crystals.Letters(['A', 5])
sage: C.weight_lattice_realization()
Ambient space of the Root system of type ['A', 5]
sage: K = crystals.KirillovReshetikhin(['A',2,1], 1, 1)
sage: K.weight_lattice_realization()
Weight lattice of the Root system of type ['A', 2, 1]
```

class SubcategoryMethods

Bases: object

Methods for all subcategories.

TensorProducts()

Return the full subcategory of objects of self constructed as tensor products.
See also:

- `tensor.TensorProductsCategory`
- `RegressiveCovariantFunctorialConstruction`

**EXAMPLES:**

```python
sage: HighestWeightCrystals().TensorProducts()
Category of tensor products of highest weight crystals
```

class *TensorProducts* (category, *args)

Bases: `TensorProductsCategory`

The category of crystals constructed by tensor product of crystals.

**extra_super_categories()**

**EXAMPLES:**

```python
sage: Crystals().TensorProducts().extra_super_categories()
[Category of crystals]
```

class *example* (choice='highwt', **kwds)

Returns an example of a crystal, as per `Category.example()`.

**INPUT:**

- `choice` – str [default: 'highwt']. Can be either 'highwt' for the highest weight crystal of type A, or 'naive' for an example of a broken crystal.
- `**kwds` – keyword arguments passed onto the constructor for the chosen crystal.

**EXAMPLES:**

```python
sage: Crystals().example(choice='highwt', n=5)
Highest weight crystal of type A_5 of highest weight omega_1
sage: Crystals().example(choice='naive')
A broken crystal, defined by digraph, of dimension five.
```

**super_categories()**

**EXAMPLES:**

```python
sage: Crystals().super_categories()
[Category of enumerated sets]
```

## 4.32 CW Complexes

**CLASS** `sage.categories.cw_complexes.CWComplexes`

Bases: `Category_singleton`

The category of CW complexes.

A CW complex is a Closure-finite cell complex in the Weak topology.

**REFERENCES:**

- Wikipedia article CW_complex
Note: The notion of “finite” is that the number of cells is finite.

EXAMPLES:

```python
sage: from sage.categories.cw_complexes import CWComplexes
sage: C = CWComplexes(); C
Category of CW complexes
```

`Compact_extra_super_categories()`

Return extraneous super categories for `CWComplexes().Compact()`.

A compact CW complex is finite, see Proposition A.1 in [Hat2002].

Todo: Fix the name of finite CW complexes.

EXAMPLES:

```python
sage: from sage.categories.cw_complexes import CWComplexes
sage: CWComplexes().Compact()  # indirect doctest
Category of finite finite dimensional CW complexes
sage: CWComplexes().Compact() is CWComplexes().Finite()
True
```

class Connected(base_category)

Bases: `CategoryWithAxiom`

The category of connected CW complexes.

class ElementMethods

Bases: object

dimension()

Return the dimension of `self`.

EXAMPLES:

```python
sage: from sage.categories.cw_complexes import CWComplexes
sage: X = CWComplexes().example()
sage: X.an_element().dimension()
2
```

class Finite(base_category)

Bases: `CategoryWithAxiom`

Category of finite CW complexes.

A finite CW complex is a CW complex with a finite number of cells.

class ParentMethods

Bases: object

dimension()

Return the dimension of `self`.

EXAMPLES:
extra_super_categories()

Return the extra super categories of self.

A finite CW complex is a compact finite-dimensional CW complex.

EXAMPLES:

```python
sage: from sage.categories.cw_complexes import CWComplexes
sage: C = CWComplexes().Finite()
```

```
[Category of finite dimensional CW complexes,
 Category of compact topological spaces]
```

class FiniteDimensional(base_category)

Bases: CategoryWithAxiom

Category of finite dimensional CW complexes.

class ParentMethods

Bases: object

cells()

Return the cells of self.

EXAMPLES:

```python
sage: from sage.categories.cw_complexes import CWComplexes
sage: X = CWComplexes().example()
```

```
[(0, (0-cell v,)),
 (1, (0-cell e1, 0-cell e2)),
 (2, (2-cell f,))]
```

dimension()

Return the dimension of self.

EXAMPLES:

```python
sage: from sage.categories.cw_complexes import CWComplexes
sage: X = CWComplexes().example()
```

```
2
```

class SubcategoryMethods

Bases: object

Connected()

Return the full subcategory of the connected objects of self.

EXAMPLES:
sage: from sage.categories.cw_complexes import CWComplexes
sage: CWComplexes().Connected()
Category of connected CW complexes

**FiniteDimensional()**
Return the full subcategory of the finite dimensional objects of `self`.

**EXAMPLES:**

sage: C = CWComplexes().FiniteDimensional(); C
Category of finite dimensional CW complexes

**super_categories()**

**EXAMPLES:**

```python
sage: from sage.categories.cw_complexes import CWComplexes
sage: CWComplexes().super_categories()
[Category of topological spaces]
```

### 4.33 Discrete Valuation Rings (DVR) and Fields (DVF)

**class** `sage.categories.discrete_valuation.DiscreteValuationFields`

**Bases:** `Category_singleton`

The category of discrete valuation fields

**EXAMPLES:**

```python
sage: Qp(7) in DiscreteValuationFields()  # needs sage.rings.padics
True
sage: TestSuite(DiscreteValuationFields()).run()
```

**class** `ElementMethods`

**Bases:** `object`

**valuation()**
Return the valuation of this element.

**EXAMPLES:**

```python
sage: # needs sage.rings.padics
sage: x = Qp(5)(50)
```

**class** `ParentMethods`

**Bases:** `object`

**residue_field()**
Return the residue field of the ring of integers of this discrete valuation field.

**EXAMPLES:**
un\texttt{iformizer}()

\texttt{return} a uniformizer of this ring.

\textbf{EXAMPLES:}

\begin{verbatim}
\texttt{sage: Qp(5).uniformizer()}
\texttt{#~ needs sage.rings.padics}
\texttt{5 + O(5^21)}
\end{verbatim}

\textbf{super\texttt{categories}()} 

\textbf{EXAMPLES:}

\begin{verbatim}
\texttt{sage: DiscreteValuationFields().super\texttt{categories}()}
\texttt{[\texttt{Category of fields}]} 
\end{verbatim}

class \texttt{sage.categories.discrete\_valuation.Discrete\_ValuationRings} 

\texttt{Bases:} \texttt{Category\_singleton} 

\texttt{The category of discrete valuation rings} 

\textbf{EXAMPLES:}

\begin{verbatim}
\texttt{sage: GF(7)[x] in Discrete\texttt{valuationRings}()}
\texttt{True}
\texttt{sage: TestSuite(Discrete\texttt{valuationRings}()).run()} 
\end{verbatim}

class \texttt{Element\texttt{Methods}} 

\texttt{Bases:} \texttt{object} 

\texttt{euclidean\texttt{degree}()} 

\texttt{return} the Euclidean degree of this element.

\texttt{gcd} \texttt{(other)} 

\texttt{return} the greatest common divisor of self and other, normalized so that it is a power of the distinguished uniformizer.

\texttt{is\texttt{unit}()} 

\texttt{return} \texttt{True} if \texttt{self} is invertible.

\textbf{EXAMPLES:}

\begin{verbatim}
\texttt{sage: # needs sage.rings.padics}
\texttt{sage: x = Zp(5)(50)}
\texttt{sage: x.is\texttt{unit}()}
\texttt{False}
\texttt{sage: # needs sage.rings.padics}
\texttt{sage: x = Zp(7)(50)}
\texttt{sage: x.is\texttt{unit}()}
\texttt{True} 
\end{verbatim}
lcm(other)
Return the least common multiple of self and other, normalized so that it is a power of the distinguished uniformizer.

quo_rem(other)
Return the quotient and remainder for Euclidean division of self by other.

EXAMPLES:

```
sage: R.<q> = GF(5)[[]]
sage: (q^2 + q).quo_rem(q)
(1 + q, 0)
sage: (q + 1).quo_rem(q^2)
(0, 1 + q)
```

valuation()
Return the valuation of this element.

EXAMPLES:

```
sage: # needs sage.rings.padics
sage: x = Zp(5)(50)
sage: x.valuation()
2
```

class ParentMethods
Bases: object

residue_field()
Return the residue field of this ring.

EXAMPLES:

```
sage: Zp(5).residue_field()
Finite Field of size 5
sage: K.<u> = QQ[[[]]
sage: K.residue_field()
Rational Field
```

uniformizer()
Return a uniformizer of this ring.

EXAMPLES:

```
sage: Zp(5).uniformizer()
5 + O(5^21)
sage: K.<u> = QQ[[[]]
sage: K.uniformizer()
u
```

super_categories()
EXAMPLES:
4.34 Distributive Magmas and Additive Magmas

class sage.categories.distributive_magmas_and_additive_magmas.DistributiveMagmasAndAdditiveMagmas:

Bases: CategoryWithAxiom_singleton

The category of sets \((S, +, *)\) with * distributing on +.

This is similar to a ring, but + and * are only required to be (additive) magmas.

EXAMPLES:

```python
sage: from sage.categories.distributive_magmas_and_additive_magmas import DistributiveMagmasAndAdditiveMagmas
sage: C = DistributiveMagmasAndAdditiveMagmas(); C
Category of distributive magmas and additive magmas
sage: C.super_categories()
[Category of magmas and additive magmas]
```

class AdditiveAssociative(base_category):

Bases: CategoryWithAxiom_singleton

class AdditiveCommutative(base_category):

Bases: CategoryWithAxiom_singleton

class AdditiveUnital(base_category):

Bases: CategoryWithAxiom_singleton

class Associative(base_category):

Bases: CategoryWithAxiom_singleton

AdditiveInverse
    alias of Rngs

Unital
    alias of Semirings

class CartesianProducts(category, *args):

Bases: CartesianProductsCategory

extra_super_categories()

Implement the fact that a Cartesian product of magmas distributing over additive magmas is a magma distributing over an additive magma.

EXAMPLES:

```python
sage: C = (Magmas() & AdditiveMagmas()).Distributive().CartesianProducts()
sage: C.extra_super_categories()
[Category of distributive magmas and additive magmas]
sage: C.axioms()
set({'Distributive'})
```
class ParentMethods
    Bases: object

4.35 Division rings

class sage.categories.division_rings.DivisionRings(base_category)
    Bases: CategoryWithAxiom_singleton

The category of division rings

A division ring (or skew field) is a not necessarily commutative ring where all non-zero elements have multiplicative inverses

EXAMPLES:

    sage: DivisionRings()
    Category of division rings
    sage: DivisionRings().super_categories()
    [Category of domains]

Commutative
    alias of Fields
class ElementMethods
    Bases: object

Finite_extra_super_categories()
    Return extraneous super categories for DivisionRings().Finite().

EXAMPLES:

    Any field is a division ring:

    sage: Fields().is_subcategory(DivisionRings())
    True

This methods specifies that, by Weddeburn theorem, the reciprocal holds in the finite case: a finite division ring is commutative and thus a field:

    sage: DivisionRings().Finite_extra_super_categories()
    (Category of commutative magmas,)
    sage: DivisionRings().Finite()
    Category of finite enumerated fields

Warning: This is not implemented in DivisionRings.Finite.extra_super_categories because the categories of finite division rings and of finite fields coincide. See the section Deduction rules in the documentation of axioms.

class ParentMethods
    Bases: object
\textbf{extra_super_categories()}

Return the \texttt{Domains} category.

This method specifies that a division ring has no zero divisors, i.e. is a domain.

See also:

The \textit{Deduction rules} section in the documentation of axioms

\textbf{EXAMPLES:}

\begin{verbatim}
sage: DivisionRings().extra_super_categories()
(Category of domains,)
sage: "NoZeroDivisors" in DivisionRings().axioms()
True
\end{verbatim}

### 4.36 Domains

\texttt{class sage.categories.domains.Domains(base_category)}

\texttt{Bases: CategoryWithAxiom_singleton}

The category of domains

A domain (or non-commutative integral domain), is a ring, not necessarily commutative, with no nonzero zero divisors.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: C = Domains(); C
Category of domains
sage: C.super_categories()
[Category of rings]
sage: C is Rings().NoZeroDivisors()
True
\end{verbatim}

\texttt{Commutative}

alias of \texttt{IntegralDomains}

\texttt{class ElementMethods}

\texttt{Bases: object}

\texttt{class ParentMethods}

\texttt{Bases: object}

\texttt{super_categories()}

\textbf{EXAMPLES:}

\begin{verbatim}
sage: Domains().super_categories()
[Category of rings]
\end{verbatim}
4.37 Enumerated sets

class sage.categories.enumerated_sets.EnumeratedSets(base_category)

Bases: CategoryWithAxiom_singleton

The category of enumerated sets

An enumerated set is a finite or countable set or multiset $S$ together with a canonical enumeration of its elements; conceptually, this is very similar to an immutable list. The main difference lies in the names and the return type of the methods, and of course the fact that the list of elements is not supposed to be expanded in memory. Whenever possible one should use one of the two sub-categories FiniteEnumeratedSets or InfiniteEnumeratedSets.

The purpose of this category is threefold:

- to fix a common interface for all these sets;
- to provide a bunch of default implementations;
- to provide consistency tests.

The standard methods for an enumerated set $S$ are:

- $S$.cardinality(): the number of elements of the set. This is the equivalent for \texttt{len} on a list except that the return value is specified to be a Sage \texttt{Integer} or infinity, instead of a Python \texttt{int}.
- $\text{iter}(S)$: an iterator for the elements of the set;
- $S$.list(): a fresh list of the elements of the set, when possible; raises a \texttt{NotImplementedError} if the list is predictably too large to be expanded in memory.
- $S$.tuple(): a tuple of the elements of the set, when possible; raises a \texttt{NotImplementedError} if the tuple is predictably too large to be expanded in memory.
- $S$.unrank(n): the $n$-th element of the set when $n$ is a sage \texttt{Integer}. This is the equivalent for $l[n]$ on a list.
- $S$.rank(e): the position of the element $e$ in the set; This is equivalent to $l.index(e)$ for a list except that the return value is specified to be a Sage \texttt{Integer}, instead of a Python \texttt{int}.
- $S$.first(): the first object of the set; it is equivalent to $S.unrank(0)$.
- $S$.next(e): the object of the set which follows $e$; it is equivalent to $S.unrank(S.rank(e) + 1)$.
- $S$.random_element(): a random generator for an element of the set. Unless otherwise stated, and for finite enumerated sets, the probability is uniform.

For examples and tests see:

- \texttt{FiniteEnumeratedSets().example()}
- \texttt{InfiniteEnumeratedSets().example()}

EXAMPLES:

```python
sage: EnumeratedSets()
Category of enumerated sets
sage: EnumeratedSets().super_categories()
[Category of sets]
sage: EnumeratedSets().all_super_categories()
[Category of enumerated sets, Category of sets, Category of sets with partial maps, Category of objects]
```
class CartesianProducts (category, *args)
    Bases: CartesianProductsCategory

class ParentMethods
    Bases: object
    first ()
        Return the first element.
        EXAMPLES:

        sage: cartesian_product([ZZ]*10).first()
        (0, 0, 0, 0, 0, 0, 0, 0, 0, 0)

class ElementMethods
    Bases: object
    rank ()
        Return the rank of self in its parent.
        See also EnumeratedSets.ElementMethods.rank()
        EXAMPLES:

        sage: F = FiniteSemigroups().example(('a','b','c'))
sage: L = list(F)
sage: L[7].rank()
7
        sage: all(x.rank() == i for i, x in enumerate(L))
        True

Finite
    alias of FiniteEnumeratedSets

Infinite
    alias of InfiniteEnumeratedSets

class ParentMethods
    Bases: object
    first ()
        The “first” element of self.
        self.first () returns the first element of the set self. This is a
generic implementation from the
category EnumeratedSets() which can be used when the method __iter__ is provided.
        EXAMPLES:

        sage: C = FiniteEnumeratedSets().example()
sage: C.first () # indirect doctest
1

is_empty ()
    Return whether this set is empty.
    EXAMPLES:
sage: F = FiniteEnumeratedSet([1,2,3])
sage: F.is_empty()
False
sage: F = FiniteEnumeratedSet([])
sage: F.is_empty()
True

**iterator_range** *(start=None, stop=None, step=None)*

Iterate over the range of elements of self starting at start, ending at stop, and stepping by step.

**See also:**

unrank(), unrank_range()

**EXAMPLES:**

```
sage: # needs sage.combinat
sage: P = Partitions()
sage: list(P.iterator_range(stop=5))
[[], [1], [2], [1, 1], [3]]
sage: list(P.iterator_range(0, 5))
[[], [1], [2], [1, 1], [3]]
sage: list(P.iterator_range(3, 5))
[[1], [3]]
sage: list(P.iterator_range(3, 10))
[[1], [3], [2, 1], [1, 1, 1], [4], [3, 1], [2, 2]]
sage: list(P.iterator_range(3, 10, 2))
[[1], [2, 1], [4], [2, 2]]
sage: it = P.iterator_range(3)
sage: [next(it) for x in range(10)]
[[1, 1], [3], [2, 1], [1, 1, 1], [4], [3, 1], [2, 2], [2, 1, 1], [1, 1, 1, 1], [5]]
sage: it = P.iterator_range(3, step=2)
sage: [next(it) for x in range(5)]
[[1, 1], [2, 1], [4], [2, 2], [1, 1, 1]]
sage: next(P.iterator_range(stop=-3))
Traceback (most recent call last):
... NotImplementedError: cannot list an infinite set
sage: next(P.iterator_range(start=-3))
Traceback (most recent call last):
... NotImplementedError: cannot list an infinite set
```

**list()**

Return a list of the elements of self.

The elements of set x are created and cached on the first call of x.list(). Then each call of x.list() returns a new list from the cached result. Thus in looping, it may be better to do for e in x:, not for e in x.list():.

If x is not known to be finite, then an exception is raised.

**EXAMPLES:**
map\( (f, \text{name}, \text{is\_injective}=\text{None})\)

Return the image \( \{f(x) | x \in \text{self}\} \) of this enumerated set by \( f \), as an enumerated set.

INPUT:

\begin{itemize}
  \item \text{is\_injective} – boolean (default: True) whether to assume that \( f \) is injective.
\end{itemize}

EXAMPLES:

\begin{verbatim}
sage: R = Compositions(4).map(attrcall('partial_sums')); R
Image of Compositions of 4 by The map \*$.partial_sums() from Compositions of 4
sage: R.cardinality()
8
sage: R.list()
[[1, 2, 3, 4], [1, 2, 4], [1, 3, 4], [1, 4], [2, 3, 4], [2, 4], [3, 4],...]
\end{verbatim}

\textbf{Warning:} If the function is not injective, then there may be repeated elements:

\begin{verbatim}
sage: P = Compositions(4)
sage: P.list()
[[1, 1, 1, 1], [1, 1, 2], [1, 2, 1], [1, 3], [2, 1, 1], [2, 2], [3, 1],...]
sage: P.map(attrcall('major_index')).list()
[6, 3, 4, 1, 5, 2, 3, 0]
\end{verbatim}

Pass \text{is\_injective}=\text{False} to get a correct result in this case:

\begin{verbatim}
sage: P.map(attrcall('major_index'), is\_injective=\text{False}).list()
[6, 3, 4, 1, 5, 2, 0]
\end{verbatim}

\textbf{next} (\text{obj})

The “next” element after \text{obj} in \text{self}.

\text{self.next(e)} returns the element of the set \text{self} which follows \text{e}. This is a generic implementation
from the category `EnumeratedSets()` which can be used when the method `__iter__` is provided.

Remark: this is the default (brute force) implementation of the category `EnumeratedSets()`. Its complexity is $O(r)$, where $r$ is the rank of `obj`.

**EXAMPLES:**

```python
sage: C = InfiniteEnumeratedSets().example()
sage: C._next_from_iterator(10) # indirect doctest 11
```

TODO: specify the behavior when `obj` is not in `self`.

**random_element()**

Return a random element in `self`.

Unless otherwise stated, and for finite enumerated sets, the probability is uniform.

This is a generic implementation from the category `EnumeratedSets()`. It raises a `NotImplementedError` since one does not know whether the set is finite.

**EXAMPLES:**

```python
sage: class broken(UniqueRepresentation, Parent):
    ....:     def __init__(self):
    ....:         Parent.__init__(self, category = EnumeratedSets())
sage: broken().random_element()
Traceback (most recent call last):
  ... Not Implemented: unknown cardinality
```

**rank(x)**

The rank of an element of `self`

`self.rank(x)` returns the rank of $x$, that is its position in the enumeration of `self`. This is an integer between 0 and $n-1$ where $n$ is the cardinality of `self`, or `None` if $x$ is not in `self`.

This is the default (brute force) implementation from the category `EnumeratedSets()` which can be used when the method `__iter__` is provided. Its complexity is $O(r)$, where $r$ is the rank of `obj`.

For infinite enumerated sets, this won’t terminate when `x` is not in `self`.

**EXAMPLES:**

```python
sage: C = FiniteEnumeratedSets().example()
sage: list(C)
[1, 2, 3]
sage: C.rank(3) # indirect doctest 2
sage: C.rank(5) # indirect doctest
```

**some_elements()**

Return some elements in `self`.

See `TestSuite` for a typical use case.

This is a generic implementation from the category `EnumeratedSets()` which can be used when the method `__iter__` is provided. It returns an iterator for up to the first 100 elements of `self`.

**EXAMPLES:**
tuple()
Return a tuple of the elements of self.
The tuple of elements of \( x \) is created and cached on the first call of \( x.tuple() \). Each following call of \( x.tuple() \) returns the same tuple.
For looping, it may be better to do `for e in x:, not for e in x.tuple():`.
If \( x \) is not known to be finite, then an exception is raised.
EXAMPLES:

```python
sage: (GF(3)^2).tuple() # needs sage.modules
((0, 0), (1, 0), (2, 0), (0, 1), (1, 1), (2, 1), (0, 2), (1, 2), (2, 2))
sage: R = Integers(11)
sage: 1 = R.tuple(); 1
(0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10)
sage: 1 is R.tuple()  
True
```

unrank \((r)\)
The \( r \)-th element of self
\( self.unrank(r) \) returns the \( r \)-th element of self, where \( r \) is an integer between 0 and \( n-1 \) where
\( n \) is the cardinality of self.
This is the default (brute force) implementation from the category `EnumeratedSets()` which can be used when the method `__iter__` is provided. Its complexity is \( O(r) \), where \( r \) is the rank of \( obj \).
EXAMPLES:

```python
sage: C = FiniteEnumeratedSets().example()
sage: C.unrank(2) # indirect doctest
3
sage: C._unrank_from_iterator(5)
Traceback (most recent call last):
  ... ValueError: the rank must be in the range from 0 to 2
sage: ZZ._unrank_from_iterator(-1)
Traceback (most recent call last):
  ... ValueError: the rank must be greater than or equal to 0
```

unrank_range \((\text{start}=\text{None}, \text{stop}=\text{None}, \text{step}=\text{None})\)
Return the range of elements of self starting at \( \text{start} \), ending at \( \text{stop} \), and stepping by \( \text{step} \).
See also:
unrank(), iterator_range()
EXAMPLES:

```python
sage: # needs sage.combinat
sage: P = Partitions()
sage: P.unrank_range(stop=5)
```
additional_structure()

Return None.

Indeed, morphisms of enumerated sets are not required to preserve the enumeration.

See also:

Category.additional_structure()

EXAMPLES:

```
sage: EnumeratedSets().additional_structure()

```

super_categories()

EXAMPLES:

```
sage: EnumeratedSets().super_categories()

[Category of sets]

```

4.38 Euclidean domains

AUTHORS:

- Teresa Gomez-Diaz (2008): initial version
- Julian Rueth (2013-09-13): added euclidean degree, quotient remainder, and their tests

class sage.categories.euclidean_domains.EuclideanDomains

Bases: Category_singleton

The category of constructive euclidean domains, i.e., one can divide producing a quotient and a remainder where the remainder is either zero or its ElementMethods.euclidean_degree() is smaller than the divisor.

EXAMPLES:
sage: EuclideanDomains()
Category of euclidean domains
sage: EuclideanDomains().super_categories()
[Category of principal ideal domains]

class ElementMethods
    Bases: object

    euclidean_degree()
    Return the degree of this element as an element of an Euclidean domain, i.e., for elements $a$, $b$ the euclidean degree $f$ satisfies the usual properties:
    1. if $b$ is not zero, then there are elements $q$ and $r$ such that $a = bq + r$ with $r = 0$ or $f(r) < f(b)$
    2. if $a, b$ are not zero, then $f(a) \leq f(ab)$

    Note: The name `euclidean_degree` was chosen because the euclidean function has different names in different contexts, e.g., absolute value for integers, degree for polynomials.

OUTPUT:
For non-zero elements, a natural number. For the zero element, this might raise an exception or produce some other output, depending on the implementation.

EXAMPLES:

```
sage: R.<x> = QQ[]
sage: x.euclidean_degree()
1
sage: ZZ.one().euclidean_degree()
1
```

gcd(other)
Return the greatest common divisor of this element and other.

INPUT:
- `other` – an element in the same ring as self

ALGORITHM:
Algorithm 3.2.1 in [Coh1993].

EXAMPLES:

```
sage: R.<x> = PolynomialRing(QQ, sparse=True)
sage: EuclideanDomains().element_class.gcd(x, x+1)
-1
```

quo_rem(other)
Return the quotient and remainder of the division of this element by the non-zero element other.

INPUT:
- `other` – an element in the same euclidean domain

OUTPUT:

a pair of elements

EXAMPLES:
class ParentMethods

Bases: object

gcd_free_basis(elts)
    Compute a set of coprime elements that can be used to express the elements of elts.

    INPUT:
    • elts - A sequence of elements of self.

    OUTPUT:
    A GCD-free basis (also called a coprime base) of elts: that is, a set of pairwise relatively prime elements of self such that any element of elts can be written as a product of elements of the set.

    ALGORITHM:
    Naive implementation of the algorithm described in Section 4.8 of Bach & Shallit [BS1996].

    EXAMPLES:

        sage: ZZ.gcd_free_basis([1])
        []
        sage: ZZ.gcd_free_basis([4, 30, 14, 49])
        [2, 15, 7]
        sage: Pol.<x> = QQ[]
        sage: sorted(Pol.gcd_free_basis([
        ....:     (x+1)^3*(x+2)^3*(x+3), (x+1)*(x+2)*(x+3),
        ....:     (x+1)*(x+2)*(x+4)]))
        [x + 3, x + 4, x^2 + 3*x + 2]

is_euclidean_domain()
    Return True, since this in an object of the category of Euclidean domains.

    EXAMPLES:

        sage: Parent(QQ,category=EuclideanDomains()).is_euclidean_domain()
        True

super_categories()
    EXAMPLES:

        sage: EuclideanDomains().super_categories()
        [Category of principal ideal domains]
4.39 Fields

class sage.categories.fields.Fields(base_category)
    Bases: CategoryWithAxiom_singleton

The category of (commutative) fields, i.e. commutative rings where all non-zero elements have multiplicative inverses

EXAMPLES:

```
sage: K = Fields()
sage: K
Category of fields
sage: Fields().super_categories()
[Category of euclidean domains, Category of division rings]
sage: K(IntegerRing())
Rational Field
sage: K(PolynomialRing(GF(3), 'x'))
Fraction Field of Univariate Polynomial Ring in x over Finite Field of size 3
sage: K(RealField())
#←needs sage.rings.real_mpfr
Real Field with 53 bits of precision
```

class ElementMethods
    Bases: object

    euclidean_degree()
        Return the degree of this element as an element of an Euclidean domain.
        In a field, this returns 0 for all but the zero element (for which it is undefined).
        EXAMPLES:

```
sage: QQ.one().euclidean_degree()
0
```

    factor()
        Return a factorization of self.
        Since self is either a unit or zero, this function is trivial.
        EXAMPLES:

```
sage: x = GF(7)(5)
sage: x.factor()
5
sage: RR(0).factor()
Traceback (most recent call last):
  ... ArithmeticError: factorization of 0.000000000000000 is not defined
```

gcd(other)
    Greatest common divisor.

Note: Since we are in a field and the greatest common divisor is only determined up to a unit, it is
correct to either return zero or one. Note that fraction fields of unique factorization domains provide a more sophisticated gcd.

EXAMPLES:

```python
sage: K = GF(5)
sage: K(2).gcd(K(1))
1
sage: K(0).gcd(K(0))
0
sage: all(x.gcd(y) == (0 if x == 0 and y == 0 else 1)
    for x in K for y in K)
True
```

For field of characteristic zero, the gcd of integers is considered as if they were elements of the integer ring:

```python
sage: gcd(15, 12)
3
```

But for other floating point numbers, the gcd is just 0.0 or 1.0:

```python
sage: gcd(3.2, 2.18)
1.00000000000000
sage: gcd(0.0, 0.0)
0.0
```

AUTHOR:
- Simon King (2011-02) – github issue #10771
- Vincent Delecroix (2015) – github issue #17671

### inverse_of_unit()

Return the inverse of this element.

EXAMPLES:

```python
sage: x = polygen(ZZ, 'x')
sage: NumberField(x^7 + 2, 'a')(2).inverse_of_unit() # needs sage.rings.number_field
1/2
```

Trying to invert the zero element typically raises a `ZeroDivisionError`:

```python
sage: QQ(0).inverse_of_unit()
Traceback (most recent call last):
...
ZeroDivisionError: rational division by zero
```

To catch that exception in a way that also works for non-units in more general rings, use something like:

```python
sage: try:
    ....:     QQ(0).inverse_of_unit()
    ....: except ArithmeticError:
    ....:     pass
```

Also note that some “fields” allow one to invert the zero element:
is_unit()

Returns True if self has a multiplicative inverse.

EXAMPLES:

```python
sage: QQ(2).is_unit()
True
sage: QQ(0).is_unit()
False
```

lcm(other)

Least common multiple.

**Note:** Since we are in a field and the least common multiple is only determined up to a unit, it is correct to either return zero or one. Note that fraction fields of unique factorization domains provide a more sophisticated lcm.

EXAMPLES:

```python
sage: GF(2)(1).lcm(GF(2)(0))
0
sage: GF(2)(1).lcm(GF(2)(1))
1
```

For field of characteristic zero, the lcm of integers is considered as if they were elements of the integer ring:

```python
sage: lcm(15.0,12.0)
60.0000000000000
```

But for others floating point numbers, it is just 0.0 or 1.0:

```python
sage: lcm(3.2, 2.18)
1.00000000000000
sage: lcm(0.0, 0.0)
0.000000000000000
```

**AUTHOR:**
- Simon King (2011-02) – github issue #10771
- Vincent Delecroix (2015) – github issue #17671

quo_rem(other)

Return the quotient with remainder of the division of this element by other.

**INPUT:**
- other – an element of the field

**EXAMPLES:**

```python
sage: f,g = QQ(1), QQ(2)
sage: f.quo_rem(g)
(1/2, 0)
```
\texttt{xgcd}(\texttt{other})

Compute the extended gcd of \texttt{self} and \texttt{other}.

\textbf{INPUT:}

\begin{itemize}
  \item \texttt{other} – an element with the same parent as \texttt{self}
\end{itemize}

\textbf{OUTPUT:}

A tuple \((r, s, t)\) of elements in the parent of \texttt{self} such that \(r = s \ast \texttt{self} + t \ast \texttt{other}\). Since the computations are done over a field, \(r\) is zero if \texttt{self} and \texttt{other} are zero, and one otherwise.

\textbf{AUTHORS:}

\begin{itemize}
  \item Julian Rueth (2012-10-19): moved here from \texttt{sage.structure.element.FieldElement}
\end{itemize}

\textbf{EXAMPLES:}

\begin{verbatim}
sage: K = GF(5)
sage: K(2).xgcd(K(1))
(1, 3, 0)
sage: K(0).xgcd(K(4))
(1, 0, 4)
sage: K(1).xgcd(K(1))
(1, 1, 0)
sage: GF(5)(0).xgcd(GF(5)(0))
(0, 0, 0)
\end{verbatim}

The \texttt{xgcd} of non-zero floating point numbers will be a triple of floating points. But if the input are two integral floating points the result is a floating point version of the standard gcd on \(\mathbb{Z}\):

\begin{verbatim}
sage: xgcd(12.0, 8.0)
(4.000000000000000, 1.000000000000000, -1.000000000000000)
sage: xgcd(3.1, 2.98714)
(1.000000000000000, 0.322580645161290, 0.000000000000000)
sage: xgcd(0.0, 1.1)
(1.000000000000000, 0.000000000000000, 0.909090909090909)
\end{verbatim}

\texttt{Finite}

\texttt{Finite} is an alias of \texttt{FiniteFields}

\textbf{class} \texttt{ParentMethods}

\texttt{Bases:} \texttt{object}

\textbf{fraction_field()}

Returns the \textit{fraction field} of \texttt{self}, which is \texttt{self}.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: QQ.fraction_field() \texttt{is} QQ
True
\end{verbatim}

\textbf{is_field} (\texttt{proof}=\texttt{True})

Returns True as \texttt{self} is a field.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: QQ.is_field()
True
sage: Parent(QQ,category=Fields()).is_field()
True
\end{verbatim}
is_integrally_closed()
Return True, as per IntegralDomain.is_integrally_closed(): for every field \( F \), \( F \) is its own field of fractions, hence every element of \( F \) is integral over \( F \).

EXAMPLES:

```python
sage: QQ.is_integrally_closed()
True
sage: QQbar.is_integrally_closed()  # needs sage.rings.number_field
True
sage: Z5 = GF(5); Z5
Finite Field of size 5
sage: Z5.is_integrally_closed()
True
```

is_perfect()
Return whether this field is perfect, i.e., its characteristic is \( p = 0 \) or every element has a \( p \)-th root.

EXAMPLES:

```python
sage: QQ.is_perfect()
True
sage: GF(2).is_perfect()
True
sage: FunctionField(GF(2), 'x').is_perfect()
False
```

vector_space(*args, **kwds)
Gives an isomorphism of this field with a vector space over a subfield.

This method is an alias for free_module, which may have more documentation.

INPUT:
- `base` — a subfield or morphism into this field (defaults to the base field)
- `basis` — a basis of the field as a vector space over the subfield; if not given, one is chosen automatically
- `map` — whether to return maps from and to the vector space

OUTPUT:
- `V` — a vector space over `base`
- `from_V` — an isomorphism from `V` to this field
- `to_V` — the inverse isomorphism from this field to `V`

EXAMPLES:

```python
sage: # needs sage.rings.padics
sage: K.<a> = Qq(125)
sage: V, fr, to = K.vector_space()
sage: v = V([1, 2, 3])
sage: fr(v, 7)
(3*a^2 + 2*a + 1) + O(5^7)
```

extra_super_categories()
EXAMPLES:

```python
sage: Fields().extra_super_categories()
[Category of euclidean domains]
```
4.40 Filtered Algebras

```
class sage.categories.filtered_algebras.FilteredAlgebras(base_category):

    Bases: FilteredModulesCategory

    The category of filtered algebras.

    An algebra $A$ over a commutative ring $R$ is filtered if $A$ is endowed with a structure of a filtered $R$-module (whose underlying $R$-module structure is identical with that of the $R$-algebra $A$) such that the indexing set $I$ (typically $I = \mathbb{N}$) is also an additive abelian monoid, the unity 1 of $A$ belongs to $F_0$, and we have $F_i \cdot F_j \subseteq F_{i+j}$ for all $i, j \in I$.

    EXAMPLES:

        sage: Algebras(ZZ).Filtered()
        Category of filtered algebras over Integer Ring
        sage: Algebras(ZZ).Filtered().super_categories()
        [Category of algebras over Integer Ring,
         Category of filtered modules over Integer Ring]

    REFERENCES:

        - Wikipedia article Filtered_algebra

    class ParentMethods

        Bases: object

        graded_algebra()

        Return the associated graded algebra to self.

        Todo: Implement a version of the associated graded algebra which does not require self to have a distinguished basis.

        EXAMPLES:

            sage: A = AlgebrasWithBasis(ZZ).Filtered().example()
            sage: A.graded_algebra()
            Graded Algebra of An example of a filtered algebra with basis: the universal enveloping algebra of Lie algebra of RR^3 with cross product over Integer Ring

4.41 Filtered Algebras With Basis

A filtered algebra with basis over a commutative ring $R$ is a filtered algebra over $R$ endowed with the structure of a filtered module with basis (with the same underlying filtered-module structure). See FilteredAlgebras and FilteredModulesWithBasis for these two notions.

```
class sage.categories.filtered_algebras_with_basis.FilteredAlgebrasWithBasis(base_category):

    Bases: FilteredModulesCategory

    The category of filtered algebras with a distinguished homogeneous basis.
A filtered algebra with basis over a commutative ring $R$ is a filtered algebra over $R$ endowed with the structure of a filtered module with basis (with the same underlying filtered-module structure). See \texttt{FilteredAlgebras} and \texttt{FilteredModulesWithBasis} for these two notions.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: C = AlgebrasWithBasis(ZZ).Filtered(); C
Category of filtered algebras with basis over Integer Ring
sage: sorted(C.super_categories(), key=str)
[Category of algebras with basis over Integer Ring,
 Category of filtered algebras over Integer Ring,
 Category of filtered modules with basis over Integer Ring]
\end{verbatim}

\textbf{class ElementMethods}

\texttt{Bases: object}

\textbf{class ParentMethods}

\texttt{Bases: object}

\texttt{from_graded_conversion()}

Return the inverse of the canonical $R$-module isomorphism $A \rightarrow \text{gr } A$ induced by the basis of $A$ (where $A = \text{"\texttt{self}"}$). This inverse is an isomorphism $\text{gr } A \rightarrow A$.

This is an isomorphism of $R$-modules, not of algebras. See the class documentation \texttt{AssociatedGradedAlgebra}.

\textbf{See also:}

\texttt{to_graded_conversion()}

\textbf{EXAMPLES:}

\begin{verbatim}
sage: A = Algebras(QQ).WithBasis().Filtered().example()
sage: p = A.an_element() + A.algebra_generators()[:3] + 2; p
U['x']^2*U['y']*U['z']*3 + 3*U['x'] + 3*U['y'] + 3
sage: q = A.to_graded_conversion()(p)
sage: A.from_graded_conversion()(q) == p
True
sage: q.parent() is A.graded_algebra()
True
\end{verbatim}

\texttt{graded_algebra()}

Return the associated graded algebra to \texttt{self}.

See \texttt{AssociatedGradedAlgebra} for the definition and the properties of this.

If the filtered algebra \texttt{self} with basis is called $A$, then this method returns $\text{gr } A$. The method \texttt{to_graded_conversion()} returns the canonical $R$-module isomorphism $A \rightarrow \text{gr } A$ induced by the basis of $A$, and the method \texttt{from_graded_conversion()} returns the inverse of this isomorphism. The method \texttt{projection()} projects elements of $A$ onto $\text{gr } A$ according to their place in the filtration on $A$.

\textbf{Warning:} When not overridden, this method returns the default implementation of an associated graded algebra – namely, \texttt{AssociatedGradedAlgebra(self)}, where \texttt{AssociatedGradedAlgebra} is \texttt{AssociatedGradedAlgebra}. But many instances of \texttt{FilteredAlgebrasWithBasis} override this method, as the associated graded algebra often is (isomorphic) to a simpler object (for instance, the associated graded algebra of a graded algebra can be identified with the graded algebra itself). Generic code that uses associated graded algebras (such as
the code of the `induced_graded_map()` method below) should make sure to only communicate with them via the `to_graded_conversion()`, `from_graded_conversion()`, and `projection()` methods (in particular, do not expect there to be a conversion from `self` to `self.graded_algebra();` this currently does not work for Clifford algebras). Similarly, when overriding `graded_algebra()`, make sure to accordingly redefine these three methods, unless their definitions below still apply to your case (this will happen whenever the basis of your `graded_algebra()` has the same indexing set as `self`, and the partition of this indexing set according to degree is the same as for `self`).

**Todo:** Maybe the thing about the conversion from `self` to `self.graded_algebra()` on the Clifford at least could be made to work? (I would still warn the user against ASSUMING that it must work – as there is probably no way to guarantee it in all cases, and we shouldn’t require users to mess with element constructors.)

**EXAMPLES:**

```python
sage: A = AlgebrasWithBasis(ZZ).Filtered().example()
sage: A.graded_algebra()
Graded Algebra of An example of a filtered algebra with basis: the universal enveloping algebra of Lie algebra of RR^3 with cross product over Integer Ring
```

**induced_graded_map**(other, f)

Return the graded linear map between the associated graded algebras of `self` and `other` canonically induced by the filtration-preserving map `f : self -> other`.

Let `A` and `B` be two filtered algebras with basis, and let `(F_i)_{i \in I}` and `(G_i)_{i \in I}` be their filtrations. Let `f : A \rightarrow B` be a linear map which preserves the filtration (i.e., satisfies `f(F_i) \subseteq G_i` for all `i \in I`). Then, there is a canonically defined graded linear map `gr f : gr A \rightarrow gr B` which satisfies

```
(gr f)(p_i(a)) = p_i(f(a))  for all i \in I and a \in F_i,
```

where the `p_i` on the left hand side is the canonical projection from `F_i` onto the `i`-th graded component of `gr A`, while the `p_i` on the right hand side is the canonical projection from `G_i` onto the `i`-th graded component of `gr B`.

**INPUT:**
- `other` - a filtered algebra with basis
- `f` - a filtration-preserving linear map from `self` to `other` (can be given as a morphism or as a function)

**OUTPUT:**
The graded linear map `gr f`.

**EXAMPLES:**

**Example 1.**

We start with the universal enveloping algebra of the Lie algebra `R^3` (with the cross product serving as Lie bracket):

```python
sage: A = AlgebrasWithBasis(QQ).Filtered().example(); A
An example of a filtered algebra with basis: the universal enveloping algebra of Lie algebra of RR^3
```
with cross product over Rational Field

```
sage: M = A.indices(); M
Free abelian monoid indexed by ('x', 'y', 'z')
sage: x, y, z = [A.basis()[M.gens()[i]] for i in "xyz"]
```

Let us define a stupid filtered map from $A$ to itself:

```
sage: def map_on_basis(m):
.....:     d = m.dict()
.....:     i = d.get('x', 0); j = d.get('y', 0); k = d.get('z', 0)
.....:     g = (y ** (i+j)) * (z ** k)
.....:     if i > 0:
.....:         g += i * (x ** (i-1)) * (y ** j) * (z ** k)
.....:     return g
```

```
sage: f = A.module_morphism(on_basis=map_on_basis,
.....:     codomain=A)
sage: f(x)
U[y] + 1
sage: f(x*y*z)
U[y]^2*U[z] + U[y]*U[z]
sage: f(x*x*y*z)
U[y]^3*U[z] + 2*U[x]*U[y]*U[z]
sage: f(A.one())
1
sage: f(y*z)
U[y]*U[z]
```

(There is nothing here that is peculiar to this universal enveloping algebra; we are only using its module structure, and we could just as well be using a polynomial algebra in its stead.)

We now compute $\text{gr } f$

```
sage: grA = A.graded_algebra(); grA
Graded Algebra of An example of a filtered algebra with
basis: the universal enveloping algebra of Lie algebra
of RR^3 with cross product over Rational Field
sage: xx, yy, zz = [A.to_graded_conversion()(i) for i in [x, y, z]]
```

```
sage: xx+yy*zz
bar(U[y]*U[z]) + bar(U[x])
```

```
sage: grf = A.induced_graded_map(A, f); grf
Generic endomorphism of Graded Algebra of An example
of a filtered algebra with basis: the universal
enveloping algebra of Lie algebra of RR^3 with cross
product over Rational Field

```
```
sage: grf(xx)
bar(U[y])
```

```
sage: grf(xx*yy*zz)
bar(U[y]^2*U[z])
```

```
sage: grf(xx*xx*yy*zz)
bar(U[y]^3*U[z])
```

```
sage: grf(grA.one())
bar(1)
```

```
sage: grf(yy*zz)
bar(U[y]*U[z])
```

```
sage: grf(yy*zz-2*yy)
bar(U[y]*U[z]) - 2*bar(U[y])
```

Example 2.
We shall now construct $\mathfrak{g} f$ for a different map $f$ out of the same $A$; the new map $f$ will lead into a graded algebra already, namely into the algebra of symmetric functions:

```python
sage: # needs sage.combinat sage.modules
sage: h = SymmetricFunctions(QQ).h()
sage: def map_on_basis(m): # redefining map_on_basis
    ...:     d = m.dict()
    ...:     i = d.get('x', 0); j = d.get('y', 0); k = d.get('z', 0)
    ...:     g += i * (h[1] ** (i+j+k))
    ...:     return g
sage: f = A.module_morphism(on_basis=map_on_basis, codomain=h) # redefining f
sage: f(x)
2*h[1]
sage: f(y)
h[]
sage: f(z)
h[]
sage: f(y**2)
h[2]
sage: f(x**2)
3*h[1, 1]
sage: f(x*y*z)
h[1] + h[1, 1, 1]
sage: f(x*x*y*y*z)
2*h[1, 1, 1, 1] + h[2, 1, 1]
```

The algebra $h$ of symmetric functions in the $h$-basis is already graded, so its associated graded algebra is implemented as itself:

```python
sage: # needs sage.combinat sage.modules
sage: grh = h.graded_algebra(); grh
is h
True
sage: grf = A.induced_graded_map(h, f); grf
Generic morphism:
   From: Graded Algebra of An example of a filtered algebra with basis: the universal enveloping algebra of Lie algebra of RR^3 with cross product over Rational Field
   To:   Symmetric Functions over Rational Field in the homogeneous basis
sage: grf(xx)
2*h[1]
sage: grf(yy)
0
sage: grf(zz)
0
sage: grf(yy**2)
h[2]
sage: grf(xx**2)
3*h[1, 1]
sage: grf(xx*y*y*z)
h[1, 1, 1]
sage: grf(xx*x*y*y*z)
2*h[1, 1, 1, 1, 1]
```

(continues on next page)
Example 3.

After having had a graded algebra as the codomain, let us try to have one as the domain instead. Our new \( f \) will go from \( h \) to \( A \):

```python
sage: grf = h.induced_graded_map(A, f); grf
Generic morphism:
    From: Symmetric Functions over Rational Field
        in the homogeneous basis
    To:   Graded Algebra of An example of a filtered
        algebra with basis: the universal enveloping
        algebra of Lie algebra of RR^3 with cross
        product over Rational Field
sage: grf(h[1])
bar(U['x']) + bar(U['y'])
sage: grf(h[2])
bar(U['x']^2) + bar(U['y']^2)
sage: grf(h[1, 1])
bar(U['x']^2) + bar(U['y']^2)
sage: grf(h[2, 2])
bar(U['x']^4) + bar(U['y']^4)
sage: grf(h[3, 2, 1])
bar(U['x']^6) + bar(U['y']^3)
sage: grf(h.one())
2
```

Example 4.

The construct \( grf \) also makes sense when \( f \) is a filtration-preserving map between graded algebras.

```python
sage: grf(h[1])
bar(U['x']) + bar(U['y'])
sage: grf(h[2])
bar(U['x']^2)
sage: grf(h[1, 1])
bar(U['x']^2) + bar(U['y']^2)
sage: grf(h[2, 2])
bar(U['x']^4)
sage: grf(h[3, 2, 1])
bar(U['x']^6)
sage: grf(h.one())
2*bar(1)
```
Example 5.

For another example, let us compute \( \text{gr} f \) for a map \( f \) between two Clifford algebras:

```python
# needs sage.modules
sage: Q = QuadraticForm(ZZ, 2, [1,2,3])
sage: B = CliffordAlgebra(Q, names=['u','v']); B
The Clifford algebra of the Quadratic form in 2 variables over Integer Ring with coefficients:
[ 1 2 ]
[ * 3 ]
sage: m = Matrix(ZZ, [[1, 2], [i, -1]])
sage: f = B.lift_module_morphism(m, names=['x','y'])
sage: A = f.domain(); A
The Clifford algebra of the Quadratic form in 2 variables over Integer Ring with coefficients:
[ 6 0 ]
[ * 3 ]
sage: x, y = A.gens()
sage: f(x)
u + v
sage: f(y)
2*u - v
sage: f(x**2)
6
sage: f(x*y)
-3*u*v + 3
sage: grA = A.graded_algebra(); grA
The exterior algebra of rank 2 over Integer Ring
sage: A.to_graded_conversion()(x)
x
sage: A.to_graded_conversion()(y)
y
sage: A.to_graded_conversion()(x*y)
x*y
```

(continues on next page)
to_graded_conversion() 

Return the canonical \( R \)-module isomorphism \( A \to \text{gr } A \) induced by the basis of \( A \) (where \( A = \text{"self"} \)). This is an isomorphism of \( R \)-modules, not of algebras. See the class documentation Associated-GradedAlgebra.

See also: 

\[ \text{from_graded_conversion()} \]

EXAMPLES:
4.42 Filtered Modules

A filtered module over a ring $R$ with a totally ordered indexing set $I$ (typically $I = \mathbb{N}$) is an $R$-module $M$ equipped with a family $(F_i)_{i \in I}$ of $R$-submodules satisfying $F_i \subseteq F_j$ for all $i, j \in I$ having $i \leq j$, and $M = \bigcup_{i \in I} F_i$. This family is called a filtration of the given module $M$.

Todo: Implement a notion for decreasing filtrations: where $F_j \subseteq F_i$ when $i \leq j$.

Todo: Implement filtrations for all concrete categories.

Todo: Implement gr as a functor.

class sage.categories.filtered_modules.FilteredModules(base_category)
    Bases: FilteredModulesCategory

The category of filtered modules over a given ring $R$.

A filtered module over a ring $R$ with a totally ordered indexing set $I$ (typically $I = \mathbb{N}$) is an $R$-module $M$ equipped with a family $(F_i)_{i \in I}$ of $R$-submodules satisfying $F_i \subseteq F_j$ for all $i, j \in I$ having $i \leq j$, and $M = \bigcup_{i \in I} F_i$. This family is called a filtration of the given module $M$.

EXAMPLES:

sage: Modules(ZZ).Filtered()
Category of filtered modules over Integer Ring
sage: Modules(ZZ).Filtered().super_categories()
[Category of modules over Integer Ring]

REFERENCES:

- Wikipedia article Filtration_(mathematics)

class Connected(base_category)
    Bases: CategoryWithAxiom_over_base_ring

class SubcategoryMethods
    Bases: object

Connected()

    Return the full subcategory of the connected objects of self.

A filtered $R$-module $M$ with filtration $(F_0, F_1, F_2, \ldots)$ (indexed by $\mathbb{N}$) is said to be connected if $F_0$ is isomorphic to $R$. 

4.42. Filtered Modules 337
**EXAMPLES:**

```python
sage: Modules(ZZ).Filtered().Connected()
Category of filtered connected modules over Integer Ring
sage: Coalgebras(QQ).Filtered().Connected()
Category of filtered connected coalgebras over Rational Field
sage: AlgebrasWithBasis(QQ).Filtered().Connected()
Category of filtered connected algebras with basis over Rational Field
```

**extra_super_categories()**

Add `VectorSpaces` to the super categories of `self` if the base ring is a field.

**EXAMPLES:**

```python
sage: Modules(QQ).Filtered().is_subcategory(VectorSpaces(QQ))
True
sage: Modules(ZZ).Filtered().extra_super_categories()
[]
```

This makes sure that `Modules(QQ).Filtered()` returns an instance of `FilteredModules` and not a join category of an instance of this class and of `VectorSpaces(QQ)`:

```python
sage: type(Modules(QQ).Filtered())
<class 'sage.categories.vector_spaces.VectorSpaces.Filtered_with_category'>
```

**Todo:** Get rid of this workaround once there is a more systematic approach for the alias `Modules(QQ) -> VectorSpaces(QQ)`. Probably the latter should be a category with axiom, and covariant constructions should play well with axioms.

**class** `sage.categories.filtered_modules.FilteredModulesCategory` *(base_category)*

**Bases:** `RegressiveCovariantConstructionCategory, Category_over_base_ring`

**EXAMPLES:**

```python
sage: C = Algebras(QQ).Filtered()
sage: C
Category of filtered algebras over Rational Field
sage: C.base_category()
Category of algebras over Rational Field
sage: sorted(C.super_categories(), key=str)
[Category of algebras over Rational Field,
 Category of filtered vector spaces over Rational Field]
sage: AlgebrasWithBasis(QQ).Filtered().base_ring()
Rational Field
sage: HopfAlgebrasWithBasis(QQ).Filtered().base_ring()
Rational Field
```
4.43 Filtered Modules With Basis

A filtered module with basis over a ring \( R \) means (for the purpose of this code) a filtered \( R \)-module \( M \) with filtration \((F_i)_{i \in I}\) (typically \( I = \mathbb{N} \)) endowed with a basis \((b_j)_{j \in J} \) of \( M \) and a partition \( J = \bigcup_{i \in I} J_i \) of the set \( J \) (it is allowed that some \( J_i \) are empty) such that for every \( n \in I \), the subfamily \((b_j)_{j \in U_n}\), where \( U_n = \bigcup_{i \leq n} J_i \), is a basis of the \( R \)-submodule \( F_n \).

For every \( i \in I \), the \( R \)-submodule of \( M \) spanned by \((b_j)_{j \in J_i}\) is called the \( i \)-th graded component (aka the \( i \)-th homogeneous component) of the filtered module with basis \( M \); the elements of this submodule are referred to as homogeneous elements of degree \( i \).

See the class documentation \texttt{FilteredModulesWithBasis} for further details.

class \texttt{sage.categories.filtered_modules_with_basis.FilteredModulesWithBasis} (base_category)

Bases: \texttt{FilteredModulesCategory}

The category of filtered modules with a distinguished basis.

A filtered module with basis over a ring \( R \) means (for the purpose of this code) a filtered \( R \)-module \( M \) with filtration \((F_i)_{i \in I}\) (typically \( I = \mathbb{N} \)) endowed with a basis \((b_j)_{j \in J} \) of \( M \) and a partition \( J = \bigcup_{i \in I} J_i \) of the set \( J \) (it is allowed that some \( J_i \) are empty) such that for every \( n \in I \), the subfamily \((b_j)_{j \in U_n}\), where \( U_n = \bigcup_{i \leq n} J_i \), is a basis of the \( R \)-submodule \( F_n \).

For every \( i \in I \), the \( R \)-submodule of \( M \) spanned by \((b_j)_{j \in J_i}\) is called the \( i \)-th graded component (aka the \( i \)-th homogeneous component) of the filtered module with basis \( M \); the elements of this submodule are referred to as homogeneous elements of degree \( i \). The \( R \)-module \( M \) is the direct sum of its \( i \)-th graded components over all \( i \in I \), and thus becomes a graded \( R \)-module with basis. Conversely, any graded \( R \)-module with basis canonically becomes a filtered \( R \)-module with basis (by defining \( F_n = \bigoplus_{i \leq n} G_i \) where \( G_i \) is the \( i \)-th graded component, and defining \( J_i \) as the indexing set of the basis of the \( i \)-th graded component). Hence, the notion of a filtered \( R \)-module with basis is equivalent to the notion of a graded \( R \)-module with basis.

However, the category of filtered \( R \)-modules with basis is not the category of graded \( R \)-modules with basis. Indeed, the morphisms of filtered \( R \)-modules with basis are defined to be morphisms of \( R \)-modules which send each \( F_n \) of the domain to the corresponding \( F_n \) of the target; in contrast, the morphisms of graded \( R \)-modules with basis must preserve each homogeneous component. Also, the notion of a filtered algebra with basis differs from that of a graded algebra with basis.

Note: Currently, to make use of the functionality of this class, an instance of \texttt{FilteredModulesWithBasis} should fulfill the contract of \texttt{CombinatorialFreeModule} (most likely by inheriting from it). It should also have the indexing set \( J \) encoded as its \_indices attribute, and \_indices.subset(size=i) should yield the subset \( J_i \) (as an iterable). If the latter conditions are not satisfied, then \texttt{basis()} must be overridden.

Note: One should implement a \texttt{degree_on_basis} method in the parent class in order to fully utilize the methods of this category. This might become a required abstract method in the future.

EXAMPLES:

```
sage: C = ModulesWithBasis(ZZ).Filtered(); C
Category of filtered modules with basis over Integer Ring
sage: sorted(C.super_categories(), key=str)
[Category of filtered modules over Integer Ring,
 Category of modules with basis over Integer Ring]
```

(continues on next page)
class ElementMethods:
    Bases: object

    degree()

    The degree of a nonzero homogeneous element self in the filtered module.

    Note: This raises an error if the element is not homogeneous. To compute
    the maximum of the degrees of the homogeneous summands of a (not
    necessarily homogeneous) element, use maximal_degree() instead.

EXAMPLES:

    sage: # needs sage.combinat sage.modules
    sage: A = ModulesWithBasis(ZZ).Filtered().example()
    sage: x = A(Partition((3,2,1)))
    sage: y = A(Partition((4,4,1)))
    sage: z = A(Partition((2,2,2)))
    sage: x.degree()
    6
    sage: (x + 2*z).degree()
    6
    sage: (y - x).degree()
    Traceback (most recent call last):
    ...  
    ValueError: element is not homogeneous

An example in a graded algebra:

    sage: # needs sage.combinat sage.modules
    sage: S = NonCommutativeSymmetricFunctions(QQ).S()
    sage: (x, y) = (S[2], S[3])
    sage: x.homogeneous_degree()
    2
    sage: (x^3 + 4*y^2).homogeneous_degree()
    6
    sage: ((1 + x)^3).homogeneous_degree()
    Traceback (most recent call last):
    ...  
    ValueError: element is not homogeneous

Let us now test a filtered algebra (but remember that the notion of homogeneity
now depends on the choice of a basis):

    sage: A = AlgebrasWithBasis(QQ).Filtered().example()
    sage: x,y,z = A.algebra_generators()
    sage: (x*y).homogeneous_degree()
    2
    sage: (y*x).homogeneous_degree()
    Traceback (most recent call last):
    ...  
    ValueError: element is not homogeneous
sage: A.one().homogeneous_degree()
0

degree_on_basis($m$)
Return the degree of the basis element indexed by $m$ in self.

EXAMPLES:

sage: A = GradedModulesWithBasis(QQ).example() #--
needs sage.combinat sage.modules
sage: A.degree_on_basis(Partition((2,1))) #--
needs sage.combinat sage.modules
3
sage: A.degree_on_basis(Partition((4,2,1,1,1,1))) #--
needs sage.combinat sage.modules
10

homogeneous_component($n$)
Return the homogeneous component of degree $n$ of the element self.

Let $m$ be an element of a filtered $R$-module $M$ with basis. Then, $m$ can be uniquely written in the form $m = \sum_{i \in I} m_i$, where each $m_i$ is a homogeneous element of degree $i$. For $n \in I$, we define the homogeneous component of degree $n$ of the element $m$ to be $m_n$.

EXAMPLES:

sage: # needs sage.combinat sage.modules
sage: A = ModulesWithBasis(ZZ).Filtered().example()
sage: x = A.an_element(); x

sage: x.homogeneous_component(-1)
0
sage: x.homogeneous_component(0)
2*P[0]

sage: x.homogeneous_component(1)
2*P[1]

sage: x.homogeneous_component(2)
3*P[2]

sage: x.homogeneous_component(3)
0

sage: # needs sage.combinat sage.modules
sage: A = ModulesWithBasis(ZZ).Graded().example()
sage: x = A.an_element(); x

sage: x.homogeneous_component(-1)
0
sage: x.homogeneous_component(0)
2*P[0]

sage: x.homogeneous_component(1)
2*P[1]

sage: x.homogeneous_component(2)
3*P[2]

sage: x.homogeneous_component(3)
0

sage: A = AlgebrasWithBasis(ZZ).Filtered().example()
homogeneous_degree()

The degree of a nonzero homogeneous element self in the filtered module.

Note: This raises an error if the element is not homogeneous. To compute the maximum of the degrees of the homogeneous summands of a (not necessarily homogeneous) element, use maximal_degree() instead.

EXAMPLES:

sage: # needs sage.combinat sage.modules
sage: A = ModulesWithBasis(ZZ).Filtered().example()
sage: x = A(Partition((3,2,1)))
sage: y = A(Partition((4,4,1)))
sage: z = A(Partition((2,2,2)))
sage: x.degree() 6
sage: (x + 2*z).degree() 6
sage: (y - x).degree() 6
Traceback (most recent call last):
  ... ValueError: element is not homogeneous

An example in a graded algebra:

sage: # needs sage.combinat sage.modules
sage: S = NonCommutativeSymmetricFunctions(QQ).S()
sage: (x, y) = (S[2], S[3])
sage: x.homogeneous_degree() 2
sage: (x^3 + 4*y^2).homogeneous_degree() 6
sage: ((1 + x)^3).homogeneous_degree() 6
Traceback (most recent call last):
  ... ValueError: element is not homogeneous

Let us now test a filtered algebra (but remember that the notion of homogeneity now depends on the
### is_homogeneous()

Return whether the element `self` is homogeneous.

**EXAMPLES:**

```python
sage: # needs sage.combinat sage.modules
sage: A = ModulesWithBasis(ZZ).Filtered().example()
sage: x = A(Partition((3,2,1)))
sage: y = A(Partition((4,4,1)))
sage: z = A(Partition((2,2,2)))
sage: (3*x).is_homogeneous()    # True
sage: (x - y).is_homogeneous()  # False
sage: (x+2*z).is_homogeneous()  # True
```

Here is an example with a graded algebra:

```python
sage: # needs sage.combinat sage.modules
sage: S = NonCommutativeSymmetricFunctions(QQ).S()
sage: (x, y) = (S[2], S[3])
sage: (3*x).is_homogeneous()    # True
sage: (x^3 - y^2).is_homogeneous()  # True
sage: ((x + y)^2).is_homogeneous()  # False
```

Let us now test a filtered algebra (but remember that the notion of homogeneity now depends on the choice of a basis, or at least on a definition of homogeneous components):

```python
sage: A = AlgebrasWithBasis(QQ).Filtered().example()
sage: x,y,z = A.algebra_generators()
sage: (x*y).is_homogeneous()    # True
sage: (y*x).is_homogeneous()   # False
sage: A.one().is_homogeneous()  # True
sage: A.zero().is_homogeneous() # True
sage: (A.one()+x).is_homogeneous()  # False
```
**maximal_degree()**

The maximum of the degrees of the homogeneous components of *self*.

This is also the smallest $i$ such that *self* belongs to $F_i$. Hence, it does not depend on the basis of the parent of *self*.

See also:

`homogeneous_degree()`

**EXAMPLES:**

```python
sage: # needs sage.combinat sage.modules
sage: A = ModulesWithBasis(ZZ).Filtered().example()
sage: x = A(Partition((3,2,1)))
sage: y = A(Partition((4,4,1)))
sage: z = A(Partition((2,2,2)))
sage: x.maximal_degree()  # doctest: +NORMALIZE_WHITESPACE
6
sage: (x + 2*z).maximal_degree()  # doctest: +NORMALIZE_WHITESPACE
6
sage: (y - x).maximal_degree()  # doctest: +NORMALIZE_WHITESPACE
9
sage: (3*z).maximal_degree()  # doctest: +NORMALIZE_WHITESPACE
6
```

Now, we test this on a graded algebra:

```python
sage: # needs sage.combinat sage.modules
sage: S = NonCommutativeSymmetricFunctions(QQ).S()
sage: (x, y) = (S[2], S[3])
sage: x.maximal_degree()  # doctest: +NORMALIZE_WHITESPACE
2
sage: (x^3 + 4*y^2).maximal_degree()  # doctest: +NORMALIZE_WHITESPACE
6
sage: ((1 + x)^3).maximal_degree()  # doctest: +NORMALIZE_WHITESPACE
6
```

Let us now test a filtered algebra:

```python
sage: # needs sage.combinat sage.modules
sage: A = AlgebrasWithBasis(QQ).Filtered().example()
sage: x,y,z = A.algebra_generators()
sage: (x*y).maximal_degree()  # doctest: +NORMALIZE_WHITESPACE
2
sage: (y*x).maximal_degree()  # doctest: +NORMALIZE_WHITESPACE
2
sage: A.one().maximal_degree()  # doctest: +NORMALIZE_WHITESPACE
0
sage: A.zero().maximal_degree()  # doctest: +NORMALIZE_WHITESPACE
Traceback (most recent call last):
  ...
ValueError: the zero element does not have a well-defined degree
sage: (A.one()+x).maximal_degree()  # doctest: +NORMALIZE_WHITESPACE
1
```

**truncate**(n)

Return the sum of the homogeneous components of degree strictly less than *n* of *self*.

See `homogeneous_component()` for the notion of a homogeneous component.
EXAMPLES:

```python
sage: # needs sage.combinat sage.modules
sage: A = ModulesWithBasis(ZZ).Filtered().example()
sage: x = A.an_element(); x
sage: x.truncate(0)
0
sage: x.truncate(1)
2*P[]
sage: x.truncate(2)
sage: x.truncate(3)

sage: A = ModulesWithBasis(ZZ).Graded().example()
sage: x = A.an_element(); x
sage: x.truncate(0)
0
sage: x.truncate(1)
2*P[]
sage: x.truncate(2)
sage: x.truncate(3)

sage: A = AlgebrasWithBasis(ZZ).Filtered().example()
sage: G = A.algebra_generators()
sage: g = A.an_element() - 2 * G['x'] * G['y']; g
U['x']^2*U['y']^2*U['z']^3 - 2*U['x']*U['y'] + 2*U['x'] + 3*U['y'] + 1
sage: g.truncate(-1)
0
sage: g.truncate(0)
0
sage: g.truncate(2)
2*U['x'] + 3*U['y'] + 1
sage: g.truncate(3)
-2*U['x']*U['y'] + 2*U['x'] + 3*U['y'] + 1
sage: g.truncate(5)
-2*U['x']*U['y'] + 2*U['x'] + 3*U['y'] + 1
sage: g.truncate(7)
-2*U['x']*U['y'] + 2*U['x'] + 3*U['y'] + 1
sage: g.truncate(8)
U['x']^2*U['y']^2*U['z']^3 - 2*U['x']*U['y'] + 2*U['x'] + 3*U['y'] + 1
```

class FiniteDimensional(base_category):
    Bases: CategoryWithAxiom_over_base_ring

class ParentMethods:
    Bases: object

    hilbert_series(prec=None)

        Return the Hilbert series of self as a polynomial.

        Let R be a commutative ring (with unit). Let \( M = \bigcup_{n=0}^{\infty} M_n \) be a filtered R-module. The Hilbert
series of $M$ is the formal power series

$$H(t) = \sum_{n=0}^{\infty} \ell(M_n/M_{n-1})t^n,$$

where $\ell(N)$ is the length of $N$, which is the longest chain of submodules (over $R$), and by convention $M_{-1} = \{0\}$. By the assumptions of the category, $M_n/M_{n-1}$ is a free $R$-module, and so $\ell(M_n/M_{n-1})$ is equal to the rank of $M_n/M_{n-1}$.

**EXAMPLES:**

```sage
sage: OS = hyperplane_arrangements.braid(3).orlik_solomon_algebra(QQ)
sage: OS.hilbert_series()
2*t^2 + 3*t + 1
sage: OS = matroids.Uniform(5, 3).orlik_solomon_algebra(ZZ)
sage: OS.hilbert_series()
t^3 + 3*t^2 + 3*t + 1
sage: OS = matroids.PG(2, 3).orlik_solomon_algebra(ZZ['x','y'])
sage: OS.hilbert_series()
27*t^3 + 39*t^2 + 13*t + 1
```

class ParentMethods

Bases: object

**basis**(\(d=\text{None}\))

Return the basis for (the \(d\)-th homogeneous component of) self.

**INPUT:**

- \(d\) – (optional, default None) nonnegative integer or None

**OUTPUT:**

If \(d\) is None, returns the basis of the module. Otherwise, returns the basis of the homogeneous component of degree \(d\) (i.e., the subfamily of the basis of the whole module which consists only of the basis vectors lying in \(F_d \setminus \bigcup_{i<d} F_i\)).

The basis is always returned as a family.

**EXAMPLES:**

```sage
sage: A = ModulesWithBasis(ZZ).Filtered().example()
sage: A.basis(4)
Lazy family (Term map from Partitions to An example of a filtered module with basis: the free module on partitions over Integer Ring(i))_{i in Partitions of the integer 4}
```

Without arguments, the full basis is returned:

```sage
sage: A.basis()
Lazy family (Term map from Partitions to An example of a filtered module with basis: the free module on partitions over Integer Ring(i))_{i in Partitions}
sage: A.basis()
Lazy family (Term map from Partitions to An example of a filtered module with basis: the free module on partitions over Integer Ring(i))_{i in Partitions}
```

Checking this method on a filtered algebra. Note that this will typically raise a `NotImplementedError` when this feature is not implemented.
Without arguments, the full basis is returned:

```python
sage: A.basis()
Lazy family (Term map from Free abelian monoid indexed by {'x', 'y', 'z'} to An example of a filtered algebra with basis: the universal enveloping algebra of Lie algebra of RR^3 with cross product over Integer Ring(i))_{i in Free abelian monoid indexed by {'x', 'y', 'z'}}
```

An example with a graded algebra:

```python
sage: E.<x,y> = ExteriorAlgebra(QQ)
sage: E.basis()
Lazy family (Term map from Subsets of {0,1} to The exterior algebra of rank 2 over Rational Field(i))_{i in Subsets of {0,1}}
```

**from_graded_conversion()**

Return the inverse of the canonical $R$-module isomorphism $A \rightarrow \text{gr} A$ induced by the basis of $A$ (where $A = \text{"self"}$). This inverse is an isomorphism $\text{gr} A \rightarrow A$.

This is an isomorphism of $R$-modules. See the class documentation AssociatedGradedAlgebra.

See also:

**to_graded_conversion()**

EXAMPLES:

```python
sage: # needs sage.combinat sage.modules
tsage: A = Modules(QQ).WithBasis().Filtered().example()
tsage: p = -2 * A.an_element(); p
tsage: q = A.to_graded_conversion()(p); q
-4*Bbar[[]] - 4*Bbar[[1]] - 6*Bbar[[2]]
tsage: A.from_graded_conversion()(q) == p
True
tsage: q.parent() is A.graded_algebra()
True
```

**graded_algebra()**

Return the associated graded module to self.

See AssociatedGradedAlgebra for the definition and the properties of this.

If the filtered module self with basis is called $A$, then this method returns $\text{gr} A$. The method `to_graded_conversion()` returns the canonical $R$-module isomorphism $A \rightarrow \text{gr} A$ induced by the basis of $A$, and the method `from_graded_conversion()` returns the inverse of this isomorphism. The method `projection()` projects elements of $A$ onto $\text{gr} A$ according to their place in the filtration on $A$. 

4.43. Filtered Modules With Basis
**Warning:** When not overridden, this method returns the default implementation of an associated graded module – namely, \( \text{AssociatedGradedAlgebra}(\text{self}) \), where \( \text{AssociatedGradedAlgebra} \) is \( \text{AssociatedGradedAlgebra} \). But some instances of \( \text{FilteredModulesWithBasis} \) override this method, as the associated graded module often is (isomorphic) to a simpler object (for instance, the associated graded module of a graded module can be identified with the graded module itself). Generic code that uses associated graded modules (such as the code of the \( \text{induced_graded_map()} \) method below) should make sure to only communicate with them via the \( \text{to_graded_conversion()}, \text{from_graded_conversion()} \) and \( \text{projection()} \) methods (in particular, do not expect there to be a conversion from \( \text{self} \) to \( \text{self.graded_algebra()} \); this currently does not work for Clifford algebras). Similarly, when overriding \( \text{graded_algebra()} \), make sure to accordingly redefine these three methods, unless their definitions below still apply to your case (this will happen whenever the basis of your \( \text{graded_algebra()} \) has the same indexing set as \( \text{self} \), and the partition of this indexing set according to degree is the same as for \( \text{self} \)).

**EXAMPLES:**

```
sage: A = ModulesWithBasis(ZZ).Filtered().example()
sage: A.graded_algebra()
Graded Module of An example of a filtered module with basis:
the free module on partitions over Integer Ring
```

**hilbert_series** (\( \text{prec=None} \))

Return the Hilbert series of \( \text{self} \).

Let \( R \) be a commutative ring (with unit). Let \( M = \bigcup_{n=0}^{\infty} M_n \) be a filtered \( R \)-module. The Hilbert series of \( M \) is the formal power series

\[
H(t) = \sum_{n=0}^{\infty} \ell(M_n/M_{n-1}) t^n,
\]

where \( \ell(N) \) is the length of \( N \), which is the longest chain of submodules (over \( R \)), and by convention \( M_{-1} = \{0\} \). By the assumptions of the category, \( M_n/M_{n-1} \) is a free \( R \)-module, and so \( \ell(M_n/M_{n-1}) \) is equal to the rank of \( M_n/M_{n-1} \).

**INPUT:**
- \( \text{prec} \) – (default: \( \infty \)) the precision

**OUTPUT:**

If the precision is finite, then this returns an element in the \( \text{PowerSeriesRing} \) over \( \text{ZZ} \). Otherwise it returns an element in the \( \text{LazyPowerSeriesRing} \) over \( \text{ZZ} \).

**EXAMPLES:**

```
sage: A = GradedModulesWithBasis(ZZ).example()
sage: A.hilbert_series()
1 + t + 2*t^2 + 3*t^3 + 5*t^4 + 7*t^5 + 11*t^6 + O(t^7)
sage: A.hilbert_series(10)
1 + t + 2*t^2 + 3*t^3 + 5*t^4 + 7*t^5 + 11*t^6 + 15*t^7 + 22*t^8 + 30*t^9 + O(t^10)
```

**homogeneous_component** (\( d \))

Return the \( d \)-th homogeneous component of \( \text{self} \).

**EXAMPLES:**
sage: A = GradedModulesWithBasis(ZZ).example()
sage: A.homogeneous_component(4)
Degree 4 homogeneous component of An example of a graded module
with basis: the free module on partitions over Integer Ring

homogeneous_component_basis(d)

Return a basis for the \( d \)-th homogeneous component of \( \text{self} \).

EXAMPLES:

sage: A = GradedModulesWithBasis(ZZ).example()
sage: A.homogeneous_component_basis(4)
Lazy family (Term map
from Partitions
to An example of a graded module with basis: the free module
on partitions over Integer Ring(i))_{i in Partitions of the integer\_\_\_->4}

sage: # needs sage.modules
cat = GradedModulesWithBasis(ZZ)
c = CombinatorialFreeModule(ZZ, ['a', 'b'], category=cat)
c.degree_on_basis = lambda x: 1 if x == 'a' else 2
c.homogeneous_component_basis(1)
Finite family {'a': B['a']}
c.homogeneous_component_basis(2)
Finite family {'b': B['b']}

induced_graded_map(other, f)

Return the graded linear map between the associated graded modules of \( \text{self} \) and \( \text{other} \) canonically induced by the filtration-preserving map \( f : \text{self} \to \text{other} \).

Let \( A \) and \( B \) be two filtered modules with basis, and let \((F_i)_{i \in I}\) and \((G_i)_{i \in I}\) be their filtrations. Let \( f : A \to B \) be a linear map which preserves the filtration (i.e., satisfies \( f(F_i) \subseteq G_i \) for all \( i \in I \)). Then, there is a canonically defined graded linear map \( \text{gr } f : \text{gr } A \to \text{gr } B \) which satisfies

\[
(\text{gr } f)(p_i(a)) = p_i(f(a)) \quad \text{for all } i \in I \text{ and } a \in F_i,
\]

where the \( p_i \) on the left hand side is the canonical projection from \( F_i \) onto the \( i \)-th graded component of \( \text{gr } A \), while the \( p_i \) on the right hand side is the canonical projection from \( G_i \) onto the \( i \)-th graded component of \( \text{gr } B \).

INPUT:

- \( \text{other} \) -- a filtered algebra with basis
- \( f \) -- a filtration-preserving linear map from \( \text{self} \) to \( \text{other} \) (can be given as a morphism or as a function)

OUTPUT:

The graded linear map \( \text{gr } f \).

EXAMPLES:

Example 1.

We start with the free \( \mathbb{Q} \)-module with basis the set of all partitions:

sage: A = Modules(QQ).WithBasis().Filtered().example(); A
An example of a filtered module with basis: the free module
(continues on next page)
Let us define a map from \( A \) to itself which acts on the basis by sending every partition \( \lambda \) to the sum of the conjugates of all partitions \( \mu \) for which \( \lambda / \mu \) is a horizontal strip:

```python
sage: def map_on_basis(lam):
   ....:   def mus(k):
   ....:       return lam.remove_horizontal_border_strip(k)
   ....:   return A.sum_of_monomials([Partition(mu).conjugate() for k in range(sum(lam) + 1) for mu in mus(k)])
```

We now compute \( \text{gr} f \)

```python
sage: grA = A.graded_algebra(); grA
Graded Module of An example of a filtered module with basis: the free module on partitions over Rational Field
```

Example 2.

We shall now construct \( \text{gr} f \) for a different map \( f \) out of the same \( A \); the new map \( f \) will lead into a graded algebra already, namely into the algebra of symmetric functions:

```python
sage: grf = A.induced_graded_map(A, f); grf
Generic endomorphism of Graded Module of An example of a filtered module with basis: the free module on partitions over Rational Field
```
The algebra $h$ of symmetric functions in the $h$-basis is already graded, so its associated graded algebra is implemented as itself:

```python
sage: # needs sage.combinat sage.modules
sage: grh = h.graded_algebra(); grh is h
True
sage: grf = A.induced_graded_map(h, f); grf
Generic morphism:
   From: Graded Module of An example of a filtered module with basis: the free module on partitions over Rational Field
   To: Symmetric Functions over Rational Field in the homogeneous basis
sage: grf(pp1)
h[1]
sage: grf(pp2)
h[1, 1]
sage: grf(pp321)
h[3, 2, 1]
sage: grf(pp2 - 3*pp1)
-3*h[1] + h[1, 1]
sage: grf(grA.zero())
0
```

Example 3.

After having had a graded module as the codomain, let us try to have one as the domain instead. Our new $f$ will go from $h$ to $A$:

```python
sage: # needs sage.combinat sage.modules
sage: def map_on_basis(lam): # redefining map_on_basis
    ....:     def mus(k):
    ....:         return lam.remove_horizontal_border_strip(k)
    ....:     return A.sum_of_monomials({Partition(mu).conjugate()
    ....:         for k in range(sum(lam) + 1)
    ....:         for mu in mus(k))
    ....:
    sage: f = h.module_morphism(on_basis=map_on_basis, codomain=h) # redefining f
sage: f(p1)
h[1] + h[1]
sage: f(p2)
h[1] + h[1] + h[1, 1]
sage: f(A.zero())
0
sage: f(p2 - 3*p1)
-2*h[1] + h[1, 1]
```

(continues on next page)
The construct $\text{gr}_f$ also makes sense when $f$ is a filtration-preserving map between graded modules.

Example 4.

The construct $\text{gr}_f$ also makes sense when $f$ is a filtration-preserving map between graded modules.
projection \( (i) \)

Return the \( i \)-th projection \( p_i : F_i \rightarrow G_i \) (in the notations of the class documentation AssociatedGradedAlgebra, where \( A = "\text{self}" \)).

This method actually does not return the map \( p_i \) itself, but an extension of \( p_i \) to the whole \( R \)-module \( A \). This extension is the composition of the \( R \)-module isomorphism \( A \rightarrow \text{gr} A \) with the canonical projection of the graded \( R \)-module \( \text{gr} A \) onto its \( i \)-th graded component \( G_i \). The codomain of this map is \( \text{gr} A \), although its actual image is \( G_i \). The map \( p_i \) is obtained from this map by restricting its domain to \( F_i \) and its image to \( G_i \).

EXAMPLES:

```sage
sage: # needs sage.combinat sage.modules
sage: A = Modules(ZZ).WithBasis().Filtered().example()
sage: p = -2 * A.an_element(); p
sage: q = A.projection(2)(p); q
-6*Bbar[[2]]
sage: q.parent() is A.graded_algebra()
True
sage: A.projection(3)(p)
0
```

to_graded_conversion()

Return the canonical \( R \)-module isomorphism \( A \rightarrow \text{gr} A \) induced by the basis of \( A \) (where \( A = "\text{self}" \)).

This is an isomorphism of \( R \)-modules. See the class documentation AssociatedGradedAlgebra.

See also:

from_graded_conversion()

EXAMPLES:

```sage
sage: # needs sage.combinat sage.modules
sage: A = Modules(QQ).WithBasis().Filtered().example()
sage: p = -2 * A.an_element(); p
sage: q = A.to_graded_conversion()(p); q
-4*Bbar[[1]] - 4*Bbar[[1]] - 6*Bbar[[2]]
sage: q.parent() is A.graded_algebra()
True
```
class Subobjects
    Bases: SubobjectsCategory

class ElementMethods
    Bases: object

degree()
    Return the degree of self.

    EXAMPLES:

    sage: # needs sage.modules
    sage: E.<x,y,z> = ExteriorAlgebra(QQ)
    sage: S = E.submodule([x + y, x*y - y*z, y])
    sage: B = S.basis()
    [x, y, x*y - y*z]
    sage: B[0].degree()
    1
    sage: B[1].degree()
    1
    sage: (B[0] + 3*B[1]).degree()
    1

    The degree of inhomogeneous elements is not defined (following the behavior of the exterior algebra):

    sage: (B[0] + B[2]).degree()          # needs sage.modules
    Traceback (most recent call last):
    ...
    ValueError: element is not homogeneous

    We can still get the maximal degree:

    sage: (B[0] + B[2]).maximal_degree()          # needs sage.modules
    2

    maximal_degree()
    The maximum of the degrees of the homogeneous components of self.
    This is also the smallest $i$ such that self belongs to $F_i$. Hence, it does not depend on the basis of
    the parent of self.
    See also:
    homogeneous_degree()

    EXAMPLES:

    sage: # needs sage.modules
    sage: E.<x,y,z> = ExteriorAlgebra(QQ)
    sage: F = E.submodule([-x*y + 1, x*y + x])
    sage: B = F.basis()
    sage: [B[0].lift(), B[1].lift()]
    [-x*y + 1, x*y + x]
    sage: B[0].maximal_degree()          # needs sage.modules
    2
    (continues on next page)
class ParentMethods

Bases: object

degree_on_basis(m)

Return the degree of the basis element indexed by m in self.

EXAMPLES:

```
sage: B[1].maximal_degree()
sage: B[1].maximal_degree()
2
```

4.44 Finite Complex Reflection Groups

class sage.categories.finite_complex_reflection_groups.FiniteComplexReflectionGroups(base_category)

Bases: CategoryWithAxiom

The category of finite complex reflection groups.

See ComplexReflectionGroups for the definition of complex reflection group. In the finite case, most of the information about the group can be recovered from its degrees and codegrees, and to a lesser extent to the explicit realization as subgroup of $GL(V)$. Hence the most important optional methods to implement are:

- ComplexReflectionGroups.Finite.ParentMethods.degrees(),
- ComplexReflectionGroups.Finite.ParentMethods.codegrees(),
- ComplexReflectionGroups.Finite.ElementMethods.to_matrix().

Finite complex reflection groups are completely classified. In particular, if the group is irreducible, then it's uniquely determined by its degrees and codegrees and whether it's reflection representation is primitive or not (see [LT2009] Chapter 2.1 for the definition of primitive).

See also:

Wikipedia article Complex_reflection_groups

EXAMPLES:

```
sage: from sage.categories.complex_reflection_groups import...
sage: ComplexReflectionGroups()
sage: ComplexReflectionGroups().Finite()
```

(continues on next page)
Category of finite complex reflection groups

```
sage: ComplexReflectionGroups().Finite().super_categories()
```

```
[Category of complex reflection groups,
 Category of finite groups,
 Category of finite finitely generated semigroups]
```

An example of a finite reflection group:

```
sage: W = ComplexReflectionGroups().Finite().example(); W
```

Reducible real reflection group of rank 4 and type $A_2 \times B_2$

```
sage: W.reflections()
```

Finite family

```
{1: (1,8)(2,5)(9,12), 2: (1,5)(2,9)(8,12),
  3: (3,10)(4,7)(11,14), 4: (3,6)(4,11)(10,13),
  5: (1,9)(2,8)(5,12), 6: (4,14)(6,13)(7,11),
  7: (3,13)(6,10)(7,14)}
```

$W$ is in the category of complex reflection groups:

```
sage: W in ComplexReflectionGroups().Finite() # optional - gap3
True
```

class ElementMethods

Bases: object

```
character_value()
```

Return the value at self of the character of the reflection representation given by `to_matrix()`.

EXAMPLES:

```
sage: W = ColoredPermutations(1,3); W
```

1-colored permutations of size 3

```
sage: [t.character_value() for t in W]               # optional - gap3
```

```
[3, 1, 1, 0, 0, 1]
```

Note that this could be a different (faithful) representation than that given by the corresponding root system:

```
sage: W = ReflectionGroup(((1,1,3)); W
```

Irreducible real reflection group of rank 2 and type $A_2$

```
sage: [t.character_value() for t in W]               # optional - gap3
```

```
[2, 0, 0, -1, -1, 0]
```

```
sage: W = ColoredPermutations(2,2); W
```

2-colored permutations of size 2

```
sage: [t.character_value() for t in W]               # optional - gap3
```

```
[2, 0, 0, -2, 0, 0, 0, 0]
```

```
sage: W = ColoredPermutations(3,1); W
```

3-colored permutations of size 1

```
sage: [t.character_value() for t in W]               # optional - gap3
```

```
[3, 1, 1, 0, 0, 1]
```

(continues on next page)
reflection_length (in_unitary_group=False)

Return the reflection length of self.

This is the minimal numbers of reflections needed to obtain self.

INPUT:

• in_unitary_group – (default: False) if True, the reflection length is computed in the unitary group which is the dimension of the move space of self

EXAMPLES:

```python
sage: W = ReflectionGroup((1, 1, 3))  # optional - gap3
eeds sage.combinat sage.groups
[1, zeta3, -zeta3 - 1]
sage: sorted([t.reflection_length() for t in W])  # optional - gap3
[0, 1, 1, 1, 2, 2]
sage: W = ReflectionGroup((2, 1, 2))  # optional - gap3
sage: sorted([t.reflection_length() for t in W])  # optional - gap3
[0, 1, 1, 1, 2, 2, 2]
sage: W = ReflectionGroup((2, 2, 2))  # optional - gap3
sage: sorted([t.reflection_length() for t in W])  # optional - gap3
[0, 1, 1, 2]
sage: W = ReflectionGroup((3, 1, 2))  # optional - gap3
sage: sorted([t.reflection_length() for t in W])  # optional - gap3
[0, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2]
```

to_matrix()

Return the matrix presentation of self acting on a vector space $V$.

EXAMPLES:

```python
sage: W = ReflectionGroup((1, 1, 3))  # optional - gap3
sage: sorted([t.to_matrix() for t in W])  # optional - gap3
[1 0
 0 1
 0 0
[-1 0
[0 1
[-1 -1]
0 1]
[0 -1]],
[0 1, [0 -1], [1 1], [1 0], [-1 -1], [-1 0]]
]
sage: W = ColoredPermutations(1, 3)  # needs sage.combinat
sage: sorted([t.to_matrix() for t in W])
[1 0 0
 0 1 0
[1 0 0]
[0 0 1]
[0 1 0]
[0 1 0]
[1 0 0]
[0 0 1]
[0 1 0],
[0 0 1], [0 1 0], [0 1 0], [1 0 0], [1 0 0]
]
```

A different representation is given by the colored permutations:

```python
sage: W = ColoredPermutations(3, 1)  # needs sage.combinat
sage: sorted([t.to_matrix() for t in W])
```

(continues on next page)
class **Irreducible** *(base_category)*
Bases: `CategoryWithAxiom`

class **ParentMethods**
Bases: `object`

**absolute_order_ideal** *(gens=None, in_unitary_group=True, return_lengths=False)*

Return all elements in `self` below given elements in the absolute order of `self`.

This order is defined by

\[ \omega \leq_R \tau \iff \ell_R(\omega) + \ell_R(\omega^{-1}\tau) = \ell_R(\tau), \]

where \( \ell_R \) denotes the reflection length.

This is, if `in_unitary_group` is `False`, then

\[ \ell_R(w) = \min \{ \ell : w = r_1 \cdots r_\ell, r_i \in R \}, \]

and otherwise

\[ \ell_R(w) = \dim \text{im}(w - 1). \]

**Note:** If `gens` are not given, `self` is assumed to be well-generated.

**INPUT:**
- `gens` – (default: `None`) if one or more elements are given, the order ideal in the absolute order generated by `gens` is returned. Otherwise, the standard Coxeter element is used as unique maximal element.
- `in_unitary_group` (default: `True`) determines the length function used to compute the order. For real groups, both possible orders coincide, and for complex non-real groups, the order in the unitary group is much faster to compute.
- `return_lengths` (default: `False`) whether or not to also return the lengths of the elements.

**EXAMPLES:**

```python
sage: W = ReflectionGroup((1,1,3)) # optional - gap3
sage: sorted(W.reduced_word()) # optional - gap3
[[], [1], [1, 2], [1, 2, 1], [2]]
sage: sorted(W.reduced_word()) # optional - gap3
[[], [1], [1, 2, 1], [2], [2, 1]]
sage: sorted(W.reduced_word()) # optional - gap3
[[], [2]]
sage: W = CoxeterGroup(['A', 3]) # optional - gap3
```
Absolute poset (in_unitary_group=False)

Return the poset induced by the absolute order of self as a finite lattice.

INPUT:
• in_unitary_group - (default: False) if False, the relation is given by \( \sigma \leq \tau \) if \( l_R(\sigma) + l_R(\sigma^{-1} \tau) = l_R(\tau) \) if True, the relation is given by \( \sigma \leq \tau \) if \( \dim(\text{Fix}(\sigma)) + \dim(\text{Fix}(\sigma^{-1} \tau)) = \dim(\text{Fix}(\tau)) \)

See also:
noncrossing_partition_lattice()

Examples:

sage: P = ReflectionGroup((1,1,3)).absolute_poset(); P # optional...

Finite poset containing 6 elements

sage: sorted(w.reduced_word() for w in P) # optional...

[[], [1], [1, 2], [1, 2, 1], [2], [2, 1]]

sage: W = ReflectionGroup(4); W # optional...

Irreducible complex reflection group of rank 2 and type ST4

sage: W.absolute_poset() # optional...

Finite poset containing 24 elements

coxeter_number()

Return the Coxeter number of an irreducible reflection group.

This is defined as \( \frac{N + N^*}{n} \) where \( N \) is the number of reflections, \( N^* \) is the number of reflection hyperplanes, and \( n \) is the rank of self.

Examples:

sage: W = ReflectionGroup(31) # optional - gap3
sage: W.coxeter_number() # optional - gap3
30

generalized_noncrossing_partitions (m, c=None, positive=False)
Return the set of all chains of length \( m \) in the noncrossing partition lattice of \( \text{self} \), see `noncrossing_partition_lattice()`.

**Note:** \( \text{self} \) is assumed to be well-generated.

**INPUT:**

- \( c \) – (default: \( \text{None} \)) if an element \( c \) in \( \text{self} \) is given, it is used as the maximal element in the interval
- \( \text{positive} \) – (default: \( \text{False} \)) if \( \text{True} \), only those generalized noncrossing partitions of full support are returned

**EXAMPLES:**

```python
sage: W = ReflectionGroup((1,1,3))  # optional
˓→ gap3
sage: chains = W.generalized_noncrossing_partitions(2)  # optional
˓→ gap3
sage: sorted([w.reduced_word() for w in chain]  # optional
˓→ gap3
....: for chain in chains)
[[], [], [1, 2]],
[[], [1], [2]],
[[], [1, 2], []],
[[], [1, 2, 1], [1]],
[[], [2], [1, 2, 1]],
[[1], [], [2]],
[[1], [2], []],
[[1, 2], [], []],
[[1, 2, 1], [1], []],
[[1, 2, 1], [], []],
[[2], [], []]]
```

```python
sage: chains = W.generalized_noncrossing_partitions(2,  # optional
˓→ gap3
....: positive=True)
˓→ gap3
....: for chain in chains)
[[], [], [1, 2]],
[[], [1], [2]],
[[], [1, 2, 1], [1]],
[[1], [2], []],
[[1, 2], [], []],
[[1, 2, 1], [1], []],
[[1, 2, 1], [], []],
[[2], [], []]]
```

`noncrossing_partition_lattice(c=None, L=None, in_unitary_group=True)`

Return the interval \([1, c]\) in the absolute order of \( \text{self} \) as a finite lattice.

**See also:**

`absolute_order_ideal()`

**INPUT:**
• \(c\) — (default: None) if an element \(c\) in \(self\) is given, it is used as the maximal element in the interval

• \(L\) — (default: None) if a subset \(L\) (must be hashable!) of \(self\) is given, it is used as the underlying set (only cover relations are checked).

• \(\text{in\_unitary\_group}\) — (default: False) if False, the relation is given by \(\sigma \leq \tau\) if \(l_R(\sigma) + l_R(\sigma^{-1}) = l_R(\tau)\); if True, the relation is given by \(\sigma \leq \tau\) if \(\dim(\text{Fix}(\sigma)) + \dim(\text{Fix}(\sigma^{-1})) = \dim(\text{Fix}(\tau))\)

**Note:** If \(L\) is given, the parameter \(c\) is ignored.

### EXAMPLES:

```python
sage: W = SymmetricGroup(4)  # needs sage.combinat sage.groups
sage: W.noncrossing_partition_lattice()  # needs sage.combinat sage.groups
Finite lattice containing 14 elements

sage: W = WeylGroup(['G', 2])  # needs sage.combinat sage.groups
sage: W.noncrossing_partition_lattice()  # needs sage.combinat sage.groups
Finite lattice containing 8 elements

sage: W = ReflectionGroup((1,1,3))  # optional - gap3
sage: sorted(w.reduced_word()  # optional - gap3
....: for w in W.noncrossing_partition_lattice())
[[], [1], [1, 2], [1, 2, 1], [2]]

sage: c21 = W.from_reduced_word([2,1])  # optional - gap3
sage: sorted(w.reduced_word()  # optional - gap3
....: for w in W.noncrossing_partition_lattice(c21))
[[], [1], [1, 2, 1], [2], [2, 1]]

sage: c2 = W.from_reduced_word([2])  # optional - gap3
sage: sorted(w.reduced_word()  # optional - gap3
....: for w in W.noncrossing_partition_lattice(c2))
[[], [2]]
```

**example()**

Return an example of an irreducible complex reflection group.

**EXAMPLES:**

```python
sage: from sage.categories.complex_reflection_groups import ComplexReflectionGroups
sage: C = ComplexReflectionGroups().Finite().Irreducible()
sage: C.example()  # optional - gap3
Irreducible complex reflection group of rank 3 and type G(4,2,3)
```

### class ParentMethods

**Bases:** object

**base_change_matrix()**

Return the base change from the standard basis of the vector space of \(self\) to the basis given by the independent roots of \(self\).
Todo: For non-well-generated groups there is a conflict with construction of the matrix for an element.

EXAMPLES:

```python
sage: W = ReflectionGroup((1,1,3))  # optional - gap3
sage: W.base_change_matrix()         # optional - gap3
[1 0]
[0 1]

sage: W = ReflectionGroup(23)        # optional - gap3
sage: W.base_change_matrix()         # optional - gap3
[1 0 0]
[0 1 0]
[0 0 1]

sage: W = ReflectionGroup((3,1,2))  # optional - gap3
sage: W.base_change_matrix()         # optional - gap3
[1 0]
[1 1]

sage: W = ReflectionGroup((4,2,2))  # optional - gap3
sage: W.base_change_matrix()         # optional - gap3
[ 1 0]
[E(4) 1]
```

cardinality()

Return the cardinality of self.

It is given by the product of the degrees of self.

EXAMPLES:

```python
sage: # needs sage.combinat sage.groups
sage: W = ColoredPermutations(1,3)
```

```
6
```

```python
sage: W = ColoredPermutations(2,3)
```

```
48
```

```python
sage: W = ColoredPermutations(4,3)
```

```
384
```

```python
sage: # optional - gap3, needs sage.combinat sage.groups
sage: W = ReflectionGroup((4,2,3))
```

```
192
```

codegrees()

Return the codegrees of self.

OUTPUT: a tuple of Sage integers

EXAMPLES:

```python
sage: W = ColoredPermutations(1,4)  # needs sage.combinat
```

(continues on next page)
degrees()

Return the degrees of self.

OUTPUT: a tuple of Sage integers

EXAMPLES:

```sage
sage: W = ColoredPermutations(1, 4)
# needs sage.combinat
sage: W.degrees()
# needs sage.combinat
(2, 3, 4)

sage: W = ColoredPermutations(3, 3)
# needs sage.combinat
sage: W.degrees()
# needs sage.combinat
(3, 6, 9)

sage: W = ReflectionGroup(31)
# optional - gap3
sage: W.degrees()
# optional - gap3
(28, 16, 12, 0)
```

is_real()

Return whether self is real.

A complex reflection group is real if it is isomorphic to a reflection group in $GL(V)$ over a real vector space $V$. Equivalently its character table has real entries.

This implementation uses the following statement: an irreducible complex reflection group is real if and only if 2 is a degree of self with multiplicity one. Hence, in general we just need to compare the number of occurrences of 2 as degree of self and the number of irreducible components.

EXAMPLES:

```sage
sage: W = ColoredPermutations(1, 3)
# needs sage.combinat
sage: W.is_real()
# needs sage.combinat
True

sage: W = ColoredPermutations(4, 3)
# needs sage.combinat
```

(continues on next page)
Todo: Add an example of non real finite complex reflection group that is generated by order 2 reflections.

is_well_generated()
Return whether self is well-generated.

A finite complex reflection group is well generated if the number of its simple reflections coincides with its rank.

See also:
ComplexReflectionGroups.Finite.WellGenerated()

Note:
• All finite real reflection groups are well generated.
• The complex reflection groups of type $G(r, 1, n)$ and of type $G(r, r, n)$ are well generated.
• The complex reflection groups of type $G(r, p, n)$ with $1 < p < r$ are not well generated.
• The direct product of two well generated finite complex reflection group is still well generated.

EXAMPLES:

sage: W = ColoredPermutations(1,3)  #...
needs sage.combinat
sage: W.is_well_generated()  #...
needs sage.combinat
True

sage: W = ColoredPermutations(4,3)  #...
needs sage.combinat
sage: W.is_well_generated()  #...
needs sage.combinat
True

sage: W = ReflectionGroup((4,2,3))
sage: W.is_well_generated()  # optional - gap3, needs sage.combinat sage.groups
False

sage: W = ReflectionGroup((4,4,3))
sage: W.is_well_generated()  # optional - gap3, needs sage.combinat sage.groups
True

milnor_fiber_poset()
Return the Milnor fiber poset of self.

The Milnor fiber poset of a finite complex reflection group $W$ is defined as the poset of (right) standard cosets $gWJ$, where $J$ is a subset of the index set $I$ of $W$, ordered by reverse inclusion. This is conjecturally a meet semilattice if and only if $W$ is well-generated.

EXAMPLES:
sage: W = ColoredPermutations(3, 2)
sage: P = W.milnor_fiber_poset()
```
Finite meet-semilattice containing 34 elements
```
sage: R.<x> = ZZ[]
sage: sum(x**P.rank(elt) for elt in P)
```
18*x^2 + 15*x + 1
```
sage: # optional - gap3
sage: W = ReflectionGroup(4)
sage: P = W.milnor_fiber_poset(); P
```
Finite meet-semilattice containing 41 elements
```
sage: sum(x**P.rank(elt) for elt in P)
```
24*x^2 + 16*x + 1
```
sage: # optional - gap3
sage: W = ReflectionGroup([4,2,2])
sage: W.is_well_generated()
False
sage: P = W.milnor_fiber_poset(); P
```
Finite poset containing 47 elements
```
sage: sum(x**P.rank(elt) for elt in P)
```
16*x^3 + 24*x^2 + 6*x + 1
sage: P.is_meet_semilattice()
False
```

number_of_reflection_hyperplanes()

Return the number of reflection hyperplanes of self.

This is also the number of distinguished reflections. For real groups, this coincides with the number of reflections.

This implementation uses that it is given by the sum of the codegrees of self plus its rank.

See also:

number_of_reflections()

EXAMPLES:

```
sage: # needs sage.combinat
sage: W = ColoredPermutations(1,3)
sage: W.number_of_reflection_hyperplanes()
3
sage: W = ColoredPermutations(2,3)
sage: W.number_of_reflection_hyperplanes()
9
sage: W = ColoredPermutations(4,3)
sage: W.number_of_reflection_hyperplanes()
15
sage: W = ReflectionGroup((4,2,3))  # optional - gap3
sage: W.number_of_reflection_hyperplanes()  # optional - gap3
15
```

number_of_reflections()

Return the number of reflections of self.

For real groups, this coincides with the number of reflection hyperplanes.

This implementation uses that it is given by the sum of the degrees of self minus its rank.
See also:

\texttt{number\_of\_reflection\_hyperplanes()}

EXAMPLES:

```python
sage: [SymmetricGroup(i).number_of_reflections() for i in range(int(8))] # needs sage.groups
[0, 0, 1, 3, 6, 10, 15, 21]

sage: W = ColoredPermutations(1,3)
sage: W.number_of_reflections()  # needs sage.combinat sage.groups
3

sage: W = ColoredPermutations(2,3)
sage: W.number_of_reflections()  # needs sage.combinat sage.groups
9

sage: W = ColoredPermutations(4,3)
sage: W.number_of_reflections()  # needs sage.combinat sage.groups
21

sage: W = ReflectionGroup((4,2,3))  # optional - gap3
sage: W.number_of_reflections()  # optional - gap3
15
```

\texttt{rank()}

Return the rank of \texttt{self}.

The rank of \texttt{self} is the dimension of the smallest faithful reflection representation of \texttt{self}.

This default implementation uses that the rank is the number of \texttt{degrees()}.

See also:

ComplexReflectionGroups.rank()

EXAMPLES:

```python
sage: W = ColoredPermutations(1,3)
sage: W.rank()  # needs sage.combinat sage.groups
2

sage: W = ColoredPermutations(2,3)
sage: W.rank()  # needs sage.combinat sage.groups
3

sage: W = ColoredPermutations(4,3)
sage: W.rank()  # needs sage.combinat sage.groups
3

sage: W = ReflectionGroup((4,2,3))  # optional - gap3, needs sage.combinat sage.groups
sage: W.rank()  # optional - gap3
3
```

class SubcategoryMethods

Bases: object

WellGenerated()

Return the full subcategory of well-generated objects of \texttt{self}.  

Chapter 4. Individual Categories
A finite complex generated group is \emph{well generated} if it is isomorphic to a subgroup of the general linear group $GL_n$ generated by $n$ reflections.

See also:

ComplexReflectionGroups.Finite.ParentMethods.is_well_generated()

EXAMPLES:

```python
sage: from sage.categories.complex_reflection_groups import ComplexReflectionGroups
sage: C = ComplexReflectionGroups().Finite().WellGenerated(); C
Category of well generated finite complex reflection groups

Here is an example of a finite well-generated complex reflection group:

```python
sage: W = C.example(); W
# optional - gap3
Reducible complex reflection group of rank 4 and type A2 x G(3,1,2)
```

All finite Coxeter groups are well generated:

```python
sage: CoxeterGroups().Finite().is_subcategory(C)
True
sage: SymmetricGroup(3) in C
# needs sage.groups
True
```

Note: The category of well generated finite complex reflection groups is currently implemented as an axiom. See discussion on \url{github issue #11187}. This may be a bit of overkill. Still it’s nice to have a full subcategory.

```python
class WellGenerated(base_category):
    Bases: CategoryWithAxiom

class Irreducible(base_category):
    Bases: CategoryWithAxiom

The category of finite irreducible well-generated finite complex reflection groups.

class ParentMethods
    Bases: object

    catalan_number (positive=False, polynomial=False)

    Return the Catalan number associated to self.

    It is defined by

    $$\prod_{i=1}^{n} \frac{d_i + h}{d_i},$$

    where $d_1, \ldots, d_n$ are the degrees and where $h$ is the Coxeter number. See [Ar2006] for further information.

    INPUT:

    • positive – optional boolean (default False) if True, return instead the positive Catalan number

    • polynomial – optional boolean (default False) if True, return instead the $q$-analogue as a polynomial in $q$
```
Note:
- For the symmetric group \( S_n \), it reduces to the Catalan number \( \frac{1}{n+1} \binom{2n}{n} \).
- The Catalan numbers for \( G(r,1,n) \) all coincide for \( r > 1 \).

EXAMPLES:

```python
sage: [ColoredPermutations(1,n).catalan_number() for n in [3,4,5]]
[5, 14, 42]

sage: [ColoredPermutations(2,n).catalan_number() for n in [3,4,5]]
[20, 70, 252]

sage: [ReflectionGroup((2,2,n)).catalan_number() for n in [3,4,5]]
[14, 50, 182]
```

coxeter_number()

Return the Coxeter number of a well-generated, irreducible reflection group. This is defined to be the order of a regular element in \( \text{self} \), and is equal to the highest degree of \( \text{self} \).

See also:
ComplexReflectionGroups.Finite.Irreducible()

Note: This method overwrites the more general method for complex reflection groups since the expression given here is quicker to compute.

EXAMPLES:

```python
sage: W = ColoredPermutations(1,3)

sage: W.coxeter_number()
3

sage: W = ColoredPermutations(4,3)

sage: W.coxeter_number()
12

sage: W = ReflectionGroup((4,4,3))

sage: W.coxeter_number()
8
```

fuss_catalan_number \((m, \text{positive}=False, \text{polynomial}=False)\)

Return the \( m \)-th Fuss-Catalan number associated to \( \text{self} \).

This is defined by

\[
\prod_{i=1}^{n} \frac{d_i + mh}{d_i},
\]
where \(d_1, \ldots, d_n\) are the degrees and \(h\) is the Coxeter number.

INPUT:
- **positive** – optional boolean (default False) if True, return instead the positive Fuss-Catalan number
- **polynomial** – optional boolean (default False) if True, return instead the \(q\)-analogue as a polynomial in \(q\)

See [Ar2006] for further information.

**Note:**
- For the symmetric group \(S_n\), it reduces to the Fuss-Catalan number \(\frac{1}{mh+1} \binom{m+1}{n}\).
- The Fuss-Catalan numbers for \(G(r, 1, n)\) all coincide for \(r > 1\).

**EXAMPLES:**

```sage
sage: W = ColoredPermutations(1,3)
  # needs sage.combinat
sage: [W.fuss_catalan_number(i) for i in [1,2,3]]
  # needs sage.combinat
[5, 12, 22]

sage: W = ColoredPermutations(1,4)
  # needs sage.combinat
sage: [W.fuss_catalan_number(i) for i in [1,2,3]]
  # needs sage.combinat
[14, 55, 140]

sage: W = ColoredPermutations(1,5)
  # needs sage.combinat
sage: [W.fuss_catalan_number(i) for i in [1,2,3]]
  # needs sage.combinat
[42, 273, 969]

sage: W = ColoredPermutations(2,2)
  # needs sage.combinat
sage: [W.fuss_catalan_number(i) for i in [1,2,3]]
  # needs sage.combinat
[6, 15, 28]

sage: W = ColoredPermutations(2,3)
  # needs sage.combinat
sage: [W.fuss_catalan_number(i) for i in [1,2,3]]
  # needs sage.combinat
[20, 84, 220]

sage: W = ColoredPermutations(2,4)
  # needs sage.combinat
sage: [W.fuss_catalan_number(i) for i in [1,2,3]]
  # needs sage.combinat
[70, 495, 1820]
```

**number_of_reflections_of_full_support()**

Return the number of reflections with full support.

**EXAMPLES:**
sage: W = Permutations(4)
sage: W.number_of_reflections_of_full_support()
1

sage: W = ColoredPermutations(1,4)  # needs sage.combinat
sage: W.number_of_reflections_of_full_support()
1

sage: W = CoxeterGroup("B3")  # needs sage.combinat sage.groups
sage: W.number_of_reflections_of_full_support()  # needs sage.combinat sage.groups
3

sage: W = ColoredPermutations(3,3)  # needs sage.combinat
sage: W.number_of_reflections_of_full_support()  # needs sage.combinat
3

rational_catalan_number(p, polynomial=False)

Return the p-th rational Catalan number associated to self.

It is defined by

\[ \prod_{i=1}^{n} \frac{p + (p(d_i - 1))}{d_i} \mod h, \]

where \(d_1, \ldots, d_n\) are the degrees and \(h\) is the Coxeter number. See [STW2016] for this formula.

INPUT:

* polynomial – optional boolean (default False) if True, return instead the \(q\)-anologue as a polynomial in \(q\)

EXAMPLES:

sage: W = ColoredPermutations(1,3)  # needs sage.combinat
sage: [W.rational_catalan_number(p) for p in [5, 7, 8]]  # needs sage.combinat
[7, 12, 15]

sage: W = ColoredPermutations(2,2)  # needs sage.combinat
sage: [W.rational_catalan_number(p) for p in [7, 9, 11]]  # needs sage.combinat
[10, 15, 21]

element()

Return an example of an irreducible well-generated complex reflection group.

EXAMPLES:

sage: from sage.categories.complex_reflection_groups import ComplexReflectionGroups
sage: C = ComplexReflectionGroups().Finite().WellGenerated().Irreducible()
class ParentMethods
Bases: object
coxeter_element()

Return a Coxeter element.

The result is the product of the simple reflections, in some order.

Note: This implementation is shared with well generated complex reflection groups. It would be
nicer to put it in some joint super category; however, in the current state of the art, there is none
where it is clear that this is the right construction for obtaining a Coxeter element.

In this context, this is an element having a regular eigenvector (a vector not contained in any reflection
hyperplane of self).

EXAMPLES:

sage: # needs sage.combinat sage.groups
sage: CoxeterGroup(['A', 4]).coxeter_element().reduced_word()
[1, 2, 3, 4]
sage: CoxeterGroup(['B', 4]).coxeter_element().reduced_word()
[1, 2, 3, 4]
sage: CoxeterGroup(['D', 4]).coxeter_element().reduced_word()
[1, 2, 4, 3]
sage: CoxeterGroup(['F', 4]).coxeter_element().reduced_word()
[1, 2, 3, 4]
sage: CoxeterGroup(['E', 8]).coxeter_element().reduced_word()
[1, 3, 2, 4, 5, 6, 7, 8]
sage: CoxeterGroup(['H', 3]).coxeter_element().reduced_word()
[1, 2, 3]

This method is also used for well generated finite complex reflection groups:

sage: W = ReflectionGroup((1,1,4)) # optional - gap3
sage: W.coxeter_element().reduced_word() # optional - gap3
[1, 2, 3]
sage: W = ReflectionGroup((2,1,4)) # optional - gap3
sage: W.coxeter_element().reduced_word() # optional - gap3
[1, 2, 3, 4]
sage: W = ReflectionGroup((4,1,4)) # optional - gap3
sage: W.coxeter_element().reduced_word() # optional - gap3
[1, 2, 3, 4]
sage: W = ReflectionGroup((4,4,4)) # optional - gap3
sage: W.coxeter_element().reduced_word() # optional - gap3
[1, 2, 3, 4]

coxeter_elements()

Return the (unique) conjugacy class in self containing all Coxeter elements.
A Coxeter element is an element that has an eigenvalue $e^{2\pi j/h}$ where $h$ is the Coxeter number.

In case of finite Coxeter groups, these are exactly the elements that are conjugate to one (or, equivalently, all) standard Coxeter element, this is, to an element that is the product of the simple generators in some order.

See also:

`standard_coxeter_elements()`

**EXAMPLES:**

```python
sage: W = ReflectionGroup((1,1,3))  # optional - gap3
sage: sorted(c.reduced_word())       # optional - gap3
....:     for c in W.coxeter_elements()
[[1, 2], [2, 1]]
```

`is_well_generated()`

Return True as self is well-generated.

**EXAMPLES:**

```python
sage: W = ReflectionGroup((3,1,2))  # optional - gap3
sage: W.is_well_generated()          # optional - gap3
True
```

`milnor_fiber_complex()`

Return the Milnor fiber complex of self.

The Milnor fiber complex of a finite well-generated complex reflection group $W$ is the simplicial complex whose face poset is given by `milnor_fiber_poset()`. When $W$ is an irreducible Shephard group, it is also an equivariant strong deformation retract of the Milnor fiber $f_1^{-1}(1)$, where $f_1:V \to \mathbb{C}$ is the polynomial invariant of smallest degree acting on the reflection representation $V$.

When $W$ is a Coxeter group, this is isomorphic to the Coxeter complex of $W$.

**EXAMPLES:**

```python
sage: W = ColoredPermutations(3, 2)
sage: C = W.milnor_fiber_complex()
sage: C.homology()
{0: 0, 1: Z x Z x Z x Z x Z}
```

`standard_coxeter_elements()`

Return all standard Coxeter elements in self.

This is the set of all elements in self obtained from any product of the simple reflections in self.
• self is assumed to be well-generated.
• This works even beyond real reflection groups, but the conjugacy class is not unique and we only obtain one such class.

EXAMPLES:

```python
sage: W = ReflectionGroup(4)  # optional - gap3
sage: sorted(W.standard_coxeter_elements())  # optional - gap3
[(1,7,6,12,23,20)(2,8,17,24,9,5)(3,16,10,19,15,21)(4,14,11,22,18,13),
 (1,10,4,12,21,22)(2,11,19,24,13,3)(5,15,7,17,16,23)(6,18,8,20,14,9)]
```

```python
example()
Return an example of a well-generated complex reflection group.

EXAMPLES:

```python
sage: from sage.categories.complex_reflection_groups import ComplexReflectionGroups
sage: C = ComplexReflectionGroups().Finite().WellGenerated()
sage: C.example()  # optional - gap3
Reducible complex reflection group of rank 4 and type A2 x G(3,1,2)
```

example()
Return an example of a complex reflection group.

EXAMPLES:

```python
sage: from sage.categories.complex_reflection_groups import ComplexReflectionGroups
sage: ComplexReflectionGroups().Finite().example()  # optional - gap3
Reducible real reflection group of rank 4 and type A2 x B2
```

### 4.45 Finite Coxeter Groups

class sage.categories.finite_coxeter_groups.FiniteCoxeterGroups(base_category)

Bases: CategoryWithAxiom

The category of finite Coxeter groups.

EXAMPLES:

```python
sage: CoxeterGroups.Finite()
Category of finite Coxeter groups
sage: FiniteCoxeterGroups().super_categories()
[Category of finite generalized Coxeter groups,
 Category of Coxeter groups]
```

```python
sage: G = CoxeterGroups().Finite().example()
sage: G.cayley_graph(side = "right").plot()
Graphics object consisting of 40 graphics primitives
```

Here are some further examples:
sage: WeylGroups().Finite().example()
The symmetric group on (0, ..., 3)

sage: WeylGroup(["B", 3])
Weyl Group of type ['B', 3] (as a matrix group acting on the ambient space)

Those other examples will eventually be also in this category:

sage: SymmetricGroup(4)
Symmetric group of order 4! as a permutation group
sage: DihedralGroup(5)
Dihedral group of order 10 as a permutation group

class ElementMethods
Bases: object

absolute_length()
Return the absolute length of self.
The absolute length is the length of the shortest expression of the element as a product of reflections. For finite Coxeter groups, the absolute length is the codimension of the 1-eigenspace of the element (Lemmas 1-3 in [Car1972a]).
For permutations in the symmetric groups, the absolute length is the size minus the number of its disjoint cycles.
See also:
absolute_le()

EXAMPLES:

sage: W = WeylGroup(["A", 3])
#-- needs sage.combinat sage.groups
sage: s = W.simple_reflections()
#-- needs sage.combinat sage.groups
sage: (s[1]*s[2]*s[3]).absolute_length()
#-- needs sage.combinat sage.groups
3

sage: W = SymmetricGroup(4)
#-- needs sage.groups
sage: s = W.simple_reflections()
#-- needs sage.groups
sage: (s[3]*s[2]*s[1]).absolute_length()
#-- needs sage.combinat sage.groups
3

bruhat_upper_covers()
Returns all the elements that cover self in Bruhat order.

EXAMPLES:

sage: W = WeylGroup(["A",4])
sage: w = W.from_reduced_word([3,2])
sage: print([v.reduced_word() for v in w.bruhat_upper_covers()])
[[4, 3, 2], [3, 4, 2], [2, 3, 2], [3, 1, 2], [3, 2, 1]]

(continues on next page)
Recursive algorithm: write $w$ for $\textbf{self}$. If $i$ is a non-descent of $w$, then the covers of $w$ are exactly
\{ $ws_i, u_1s_i, u_2s_i, \ldots, u_js_i$ \}, where the $u_k$ are those covers of $ws_i$ that have a descent at $i$.

covered_reflections_subgroup()

Return the subgroup of $W$ generated by the conjugates by $w$ of the simple reflections indexed by right descents of $w$.

This is used to compute the shard intersection order on $W$.

EXAMPLES:

```python
sage: W = CoxeterGroup(['A',3], base_ring=ZZ)
sage: len(W.long_element().covered_reflections_subgroup())
24
sage: s = W.simple_reflection(1)
sage: Gs = s.covered_reflections_subgroup()
sage: len(Gs)
2
sage: s in [u.lift() for u in Gs]
True
sage: len(W.one().covered_reflections_subgroup())
1
```

coxeter_knuth_graph()

Return the Coxeter-Knuth graph of type $A$.

The Coxeter-Knuth graph of type $A$ is generated by the Coxeter-Knuth relations which are given by
$aa + 1a \sim a + 1aa + 1$, $abc \sim acb$ if $b < a < c$ and $abc \sim bac$ if $a < c < b$.

EXAMPLES:

```python
sage: W = WeylGroup(['A',4], prefix='s')
sage: w = W.from_reduced_word([1,2,1,3,2])
sage: D = w.coxeter_knuth_graph()
sage: D.vertices(sort=True)
[(1, 2, 1, 3, 2), (1, 2, 3, 1, 2), (2, 1, 2, 3, 2), (2, 1, 3, 2, 3), ...
```

(continues on next page)
sage: D.edges(sort=True)
[((1, 2, 1, 3, 2), (1, 2, 3, 1, 2), None),
 (1, 2, 1, 3, 2), (2, 1, 2, 3, 2), None),
 ((2, 1, 2, 3, 2), (2, 1, 3, 2, 3), None),
 ((2, 1, 3, 2, 3), (2, 3, 1, 2, 3), None)]

sage: w = W.from_reduced_word([1, 3])
sage: D = w.coxeter_knuth_graph()
sage: D.vertices(sort=True)
[(1, 3), (3, 1)]

sage: D.edges(sort=False)
[]

coxeter_knuth_neighbor(w)
Return the Coxeter-Knuth (oriented) neighbors of the reduced word w of self.

INPUT:
• w – reduced word of self

The Coxeter-Knuth relations are given by

\[ a a + 1 a \sim a + 1 a a + 1, \]

\[ a b c \sim a c b \text{ if } b < a < c \]

and

\[ a b c \sim b a c \text{ if } a < c < b. \]

This method returns all neighbors of w under the Coxeter-Knuth relations
oriented from left to right.

EXAMPLES:

sage: W = WeylGroup(['A', 4], prefix='s')
sage: word = [1, 2, 1, 3, 2]
sage: w = W.from_reduced_word(word)
sage: w.coxeter_knuth_neighbor(word)
{(1, 2, 3, 1, 2), (2, 1, 2, 3, 2)}

sage: word = [1, 2, 1, 3, 2, 4, 3]
sage: w = W.from_reduced_word(word)
sage: w.coxeter_knuth_neighbor(word)
{(1, 2, 1, 3, 4, 2, 3), (1, 2, 3, 1, 2, 4, 3), (2, 1, 2, 3, 2, 4, 3)}

is_coxeter_element()
Return whether this is a Coxeter element.

This is, whether self has an eigenvalue \( e^{2\pi i / h} \) where h is the Coxeter number.

See also:

coxeter_elements()

EXAMPLES:

sage: W = CoxeterGroup(['A', 2])
sage: c = prod(W.gens())
sage: c.is_coxeter_element()
True

sage: W.one().is_coxeter_element()
False

sage: W = WeylGroup(['G', 2])
sage: c = prod(W.gens())
sage: c.is_coxeter_element()
True
class ParentMethods

Bases: object

Ambiguity resolution: the implementation of some_elements is preferable to that of FiniteGroups. The same holds for __iter__, although a breadth first search would be more natural; at least this maintains backward compatibility after github issue #13589.

bhz_poset()

Return the Bergeron-Hohlweg-Zabrocki partial order on the Coxeter group. This is a partial order on the elements of a finite Coxeter group $W$, which is distinct from the Bruhat order, the weak order and the shard intersection order. It was defined in [BHZ2005].

This partial order is not a lattice, as there is no unique maximal element. It can be succinctly defined as follows.

Let $u$ and $v$ be two elements of the Coxeter group $W$. Let $S(u)$ be the support of $u$. Then $u \leq v$ if and only if $v_{S(u)} = u$ (here $v = v^I v^J$ denotes the usual parabolic decomposition with respect to the standard parabolic subgroup $W_I$).

See also:

bruhat_poset(), shard_poset(), weak_poset()

EXAMPLES:

```
sage: W = CoxeterGroup(['A',3], base_ring=ZZ)
sage: P = W.bhz_poset(); P
Finite poset containing 24 elements
sage: P.relations_number()
103
sage: P.chain_polynomial()
34*q^4 + 90*q^3 + 79*q^2 + 24*q + 1
sage: len(P.maximal_elements())
13
```

bruhat_poset (facade=False)

Return the Bruhat poset of self.

See also:

bhz_poset(), shard_poset(), weak_poset()

EXAMPLES:

```
sage: W = WeylGroup(['A', 2])
sage: P = W.bruhat_poset()
sage: P
Finite poset containing 6 elements
sage: P.show()
```

Here are some typical operations on this poset:

```
sage: W = WeylGroup(['A', 3])
sage: P = W.bruhat_poset()
sage: u = W.from_reduced_word([3,1])
```
By default, the elements of $P$ are aware that they belong to $P$:

\begin{verbatim}
sage: P.an_element().parent()
Finite poset containing 24 elements
\end{verbatim}

If instead one wants the elements to be plain elements of the Coxeter group, one can use the `facade` option:

\begin{verbatim}
sage: P = W.bruhat_poset(facade = True)
sage: P.an_element().parent()
Weyl Group of type ['A', 3] (as a matrix group acting on the ambient space)
\end{verbatim}

See also: `Poset()` for more on posets and facade posets.

Todo:
- Use the symmetric group in the examples (for nicer output), and print the edges for a stronger test.
- The constructed poset should be lazy, in order to handle large / infinite Coxeter groups.

### `cambrian_lattice(c, on_roots=False)`

Return the $c$-Cambrian lattice on delta sequences.


Delta sequences are certain 2-colored minimal factorizations of $c$ into reflections.

**INPUT:**
- $c$ -- a standard Coxeter element in `self` (as a tuple, or as an element of `self`)
- `on_roots` (optional, default `False`) -- if `on_roots` is `True`, the lattice is realized on roots rather than on reflections. In order for this to work, the ElementMethod `reflection_to_root` must be available.

**EXAMPLES:**

\begin{verbatim}
sage: CoxeterGroup(['A', 2]).cambrian_lattice((1,2))
Finite lattice containing 5 elements
\end{verbatim}

\begin{verbatim}
sage: CoxeterGroup(['B', 2]).cambrian_lattice((1,2))
Finite lattice containing 6 elements
\end{verbatim}

\begin{verbatim}
sage: CoxeterGroup(['G', 2]).cambrian_lattice((1,2))
Finite lattice containing 8 elements
\end{verbatim}

### `codegrees()`

Return the codegrees of the Coxeter group.

These are just the degrees minus 2.
EXAMPLES:

```python
sage: CoxeterGroup(['A', 4]).codegrees()
(0, 1, 2, 3)
sage: CoxeterGroup(['B', 4]).codegrees()
(0, 2, 4, 6)
sage: CoxeterGroup(['D', 4]).codegrees()
(0, 2, 2, 4)
sage: CoxeterGroup(['F', 4]).codegrees()
(0, 4, 6, 10)
sage: CoxeterGroup(['E', 8]).codegrees()
(0, 6, 10, 12, 16, 18, 22, 28)
sage: CoxeterGroup(['H', 3]).codegrees()
(0, 4, 8)
sage: WeylGroup(["A",3], ["A",3], ["B",2]).codegrees()
(0, 1, 2, 0, 1, 2, 0, 2)
```

**coxeter_complex()**

Return the Coxeter complex of self.

Let $W$ be a Coxeter group, and let $X$ be the corresponding Tits cone, which is constructed as the $W$ orbit of the fundamental chamber in the reflection representation. The Coxeter complex of $W$ is the simplicial complex $(X \setminus \{0\})/\mathbb{R}_{>0}$. The face poset of this simplicial complex is given by the **coxeter_poset()**. When $W$ is a finite group, then the Coxeter complex is homeomorphic to an $(n - 1)$-dimensional sphere, where $n$ is the rank of $W$.

EXAMPLES:

```python
sage: W = CoxeterGroup(['A', 3])
sage: C = W.coxeter_complex()
sage: C
Simplicial complex with 14 vertices and 24 facets
sage: C.homology()
{0: 0, 1: 0, 2: \mathbb{Z}}

sage: W = WeylGroup(['B', 3])
sage: C = W.coxeter_complex()
sage: C
Simplicial complex with 26 vertices and 48 facets
sage: C.homology()
{0: 0, 1: 0, 2: \mathbb{Z}}

sage: W = CoxeterGroup(['I', 7])
sage: C = W.coxeter_complex()
sage: C
Simplicial complex with 14 vertices and 14 facets
sage: C.homology()
{0: 0, 1: \mathbb{Z}}

sage: W = CoxeterGroup(['H', 3])
sage: C = W.coxeter_complex()
sage: C
Simplicial complex with 62 vertices and 120 facets
sage: C.homology()
{0: 0, 1: 0, 2: \mathbb{Z}}

sage: # optional - gap3
```

(continues on next page)
sage: W = CoxeterGroup(['H', 3], implementation="permutation")
sage: C = W.coxeter_complex()
sage: C
Simplicial complex with 62 vertices and 120 facets
sage: C.homology()
{0: 0, 1: 0, 2: ℤ}

**coxeter_poset()**

Return the Coxeter poset of self.

Let $W$ be a Coxeter group. The **Coxeter poset** is defined as the set of (right) standard cosets $gW_J$, where $J$ is a subset of the index set $I$ of $W$, ordered by reverse inclusion.

This is equal to the face poset of the **Coxeter complex**.

**EXAMPLES:**

sage: W = CoxeterGroup(['A', 3])
sage: P = W.coxeter_poset()
sage: P
Finite meet-semilattice containing 75 elements
sage: P.rank()
3

sage: W = WeylGroup(['B', 3])
sage: P = W.coxeter_poset()
sage: P
Finite meet-semilattice containing 147 elements
sage: P.rank()
3

sage: W = CoxeterGroup(['I', 7])
sage: P = W.coxeter_poset()
sage: P
Finite meet-semilattice containing 29 elements
sage: P.rank()
2

sage: W = CoxeterGroup(['H', 3])
sage: P = W.coxeter_poset()
sage: P
Finite meet-semilattice containing 363 elements
sage: P.rank()
3

sage: # optional - gap3
sage: W = CoxeterGroup(['H', 3], implementation="permutation")

**degrees()**

Return the degrees of the Coxeter group.

The output is an increasing list of integers.

**EXAMPLES:**
sage: CoxeterGroup(['A', 4]).degrees()  
(2, 3, 4, 5)  
sage: CoxeterGroup(['B', 4]).degrees()  
(2, 4, 6, 8)  
sage: CoxeterGroup(['D', 4]).degrees()  
(2, 4, 4, 6)  
sage: CoxeterGroup(['F', 4]).degrees()  
(2, 6, 8, 12)  
sage: CoxeterGroup(['E', 8]).degrees()  
(2, 8, 12, 14, 18, 20, 24, 30)  
sage: CoxeterGroup(['H', 3]).degrees()  
(2, 6, 10)  
sage: WeylGroup([['A',3], ['A',3], ['B',2]]).degrees()  
(2, 3, 4, 2, 3, 4, 2, 4)

inversion_sequence(word)

Return the inversion sequence corresponding to the word in indices of simple generators of self.

If word corresponds to \([w_0, w_1, ... w_k]\), the output is \([w_0, w_0 w_1 w_0, ..., w_0 w_1 ... w_k ... w_1 w_0]\).

INPUT:

• word – a word in the indices of the simple generators of self.

EXAMPLES:

sage: CoxeterGroup(['A', 2]).inversion_sequence([1,2,1])  

\([[-1 1] \ [0 -1] \ [1 0] \ 
[0 1], [-1 0], [1 -1] \]

sage: [t.reduced_word() for t in CoxeterGroup(['A',3]).inversion_sequence([2,1,3,2,1,3])]  

\([[2], \ [1, 2, 1], \ [2, 3, 2], \ [1, 2, 3, 2, 1], \ [3], \ [1]]\)

is_real()

Return True since self is a real reflection group.

EXAMPLES:

sage: CoxeterGroup(['F',4]).is_real()  

True  
sage: CoxeterGroup(['H',4]).is_real()  

True

long_element(index_set=None, as_word=False)

Return the longest element of self, or of the parabolic subgroup corresponding to the given index_set.

INPUT:

• index_set – a subset (as a list or iterable) of the nodes of the Dynkin diagram; (default: all of them)
• as_word – boolean (default False). If True, then return instead a reduced decomposition of the longest element.

Should this method be called maximal_element? longest_element?

EXAMPLES:
One can require instead a reduced word for $w_0$:

```
sage: A3 = CoxeterGroup(['A', 3])
sage: A3.long_element(as_word=True)
[1, 2, 1, 3, 2, 1]
```

$m$-Cambrian lattice $(c, m=1, \text{on}_\text{roots}=False)$

Return the $m$-Cambrian lattice on $m$-delta sequences.


The $m$-delta sequences are certain $m$-colored minimal factorizations of $c$ into reflections.

**INPUT:**
- $c$ – a Coxeter element of `self` (as a tuple, or as an element of `self`)
- $m$ – a positive integer (optional, default 1)
- `on_roots` (optional, default False) – if `on_roots` is True, the lattice is realized on roots rather than on reflections. In order for this to work, the ElementMethod `reflection_to_root` must be available.

**EXAMPLES:**

```
sage: CoxeterGroup(['A',2]).m_cambrian_lattice((1,2))
Finite lattice containing 5 elements
sage: CoxeterGroup(['A',2]).m_cambrian_lattice((1,2),2)
Finite lattice containing 12 elements
```

permutahedron $(point=\text{None}, \text{base}_\text{ring}=\text{None})$

Return the permutahedron of `self`.

This is the convex hull of the point `point` in the weight basis under the action of `self` on the underlying vector space $V$.

**See also:**

permutahedron()

**INPUT:**
- `point` – optional, a point given by its coordinates in the weight basis (default is $(1,1,1,\ldots)$)
- `base_ring` – optional, the base ring of the polytope

**Note:** The result is expressed in the root basis coordinates.
Note: If function is too slow, switching the base ring to RDF will almost certainly speed things up.

EXAMPLES:

```python
sage: W = CoxeterGroup(['H',3], base_ring=RDF)
sage: W.permutahedron()
doctest:warning
...
UserWarning: This polyhedron data is numerically complicated; cdd could...
→ not convert between the inexact V and H representation without loss of...
→ data. The resulting object might show inconsistencies.
A 3-dimensional polyhedron in RDF^3 defined as the convex hull of 120...
→ vertices

sage: W = CoxeterGroup(['I',7])
sage: W.permutahedron()
A 2-dimensional polyhedron in AA^2 defined as the convex hull of 14...
→ vertices

sage: W.permutahedron(base_ring=RDF)
A 2-dimensional polyhedron in RDF^2 defined as the convex hull of 14...
→ vertices

sage: W = ReflectionGroup(['A',3])
# optional - gap3
sage: W.permutahedron()
# optional - gap3
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 24 vertices

sage: W = ReflectionGroup(['A',3],['B',2])
# optional - gap3
sage: W.permutahedron()
# optional - gap3
A 5-dimensional polyhedron in QQ^5 defined as the convex hull of 192...
→ vertices
```

**reflections_from_w0()**

Return the reflections of self using the inversion set of w_0.

**EXAMPLES:**
**shard_poset** *(side='right')*

Return the shard intersection order attached to $W$.

This is a lattice structure on $W$, introduced in [Rea2009]. It contains the noncrossing partition lattice, as the induced lattice on the subset of $c$-sortable elements.

The partial order is given by simultaneous inclusion of inversion sets and subgroups attached to every element.

The precise description used here can be found in [STW2018].

Another implementation for the symmetric group is available as `shard_poset()`.

See also:

- `bhz_poset()`, `bruhat_poset()`, `weak_poset()`

**EXAMPLES:**

```python
sage: W = CoxeterGroup(['A',3], base_ring=ZZ)
sage: SH = W.shard_poset(); SH
Finite lattice containing 24 elements
sage: SH.is_graded()
True
sage: SH.characteristic_polynomial()
q^3 - 11*q^2 + 23*q - 13
sage: SH.f_polynomial()
34*q^3 + 22*q^2 + q
```

**w0()**

Return the longest element of `self`.

This attribute is deprecated, use `long_element()` instead.

**EXAMPLES:**

```python
sage: D8 = FiniteCoxeterGroups().example(8)
sage: D8.w0
(1, 2, 1, 2, 1, 2, 1, 2)
sage: D3 = FiniteCoxeterGroups().example(3)
sage: D3.w0
(1, 2, 1)
```

**weak_lattice** *(side='right', facade=False)*

**INPUT:**
Returns the left (resp. right) poset for weak order. In this poset, \( u \) is smaller than \( v \) if some reduced word of \( u \) is a right (resp. left) factor of some reduced word of \( v \).

See also:

- `bhz_poset()`, `bruhat_poset()`, `shard_poset()`

**EXAMPLES:**

```python
sage: W = WeylGroup(['A', 2])
sage: P = W.weak_poset()
sage: P
Finite lattice containing 6 elements
sage: P.show()
```

This poset is in fact a lattice:

```python
sage: W = WeylGroup(['B', 3])
sage: P = W.weak_poset(side = "left")
sage: P.is_lattice()
True
```

so this method has an alias `weak_lattice()`:

```python
sage: W.weak_lattice(side = "left") is W.weak_poset(side = "left")
True
```

As a bonus feature, one can create the left-right weak poset:

```python
sage: W = WeylGroup(['A',2])
sage: P = W.weak_poset(side = "twosided")
sage: P.show()
sage: len(P.hasse_diagram().edges(sort=False))
8
```

This is the transitive closure of the union of left and right order. In this poset, \( u \) is smaller than \( v \) if some reduced word of \( u \) is a factor of some reduced word of \( v \). Note that this is not a lattice:

```python
sage: P.is_lattice()
False
```

By default, the elements of \( P \) are aware of that they belong to \( P \):

```python
sage: P.an_element().parent()
Finite poset containing 6 elements
```

If instead one wants the elements to be plain elements of the Coxeter group, one can use the `facade` option:

```python
sage: P = W.weak_poset(facade = True)
sage: P.an_element().parent()
Weyl Group of type ['A', 2] (as a matrix group acting on the ambient...
```

**See also:**

- `Poset()` for more on posets and facade posets.
Todo:
• Use the symmetric group in the examples (for nicer output), and print the edges for a stronger test.
• The constructed poset should be lazy, in order to handle large / infinite Coxeter groups.

weak_poset (side='right', facade=False)

INPUT:
• side = “left”, “right”, or “twosided” (default: “right”)
• facade = a boolean (default: False)

Returns the left (resp. right) poset for weak order. In this poset, **u** is smaller than **v** if some reduced word of **u** is a right (resp. left) factor of some reduced word of **v**.

See also:
bhz_poset(), bruhat_poset(), shard_poset()

EXAMPLES:

```
sage: W = WeylGroup(['A', 2])
sage: P = W.weak_poset()
sage: P
Finite lattice containing 6 elements
sage: P.show()

This poset is in fact a lattice:

```
sage: W = WeylGroup(['B', 3])
sage: P = W.weak_poset(side = "left")
sage: P.is_lattice()
True

so this method has an alias weak_lattice():

```
sage: W.weak_lattice(side = "left") is W.weak_poset(side = "left")
True
```

As a bonus feature, one can create the left-right weak poset:

```
sage: W = WeylGroup(['A',2])
sage: P = W.weak_poset(side = "twosided")
sage: P.show()
sage: len(P.hasse_diagram().edges(sort=False))
8
```

This is the transitive closure of the union of left and right order. In this poset, **u** is smaller than **v** if some reduced word of **u** is a factor of some reduced word of **v**. Note that this is not a lattice:

```
sage: P.is_lattice()
False
```

By default, the elements of **P** are aware of that they belong to **P**:

```
sage: P.an_element().parent()
Finite poset containing 6 elements
```

If instead one wants the elements to be plain elements of the Coxeter group, one can use the facade option:
Category Framework, Release 10.3

```python
sage: P = W.weak_poset(facade = True)
sage: P.an_element().parent()
Weyl Group of type ['A', 2] (as a matrix group acting on the ambient...
˓→space)
```

See also:

Poset() for more on posets and facade posets.

Todo:

- Use the symmetric group in the examples (for nicer output), and print the edges for a stronger test.
- The constructed poset should be lazy, in order to handle large / infinite Coxeter groups.

```python
extra_super_categories()
```

EXAMPLES:

```python
sage: CoxeterGroups().Finite().super_categories()
[Category of finite generalized Coxeter groups,
 Category of Coxeter groups]
```

4.46 Finite Crystals

class sage.categories.finite_crystals.FiniteCrystals(base_category)

Bases: CategoryWithAxiom_singleton

The category of finite crystals.

EXAMPLES:

```python
sage: C = FiniteCrystals()
sage: C
Category of finite crystals
sage: C.super_categories()
[Category of crystals, Category of finite enumerated sets]
sage: C.example()
Highest weight crystal of type A_3 of highest weight omega_1
```

class TensorProducts(category, *args)

Bases: TensorProductsCategory

The category of finite crystals constructed by tensor product of finite crystals.

```python
extra_super_categories()
```

EXAMPLES:

```python
sage: FiniteCrystals().TensorProducts().extra_super_categories()
[Category of finite crystals]
```

example (n=3)

Returns an example of highest weight crystals, as per Category.example().

EXAMPLES:
4.47 Finite dimensional algebras with basis

**Todo:**
- Quotients of polynomial rings.
- Quotients in general.
- Matrix rings.

**REFERENCES:**
- [CR1962]

```python
class Cellular(base_category):
    Bases: CategoryWithAxiom_over_base_ring

    Cellular algebras.

    Let $R$ be a commutative ring. A $R$-algebra $A$ is a cellular algebra if it has a cell datum, which is a tuple $(\Lambda, i, M, C)$, where $\Lambda$ is finite poset with order $\geq$, if $\mu \in \Lambda$ then $T(\mu)$ is a finite set and

    $$C: \prod_{\mu \in \Lambda} T(\mu) \times T(\mu) \to A; (\mu, s, t) \mapsto c_{st}^{\mu}$$

    is an injective map such that the following holds:
    - The set $\{ c_{st}^{\mu} | \mu \in \Lambda, s, t \in T(\mu) \}$ is a basis of $A$.
```
• If \( a \in A \) and \( \mu \in \Lambda, s, t \in T(\mu) \) then:

\[
a c^\mu_{st} = \sum_{u \in T(\mu)} r_a(s, u)c^\mu_{ut} \pmod{A > \mu},
\]

where \( A > \mu \) is spanned by

\[
\{ c^\nu_{ab} \mid \nu > \mu \text{ and } a, b \in T(\nu) \}.
\]

Moreover, the scalar \( r_a(s, u) \) depends only on \( a, s \) and \( u \) and, in particular, is independent of \( t \).

• The map \( \iota: A \rightarrow A; c^\mu_{st} \mapsto c^\mu_{ts} \) is an algebra anti-isomorphism.

A cellular basis for \( A \) is any basis of the form \( \{ c^\mu_{st} \mid \mu \in \Lambda, s, t \in T(\mu) \} \).

Note that in particular, the scalars \( r_a(u, s) \) in the second condition do not depend on \( t \).

REFERENCES:

• [GrLe1996]
• [KX1998]
• [Mat1999]
• Wikipedia article Cellular_algebra

class ElementMethods

    Bases: object

    cellular_involution()

        Return the cellular involution on self.

    EXAMPLES:

    sage: # needs sage.groups sage.modules
    sage: S = SymmetricGroupAlgebra(QQ, 4)
    sage: elt = S([[3,1,2,4]])
    sage: ci = elt.cellular_involution(); ci
    7/48*[1, 3, 2, 4] + 49/48*[2, 3, 1, 4] - 1/48*[3, 1, 2, 4] - 7/48*[3, 2, 1, 4]
    sage: ci.cellular_involution()
    [3, 1, 2, 4]

class ParentMethods

    Bases: object

    cell_module(mu, **kwds)

        Return the cell module indexed by \( \mu \).

    EXAMPLES:

    sage: S = SymmetricGroupAlgebra(QQ, 3)  # needs sage.groups sage.modules
    sage: S.cell_module(Partition([2,1]))  # needs sage.combinat sage.groups sage.modules
    Cell module indexed by [2, 1] of Cellular basis of
    Symmetric group algebra of order 3 over Rational Field
**cell_module_indices**(mu)

Return the indices of the cell module of self indexed by mu.

This is the finite set $M(\lambda)$.

**EXAMPLES:**

```python
sage: S = SymmetricGroupAlgebra(QQ, 3)  # needs sage.groups sage.modules
sage: S.cell_module_indices([2,1])  # needs sage.groups sage.modules
Standard tableaux of shape [2, 1]
```

**cell_poset()**

Return the cell poset of self.

**EXAMPLES:**

```python
sage: S = SymmetricGroupAlgebra(QQ, 4)  # needs sage.groups sage.modules
sage: S.cell_poset()  # needs sage.groups sage.modules
Finite poset containing 5 elements
```

**cells()**

Return the cells of self.

**EXAMPLES:**

```python
sage: S = SymmetricGroupAlgebra(QQ, 3)  # needs sage.groups sage.modules
sage: dict(S.cells())  # needs sage.groups sage.modules
{[1, 1, 1]: Standard tableaux of shape [1, 1, 1],
 [2, 1]: Standard tableaux of shape [2, 1],
 [3]: Standard tableaux of shape [3]}
```

**cellular_basis()**

Return the cellular basis of self.

**EXAMPLES:**

```python
sage: S = SymmetricGroupAlgebra(QQ, 3)  # needs sage.groups sage.modules
sage: S.cellular_basis()  # needs sage.groups sage.modules
Cellular basis of Symmetric group algebra of order 3 over Rational Field
```

**cellular_involution**(x)

Return the cellular involution of x in self.

**EXAMPLES:**

```python
sage: S = SymmetricGroupAlgebra(QQ, 3)  # needs sage.groups sage.modules
sage: for b in S.basis(): b, S.cellular_involution(b)  # needs sage.groups sage.modules
```
simple_module_parameterization()

Return a parameterization of the simple modules of self.

The set of simple modules are parameterized by \( \lambda \in \Lambda \) such that the cell module bilinear form \( \Phi_\lambda \neq 0 \).

**EXAMPLES:**

```
sage: S = SymmetricGroupAlgebra(QQ, 4)

sage: S.simple_module_parameterization()

([1, 2, 3], [1, 1, 1], [2, 1, 1], [2, 2], [3, 1], [4])
```

```sage
sage: S = SymmetricGroupAlgebra(GF(3), 4)

sage: S.simple_module_parameterization()

([2, 1, 1], [2, 2], [3, 1], [4])
```

```sage
sage: S = SymmetricGroupAlgebra(GF(4), 4)

sage: S.simple_module_parameterization()

([3, 1], [4])
```

```class TensorProducts (category, *args)

Bases: TensorProductsCategory

The category of cellular algebras constructed by tensor product of cellular algebras.
```

```class ParentMethods

Bases: object

cell_module_indices (mu)

Return the indices of the cell module of self indexed by mu.

This is the finite set \( M(\lambda) \).

**EXAMPLES:**

```
sage: S = SymmetricGroupAlgebra(QQ, 2)
sage: T = S2.tensor(S3)
sage: T.cell_module_indices([[1,1], [2,1]])

(continues on next page)```
The Cartesian product of (Standard tableaux of shape [1, 1],
Standard tableaux of shape [2, 1])

**cell_poset()**

Return the cell poset of self.

**EXAMPLES:**

```
sage: # needs sage.groups sage.modules
sage: S2 = SymmetricGroupAlgebra(QQ, 2)
sage: S3 = SymmetricGroupAlgebra(QQ, 3)
sage: T = S2.tensor(S3)
sage: T.cell_poset()  #...
```

```
Finite poset containing 6 elements
```

**cellular_involution()**

Return the image of the cellular involution of the basis element indexed by i.

**EXAMPLES:**

```
sage: # needs sage.groups sage.modules
sage: S2 = SymmetricGroupAlgebra(QQ, 2)
sage: S3 = SymmetricGroupAlgebra(QQ, 3)
sage: T = S2.tensor(S3)
sage: for b in T.basis(): b, T.cellular_involution(b)
```

```
([1, 2] # [1, 2, 3], [1, 2] # [1, 2, 3])
([1, 2] # [1, 2, 3], [1, 2] # [1, 2, 3])
([1, 2] # [1, 2, 3], [1, 2] # [1, 2, 3])
([1, 2] # [1, 2, 3], [1, 2] # [1, 2, 3])
([1, 2] # [1, 2, 3], [1, 2] # [1, 2, 3])
```

**extra_super_categories()**

Tensor products of cellular algebras are cellular.
class ElementMethods

    Bases: object

    on_left_matrix(base_ring=None, action=<built-in function mul>, side='left')

    Return the matrix of the action of self on the algebra.

    INPUT:
    • base_ring – the base ring for the matrix to be constructed
    • action – a bivariate function (default: operator.mul())
    • side – ‘left’ or ‘right’ (default: ‘left’)

    EXAMPLES:

    sage: # needs sage.groups sage.modules
    sage: QS3 = SymmetricGroupAlgebra(QQ, 3)
    sage: a = QS3([2,1,3])
    sage: a.on_left_matrix(side='left')
    [0 0 1 0 0 0]
    [0 0 0 0 1 0]
    [1 0 0 0 0 0]
    [0 0 0 0 0 1]
    [0 1 0 0 0 0]
    [0 0 1 0 0 0]
    sage: a.on_left_matrix(side='right')
    [0 0 1 0 0 0]
    [0 0 0 1 0 0]
    [1 0 0 0 0 0]
    [0 1 0 0 0 0]
    [0 0 0 0 0 1]
    [0 0 0 0 1 0]
    sage: a.on_matrix(base_ring=RDF, side="left")
    [[0.0 0.0 1.0 0.0 0.0 0.0]
     [0.0 0.0 0.0 0.0 1.0 0.0]
     [1.0 0.0 0.0 0.0 0.0 0.0]
     [0.0 0.0 0.0 0.0 0.0 1.0]
     [0.0 1.0 0.0 0.0 0.0 0.0]
     [0.0 0.0 0.0 1.0 0.0 0.0]]

    AUTHORS: Mike Hansen, ...

    to_matrix(base_ring=None, action=<built-in function mul>, side='left')

    Return the matrix of the action of self on the algebra.

    INPUT:
    • base_ring – the base ring for the matrix to be constructed
    • action – a bivariate function (default: operator.mul())
    • side – ‘left’ or ‘right’ (default: ‘left’)

    EXAMPLES:

    sage: # needs sage.groups sage.modules
    sage: QS3 = SymmetricGroupAlgebra(QQ, 3)
    sage: a = QS3([2,1,3])
    sage: a.to_matrix(base_ring=RDF, side="left")
    ([0.0 0.0 1.0 0.0 0.0 0.0]
     [0.0 0.0 0.0 0.0 1.0 0.0]
     [1.0 0.0 0.0 0.0 0.0 0.0]
     [0.0 0.0 0.0 0.0 0.0 1.0]
     [0.0 1.0 0.0 0.0 0.0 0.0]
     [0.0 0.0 0.0 1.0 0.0 0.0])

    (continues on next page)
AUTHORS: Mike Hansen, …

class ParentMethods

    Bases: object

    cartan_invariants_matrix()

    Return the Cartan invariants matrix of the algebra.

    OUTPUT: a matrix of non negative integers

    Let $A$ be this finite dimensional algebra and $(S_i)_{i \in I}$ be representatives of the right simple modules of $A$. Note that their adjoints $S_i^*$ are representatives of the left simple modules.

    Let $(P_L^i)_{i \in I}$ and $(P_R^i)_{i \in I}$ be respectively representatives of the corresponding indecomposable projective left and right modules of $A$. In particular, we assume that the indexing is consistent so that $S_i^* = \text{top} P_L^i$ and $S_i = \text{top} P_R^i$.

    The Cartan invariant matrix $(C_{i,j})_{i,j \in I}$ is a matrix of non negative integers that encodes much of the representation theory of $A$; namely:

    • $C_{i,j}$ counts how many times $S_i^* \otimes S_j$ appears as composition factor of $A$ seen as a bimodule over itself;
    • $C_{i,j} = \dim \text{Hom}_A(P_R^i, P_R^j)$;
    • $C_{i,j}$ counts how many times $S_j$ appears as composition factor of $P_R^i$;
    • $C_{i,j} = \dim \text{Hom}_A(P_L^i, P_L^j)$;
    • $C_{i,j}$ counts how many times $S_i^*$ appears as composition factor of $P_R^j$.

    In the commutative case, the Cartan invariant matrix is diagonal. In the context of solving systems of multivariate polynomial equations of dimension zero, $A$ is the quotient of the polynomial ring by the ideal generated by the equations, the simple modules correspond to the roots, and the numbers $C_{i,i}$ give the multiplicities of those roots.

    Note: For simplicity, the current implementation assumes that the index set $I$ is of the form $\{0, \ldots, n-1\}$. Better indexations will be possible in the future.

    ALGORITHM:
The Cartan invariant matrix of $A$ is computed from the dimension of the summands of its Peirce decomposition.

See also:

- `peirce_decomposition()`
- `isotypic_projective_modules()`

**EXAMPLES:**

For a semisimple algebra, in particular for group algebras in characteristic zero, the Cartan invariants matrix is the identity:

```python
sage: A3 = SymmetricGroup(3).algebra(QQ)  # needs sage.groups sage.modules
sage: A3.cartan_invariants_matrix()       # needs sage.groups sage.modules
[1 0 0]
[0 1 0]
[0 0 1]
```

For the path algebra of a quiver, the Cartan invariants matrix counts the number of paths between two vertices:

```python
sage: A = Algebras(QQ).FiniteDimensional().WithBasis().example()  
sage: A.cartan_invariants_matrix()                              # needs sage.modules sage.rings.number_field
[1 2]
[0 1]
```

In the commutative case, the Cartan invariant matrix is diagonal:

```python
sage: Z12 = Monoids().Finite().example(); Z12  
An example of a finite multiplicative monoid: the integers modulo 12
sage: A = Z12.algebra(QQ)                                    # needs sage.modules
sage: A.cartan_invariants_matrix()                           # needs sage.modules sage.rings.number_field
[1 0 0 0 0 0 0 0 0]
[0 1 0 0 0 0 0 0 0]
[0 0 2 0 0 0 0 0 0]
[0 0 0 1 0 0 0 0 0]
[0 0 0 0 2 0 0 0 0]
[0 0 0 0 0 1 0 0 0]
[0 0 0 0 0 0 1 0 0]
[0 0 0 0 0 0 0 2 0]
[0 0 0 0 0 0 0 0 1]
```

With the algebra of the 0-Hecke monoid:

```python
sage: A = HeckeMonoid(SymmetricGroup(4)).algebra(QQ)           # needs sage.combinat sage.groups sage.modules
sage: A.cartan_invariants_matrix()                             # needs sage.rings.number_field
[1 0 0 0 0 0 0 0]
[0 2 1 0 1 1 0 0]
[0 0 1 1 0 1 0 0]
[0 0 1 0 1 1 0 0]
```

(continues on next page)
center()

Return the center of self.

See also:

center_basis()

EXAMPLES:

sage: # needs sage.graphs sage.modules
sage: A = Algebras(QQ).FiniteDimensional().WithBasis().example(); A
An example of a finite dimensional algebra with basis: the path algebra of the Kronecker quiver (containing the arrows a:x->y and b:x->y) over Rational Field
sage: center = A.center(); center
Center of An example of a finite dimensional algebra with basis: the path algebra of the Kronecker quiver (containing the arrows a:x->y and b:x->y) over Rational Field
sage: center in Algebras(QQ).WithBasis().FiniteDimensional().Commutative()
True
sage: center.dimension()
1
sage: center.basis()
Finite family {0: B[0]}

The center of a semisimple algebra is semisimple:

sage: A = DihedralGroup(6).algebra(QQ)  # needs sage.groups sage.modules
sage: A.center() in Algebras(QQ).Semisimple()  # needs sage.groups sage.modules
True

Todo:

• Pickling by construction, as A.center()?
• Lazy evaluation of _repr_

center_basis()

Return a basis of the center of self.

OUTPUT:

• a list of elements of self.

See also:

center()

EXAMPLES:
An example of a finite dimensional algebra with basis:
the path algebra of the Kronecker quiver
(containing the arrows a:x->y and b:x->y) over Rational Field

\begin{verbatim}
A = Algebras(QQ).FiniteDimensional().WithBasis().example(); A
\end{verbatim}

\begin{verbatim}
S = A.semisimple_quotient()
x
y
\end{verbatim}

Todo: Add some non trivial example

The function `is_commutative()` returns whether `self` is a commutative algebra.

\begin{verbatim}
S4 = SymmetricGroupAlgebra(QQ, 4)
S4.is_commutative()
False
S2 = SymmetricGroupAlgebra(QQ, 2)
S2.is_commutative()
True
\end{verbatim}

The function `is_identity_decomposition_into_orthogonal_idempotents(l)` returns whether `l` is a decomposition of the identity into orthogonal idempotents.

\begin{verbatim}
\end{verbatim}
An example of a finite dimensional algebra with basis: the path algebra of the Kronecker quiver (containing the arrows a:x->y and b:x->y) over Rational Field:

(x, y, a, b)

Here the idempotents do not sum up to 1:

Here 1 + x and −x are neither idempotent nor orthogonal:

With the algebra of the 0-Hecke monoid:

Here are some more counterexamples:
1. Some orthogonal elements summing to 1 but not being idempotent:
....:     def product_on_basis(self, w1, w2):
....:         return self.from_vector(vector(w1 * w2))

sage: R.<x> = PolynomialRing(QQ)
sage: A = PQAlgebra(QQ, x**3 - x**2 + x + 1); y = A.x()
sage: a, b = y, 1 - y
sage: A.is_identity_decomposition_into_orthogonal_idempotents((a, b))
False

For comparison:

sage: # needs sage.libs.pari sage.modules
sage: A = PQAlgebra(QQ, x**2 - x); y = A.x()
sage: a, b = y, 1-y
sage: A.is_identity_decomposition_into_orthogonal_idempotents((a, b))
True
sage: A.is_identity_decomposition_into_orthogonal_idempotents((a, A.zero(), b))
True
sage: A = PQAlgebra(QQ, x**3 - x**2 + x - 1); y = A.x()
sage: a = (y**2 + 1) / 2
sage: b = 1 - a
sage: A.is_identity_decomposition_into_orthogonal_idempotents((a, b))
True

2. Some idempotents summing to 1 but not orthogonal:

sage: # needs sage.libs.pari sage.modules
sage: R.<x> = PolynomialRing(GF(2))
sage: A = PQAlgebra(GF(2), x)
sage: a = A.one()
sage: A.is_identity_decomposition_into_orthogonal_idempotents((a,))
True
sage: A.is_identity_decomposition_into_orthogonal_idempotents((a, a, a))
False

3. Some orthogonal idempotents not summing to the identity:

sage: # needs sage.libs.pari sage.modules
sage: A.is_identity_decomposition_into_orthogonal_idempotents((a,a))
False
sage: A.is_identity_decomposition_into_orthogonal_idempotents(())
False

**isotypic_projective_modules**(side='left')

Return the isotypic projective side self-modules.

Let $P_i$ be representatives of the indecomposable projective side-modules of this finite dimensional algebra $A$, and $S_i$ be the associated simple modules.

The regular side representation of $A$ can be decomposed as a direct sum $A = \bigoplus_i Q_i$ where each $Q_i$ is an isotypic projective module; namely $Q_i$ is the direct sum of dim $S_i$ copies of the indecomposable projective module $P_i$. This decomposition is not unique.

The isotypic projective modules are constructed as $Q_i = e_i A$, where the $(e_i)_i$ is the decomposition of the identity into orthogonal idempotents obtained by lifting the central orthogonal idempotents of the semisimple quotient of $A$.

**INPUT:**
• side – ‘left’ or ‘right’ (default: ‘left’)

OUTPUT: a list of subspaces of self.

EXAMPLES:

```python
sage: # needs sage.graphs sage.modules sage.rings.number_field
sage: A = Algebras(QQ).FiniteDimensional().WithBasis().example(); A
An example of a finite dimensional algebra with basis:
the path algebra of the Kronecker quiver
(containing the arrows a:x->y and b:x->y) over Rational Field
sage: Q = A.isotypic_projective_modules(side="left"); Q
[Free module generated by {0} over Rational Field,
 Free module generated by {0, 1, 2} over Rational Field]
sage: [[x.lift() for x in Qi.basis()]
 ....: for Qi in Q]
[[x],
[y, a, b]]
```

We check that the sum of the dimensions of the isotypic projective modules is the dimension of self:

```python
sage: sum([Qi.dimension() for Qi in Q]) == A.dimension() #...
True
```

See also:

• `orthogonal_idempotents_central_mod_radical()`
  • `peirce_decomposition()`

**orthogonal_idempotents_central_mod_radical()**

Return a family of orthogonal idempotents of self that project on the central orthogonal idempotents of the semisimple quotient.

OUTPUT:

• a list of orthogonal idempotents obtained by lifting the central orthogonal idempotents of the semisimple quotient.

ALGORITHM:

The orthogonal idempotents of \( A \) are obtained by lifting the central orthogonal idempotents of the semisimple quotient \( \overline{A} \).

Namely, let \((\overline{f_i})\) be the central orthogonal idempotents of the semisimple quotient of \( A \). We recursively construct orthogonal idempotents of \( A \) by the following procedure: assuming \((f_i)_{i<n}\) is a set of already constructed orthogonal idempotent, we construct \( f_k \) by idempotent lifting of \((1-f)g(1-f)\), where \( g \) is any lift of \( \overline{f_k} \) and \( f = \sum_{i<k} f_i \).

See [CR1962] for correctness and termination proofs.

See also:

  • `idempotent_lift()`

EXAMPLES:

```python
sage: # needs sage.graphs sage.modules
sage: A = Algebras(QQ).FiniteDimensional().WithBasis().example(); A
An example of a finite dimensional algebra with basis:
the path algebra of the Kronecker quiver
```

(continues on next page)
(containing the arrows a:x->y and b:x->y) over Rational Field

```
sage: A.orthogonal_idempotents_central_mod_radical()  # needs sage.rings.number_field
(x, y)
```

```sage
# needs sage.modules sage.rings.number_field
sage: Z12 = Monoids().Finite().example(); Z12
An example of a finite multiplicative monoid: the integers modulo 12
sage: A = Z12.algebra(QQ)
sage: idempotents = A.orthogonal_idempotents_central_mod_radical()
sage: sorted(idempotents, key=str)
 1/2*B[9] - 1/2*B[3],
 0]
sage: sum(idempotents) == 1
True
sage: all(e*e == e for e in idempotents)
True
sage: all(e*f == 0 and f*e == 0
....:    for e in idempotents for f in idempotents if e != f)
True
```

This is best tested with:

```
sage: A.is_identity_decomposition_into_orthogonal_idempotents(idempotents)  # needs sage.graphs sage.modules sage.rings.number_field
True
```

We construct orthogonal idempotents for the algebra of the 0-Hecke monoid:

```
sage: # needs sage.combinat sage.graphs sage.groups sage.modules
sage: from sage.monoids.hecke_monoid import HeckeMonoid
sage: A = HeckeMonoid(SymmetricGroup(4)).algebra(QQ)
sage: idempotents = A.orthogonal_idempotents_central_mod_radical()
sage: A.is_identity_decomposition_into_orthogonal_idempotents(idempotents)
True
```

```
sage: peirce_decomposition(idempotents=None, check=True)

Return a Peirce decomposition of self.

Let \((e_i)_i\) be a collection of orthogonal idempotents of \(A\) with sum 1. The Peirce decomposition of \(A\) is the decomposition of \(A\) into the direct sum of the subspaces \(e_i Ae_j\).

With the default collection of orthogonal idempotents, one has

\[
\dim e_i Ae_j = C_{i,j} \dim S_i \dim S_j
\]

where \((S_i)_i\) are the simple modules of \(A\) and \((C_{i,j})_{i,j}\) is the Cartan invariants matrix.

INPUT:
• idempotents – a list of orthogonal idempotents \((e_i)_{i=0,...,n}\) of the algebra that sum to 1 (default: the idempotents returned by orthogonal_idempotents_central_mod_radical())
• check – (default: True) whether to check that the idempotents are indeed orthogonal and idempotent and sum to 1

OUTPUT:
A list of lists \(l\) such that \(l[i][j]\) is the subspace \(e_iAe_j\).

See also:
• orthogonal_idempotents_central_mod_radical()
• cartan_invariants_matrix()

EXAMPLES:

```sage
sage: # needs sage.graphs sage.groups sage.modules sage.rings.number_field
sage: A = Algebras(QQ).FiniteDimensional().WithBasis().example(); A
An example of a finite dimensional algebra with basis:
the path algebra of the Kronecker quiver
(containing the arrows a:x->y and b:x->y) over Rational Field
sage: A.orthogonal_idempotents_central_mod_radical()
(x, y)
sage: decomposition = A.peirce_decomposition(); decomposition
[[Free module generated by {0} over Rational Field,
  Free module generated by {0, 1} over Rational Field],
 [Free module generated by {{} over Rational Field,
  Free module generated by {0} over Rational Field]]
sage: [ [x.lift() for x in decomposition[i][j].basis()]
  for j in range(2)]
[[[x], [a, b]],
[[], [y]]]
```

We recover that the group algebra of the symmetric group \(S_4\) is a block matrix algebra:

```sage
sage: # needs sage.groups sage.modules sage.rings.number_field
sage: A = SymmetricGroup(4).algebra(QQ)
```

```sage
sage: decomposition = A.peirce_decomposition()       # long time
sage: [ [decomposition[i][j].dimension()]
  for j in range(len(decomposition))]
[[9, 0, 0, 0, 0],
 [0, 9, 0, 0, 0],
 [0, 0, 4, 0, 0],
 [0, 0, 0, 1, 0],
 [0, 0, 0, 0, 1]]
```

The dimension of each block is \(d^2\), where \(d\) is the dimension of the corresponding simple module of \(S_4\). The latter are given by:

```sage
sage: [p.standard_tableaux().cardinality() for p in Partitions(4)]       # needs sage.combinat
[1, 3, 2, 3, 1]
```

\(peirce_summand\) \((e_i, e_j)\)
Return the Peirce decomposition summand \(e_iAe_j\).

INPUT:
• self – an algebra \(A\)
• $e_i, e_j$ – two idempotents of $A$
OUTPUT: $e_i A e_j$, as a subspace of $A$.

See also:
• `peirce_decomposition()`
• `principal_ideal()`

EXAMPLES:

```python
sage: A = Algebras(QQ).FiniteDimensional().WithBasis().example()
sage: idemp = A.orthogonal_idempotents_central_mod_radical()  # needs sage.rings.number_field
sage: A.peirce_summand(idemp[0], idemp[1])  # needs sage.rings.number_field
Free module generated by {0, 1} over Rational Field
sage: A.peirce_summand(idemp[1], idemp[0])  # needs sage.rings.number_field
Free module generated by {} over Rational Field
```

We recover the $2 \times 2$ block of $\mathbb{Q}[S_4]$ corresponding to the unique simple module of dimension 2 of the symmetric group $S_4$:

```python
sage: A4 = SymmetricGroup(4).algebra(QQ)  # needs sage.groups
sage: e = A4.central_orthogonal_idempotents()[2]  # needs sage.groups sage.rings.number_field
sage: A4.peirce_summand(e, e)  # needs sage.groups sage.rings.number_field
Free module generated by {0, 1, 2, 3} over Rational Field
```

`principal_ideal (a, side='left')`
Construct the side principal ideal generated by $a$.

EXAMPLES:

In order to highlight the difference between left and right principal ideals, our first example deals with a non commutative algebra:

```python
sage: # needs sage.graphs sage.modules
sage: A = Algebras(QQ).FiniteDimensional().WithBasis().example(); A
An example of a finite dimensional algebra with basis:
the path algebra of the Kronecker quiver
(containing the arrows $a:x \to y$ and $b:x \to y$) over Rational Field
sage: x, y, a, b = A.basis()
In this algebra, multiplication on the right by $x$ annihilates all basis elements but $x$:

```python
sage: x*x, y*x, a*x, b*x
(x, 0, 0, 0)
```

so the left ideal generated by $x$ is one-dimensional:

```python
sage: Ax = A.principal_ideal(x, side='left'); Ax
Free module generated by {0} over Rational Field
```

4.47. Finite dimensional algebras with basis 403
Multiplication on the left by \( x \) annihilates only \( x \) and fixes the other basis elements:

```
sage: x*x, x*y, x*a, x*b  # needs sage.graphs sage.modules
(x, 0, a, b)
```

so the right ideal generated by \( x \) is 3-dimensional:

```
sage: xA = A.principal_ideal(x, side='right'); xA  # needs sage.graphs sage.modules
Free module generated by {0, 1, 2} over Rational Field
sage: [B.lift() for B in xA.basis()]  # needs sage.graphs sage.modules
[x, a, b]
```

See also:
- `peirce_summand()`
- `radical()`

**radical()**

Return the Jacobson radical of \( \textit{self} \).

This uses `radical_basis()`, whose default implementation handles algebras over fields of characteristic zero or fields of characteristic \( p \) in which we can compute \( x^{1/p} \).

See also:
- `radical_basis()`, `semisimple_quotient()`

**EXAMPLES:**

```
sage: # needs sage.graphs sage.modules
sage: A = Algebras(QQ).FiniteDimensional().WithBasis().example(); A
An example of a finite dimensional algebra with basis:
the path algebra of the Kronecker quiver
(containing the arrows a:x->y and b:x->y) over Rational Field
sage: radical = A.radical(); radical
Radical of An example of a finite dimensional algebra with basis:
the path algebra of the Kronecker quiver
(containing the arrows a:x->y and b:x->y) over Rational Field
sage: radical.dimension()
2
sage: radical.basis()
Finite family {0: B[0], 1: B[1]}
sage: radical.ambient() is A
True
sage: [c.lift() for c in radical.basis()]  # needs sage.graphs sage.modules
[a, b]
```

The radical is an ideal of \( A \), and thus a finite dimensional non unital associative algebra:
Todo:
• Tell Sage that the radical is in fact an ideal;
• Pickling by construction, as $A.center()$;
• Lazy evaluation of $\_\_repr\_$. 

radical\_basis ()
Return a basis of the Jacobson radical of this algebra.

Note:  This implementation handles algebras over fields of characteristic zero (using Dixon’s lemma) or fields of characteristic $p$ in which we can compute $x^{1/p}$ [FR1985], [Eb1989].

OUTPUT:
• a list of elements of self.

See also:
radical(), Algebras.Semisimple

EXAMPLES:

```
sage: # needs sage.graphs sage.modules
sage: A = Algebras(QQ).FiniteDimensional().WithBasis().example(); A
An example of a finite dimensional algebra with basis:
the path algebra of the Kronecker quiver
(containing the arrows $a:x\rightarrow y$ and $b:x\rightarrow y$) over Rational Field
sage: A.radical_basis()
(a, b)
```

We construct the group algebra of the Klein Four-Group over the rationals:

```
sage: A = KleinFourGroup().algebra(QQ) #_

This algebra belongs to the category of finite dimensional algebras over the rationals:

```
sage: A in Algebras(QQ).FiniteDimensional().WithBasis()  #_
      --needs sage.groups sage.modules
True
```

Since the field has characteristic 0, Maschke’s Theorem tells us that the group algebra is semisimple. So its radical is the zero ideal:

```
sage: A in Algebras(QQ).Semisimple()  #_
      --needs sage.groups sage.modules
True
sage: A.radical_basis()  #_
      --needs sage.groups sage.modules
()
```

Let’s work instead over a field of characteristic 2:

```
sage: A = KleinFourGroup().algebra(GF(2))  #_

(continues on next page)
We now implement the algebra \( A = K[x]/(x^p - 1) \), where \( K \) is a finite field of characteristic \( p \), and check its radical; alas, we currently need to wrap \( A \) to make it a proper ModulesWithBasis:

```python
sage: # needs sage.modules
sage: class AnAlgebra(CombinatorialFreeModule):
....:     def __init__(self, F):
....:         R.<x> = PolynomialRing(F)
....:         I = R.ideal(x**F.characteristic()-F.one())
....:         self._xbar = R.quotient(I).gen()
....:         basis_keys = [self._xbar**i for i in range(F.characteristic())]
....:         CombinatorialFreeModule.__init__(self, F, basis_keys,
....:                                         category=Algebras(F).FiniteDimensional().WithBasis())
....:     def one(self):
....:         return self.basis()[self.base_ring().one()]
....:     def product_on_basis(self, w1, w2):
....:         return self.from_vector(vector(w1*w2))

sage: AnAlgebra(GF(3)).radical_basis()
(B[1] + 2*B[xbar^2], B[xbar] + 2*B[xbar^2])

sage: AnAlgebra(GF(16,'a')).radical_basis()  # needs sage.rings.finite_rings
(B[1] + B[xbar],)

sage: AnAlgebra(GF(49,'a')).radical_basis()  # needs sage.rings.finite_rings
```

**semisimple_quotient()**

Return the semisimple quotient of \( self \).

This is the quotient of \( self \) by its radical.

See also:

**radical()**

EXAMPLES:

```python
sage: # needs sage.graphs sage.modules
sage: A = Algebras(QQ).FiniteDimensional().WithBasis().example(); A
An example of a finite dimensional algebra with basis:
the path algebra of the Kronecker quiver
(containing the arrows a:x->y and b:x->y) over Rational Field

sage: a,b,x,y = sorted(A.basis())

sage: S = A.semisimple_quotient(); S
Semisimple quotient of An example of a finite dimensional algebra with basis:
the path algebra of the Kronecker quiver
(containing the arrows a:x->y and b:x->y) over Rational Field

sage: S in Algebras(QQ).Semisimple()
True
```

(continues on next page)
Sanity check: the semisimple quotient of the $n$-th descent algebra of the symmetric group is of dimension the number of partitions of $n$:

```
sage: [ DescentAlgebra(QQ,n).B().semisimple_quotient().dimension()  # needs sage.combinat sage.modules
   ....:   for n in range(6) ]
[1, 1, 2, 3, 5, 7]
sage: [Partitions(n).cardinality()  # needs sage.combinat
   ....:   for n in range(10)]
[1, 1, 2, 3, 5, 7, 11, 15, 22, 30]
```

Todo:
- Pickling by construction, as $A$.semisimple_quotient()?
- Lazy evaluation of `_repr_`

### class SubcategoryMethods
Bases: object

#### Cellular()
Return the full subcategory of the cellular objects of $self$.

See also:

Wikipedia article Cellular_algebra

**EXAMPLES:**

```
sage: Algebras(QQ).FiniteDimensional().WithBasis().Cellular()
Category of finite dimensional cellular algebras with basis
over Rational Field
```

## 4.48 Finite dimensional bialgebras with basis

The category of finite dimensional bialgebras with a distinguished basis

**EXAMPLES:**

```
sage: C = FiniteDimensionalBialgebrasWithBasis(QQ); C
Category of finite dimensional bialgebras with basis over Rational Field
sage: sorted(C.super_categories(), key=str)
[Category of bialgebras with basis over Rational Field,
 Category of finite dimensional algebras with basis over Rational Field]
sage: C is Bialgebras(QQ).WithBasis().FiniteDimensional()
True
```
4.49 Finite dimensional coalgebras with basis

The category of finite dimensional coalgebras with a distinguished basis

**EXAMPLES:**

```python
sage: C = FiniteDimensionalCoalgebrasWithBasis(QQ); C
Category of finite dimensional coalgebras with basis over Rational Field
sage: sorted(C.super_categories(), key=str)
[Category of coalgebras with basis over Rational Field,
 Category of finite dimensional vector spaces with basis over Rational Field]
```

4.50 Finite Dimensional Graded Lie Algebras With Basis

AUTHORS:

- Eero Hakavuori (2018-08-16): initial version

**EXAMPLES:**

```python
sage: C = LieAlgebras(ZZ).WithBasis().FiniteDimensional().Graded(); C
Category of finite dimensional graded Lie algebras with basis over Integer Ring
sage: C.is(Category of graded Lie algebras with basis over Integer Ring, 
    Category of finite dimensional filtered modules with basis over Integer Ring, 
    Category of finite dimensional Lie algebras with basis over Integer Ring)
True
```

**class ParentMethods**

**Bases:** `object`

**homogeneous_component_as_submodule**(*d*)

Return the *d*-th homogeneous component of `self` as a submodule.

**EXAMPLES:**

```python
sage: C = LieAlgebras(QQ).WithBasis().Graded()
```
class Stratified(base_category)

Bases: CategoryWithAxiom_over_base_ring

Category of finite dimensional stratified Lie algebras with a basis.

A stratified Lie algebra is a graded Lie algebra that is generated as a Lie algebra by its homogeneous component of degree 1. That is to say, for a graded Lie algebra $L = \bigoplus_{k=1}^{M} L_k$, we have $L_{k+1} = [L_1, L_k]$.

EXAMPLES:

```python
sage: C = LieAlgebras(QQ).WithBasis().Graded().Stratified().FiniteDimensional()
sage: C
Category of finite dimensional stratified Lie algebras with basis over Rational Field

A finite-dimensional stratified Lie algebra is nilpotent:

```python
sage: C is C.Nilpotent()
True
```

class ParentMethods

Bases: object

degree_on_basis($m$)

Return the degree of the basis element indexed by $m$.

If the degrees of the basis elements are not defined, they will be computed. By assumption the stratification $L_1 \oplus \cdots \oplus L_s$ of self is such that each component $L_k$ is spanned by some subset of the basis.

The degree of a basis element $X$ is therefore the largest index $k$ such that $X \in L_k \oplus \cdots \oplus L_s$. The space $L_k \oplus \cdots \oplus L_s$ is by assumption the $k$-th term of the lower central series.

EXAMPLES:

```python
sage: C = LieAlgebras(QQ).WithBasis().Graded().Stratified().Nilpotent()
sage: sc = {(X,Y): {Z: 1}}
sage: L.<X,Y,Z> = LieAlgebra(QQ, sc, nilpotent=True, category=C)
sage: L.degree_on_basis(X.leading_support())
1
sage: X.degree()
1
sage: Y.degree()
1
sage: L[X, Y]
Z
sage: Z.degree()
2
```
4.51 Finite dimensional Hopf algebras with basis

```python
class sage.categories.finite_dimensional_hopf_algebras_with_basis.FiniteDimensionalHopfAlgebrasWithBasis

Bases: CategoryWithAxiom_over_base_ring

The category of finite dimensional Hopf algebras with a distinguished basis.

EXAMPLES:
```

```python
sage: FiniteDimensionalHopfAlgebrasWithBasis(QQ)
Category of finite dimensional Hopf algebras with basis over Rational Field
sage: FiniteDimensionalHopfAlgebrasWithBasis(QQ).super_categories()

[Category of Hopf algebras with basis over Rational Field,
  Category of finite dimensional algebras with basis over Rational Field]
```

```python
class ElementMethods

Bases: object

class ParentMethods

Bases: object
```

4.52 Finite Dimensional Lie Algebras With Basis

AUTHORS:

- Travis Scrimshaw (07-15-2013): Initial implementation

```python
class sage.categories.finite_dimensional_lie_algebras_with_basis.FiniteDimensionalLieAlgebrasWithBasis

Bases: CategoryWithAxiom_over_base_ring

Category of finite dimensional Lie algebras with a basis.

Todo: Many of these tests should use non-abelian Lie algebras and need to be added after github issue #16820.

```python
class ElementMethods

Bases: object

```python
adjoint_matrix(sparse=False)

Return the matrix of the adjoint action of self.

EXAMPLES:
```
We verify that this forms a representation:

```sage
sage: # needs sage.combinat sage.modules
sage: sl3 = lie_algebras.sl(QQ, 3)
sage: e1, e2 = sl3.e(1), sl3.e(2)
sage: e12 = e1.bracket(e2)
sage: E1, E2 = e1.adjoint_matrix(), e2.adjoint_matrix()
sage: E1 * E2 - E2 * E1 == e12.adjoint_matrix()
True
```

### to_vector(order=None, sparse=False)

Return the vector in `g.module()` corresponding to the element `self` of `g` (where `g` is the parent of `self`).

Implement this if you implement `g.module()`. See `sage.categories.lie_algebras.LieAlgebras.module()` for how this is to be done.

**EXAMPLES:**

```sage
sage: # needs sage.combinat sage.modules
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()
sage: L.an_element().to_vector()
(0, 0, 0)
sage: L.an_element().to_vector(sparse=True)
(0, 0, 0)
sage: # needs sage.combinat sage.groups sage.modules
sage: D = DescentAlgebra(QQ, 4).D()
sage: L = LieAlgebra(associative=D)
sage: L.an_element().to_vector()
(1, 1, 1, 1, 1, 1, 1, 1)
```

### Nilpotent

alias of `FiniteDimensionalNilpotentLieAlgebrasWithBasis`

class ParentMethods

Bases: object

**as_finite_dimensional_algebra()**

Return `self` as a `FiniteDimensionalAlgebra`.

**EXAMPLES:**

```sage
sage: # needs sage.combinat sage.modules
sage: L = lie_algebras.cross_product(QQ)
sage: x, y, z = L.basis()
sage: F = L.as_finite_dimensional_algebra()
sage: X, Y, Z = F.basis()
```

(continues on next page)
Return the Casimir element in the universal enveloping algebra of `self`.

A Casimir element of order $k$ is a distinguished basis element for the center of $U(g)$ of homogeneous degree $k$ (that is, it is an element of $U_k \setminus U_{k-1}$, where $\{U_i\}_{i=0}^\infty$ is the natural filtration of $U(g)$). When $g$ is a simple Lie algebra, then this spans $Z(U(g))_k$.

**INPUT:**
- `order` – (default: 2) the order of the Casimir element
- `UEA` – (optional) the universal enveloping algebra to return the result in
- `force_generic` – (default: False) if True for the quadratic order, then this uses the default algorithm; otherwise this is ignored

**ALGORITHM:**

For the quadratic order (i.e., `order=2`), then this uses $K^{ij}$, the inverse of the Killing form matrix, to compute $C(2) = \sum_{i,j} K^{ij} X_i \cdots X_j$, where $\{X_1, \ldots, X_n\}$ is a basis for $g$. Otherwise this solves the system of equations

$$f_{a_1}^{b_1} K^{c_1 \cdots d} + f_{a_2}^{c} K^{d_2 \cdots d} + \cdots + f_{a_k}^{d_k} K^{b_1 \cdots b_k}$$

for the symmetric tensor $\kappa^{i_1 \cdots i_k}$, where $k$ is the order. This system comes from $[X_i, C(k)] = 0$ with

$$C(k) = \sum_{i_1, \ldots, i_k} \kappa^{i_1 \cdots i_k} X_{i_1} \cdots X_{i_k}.$$
Todo: Use the symmetry of the tensor to reduce the number of equations and/or variables to solve.

center()  
Return the center of self.

EXAMPLES:

centralizer($S$)  
Return the centralizer of $S$ in self.

INPUT:

• $S$ – a subalgebra of self or a list of elements that represent generators for a subalgebra

See also:  
centralizer_basis()  

EXAMPLES:
centralizer_basis(\(S\))
Return a basis of the centralizer of \(S\) in \(self\).

**INPUT:**
- \(S\) – a subalgebra of \(self\) or a list of elements that represent generators for a subalgebra

**See also:**
centralizer()

**EXAMPLES:**

```sage
sage: # needs sage.combinat sage.modules
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()
sage: a, b, c = L.lie_algebra_generators()
sage: L.centralizer_basis([a + b, 2*a + c])

[(1, 0, 0), (0, 1, 0), (0, 0, 1)]
```

```sage
sage: # needs sage.combinat sage.modules
sage: H = lie_algebras.Heisenberg(QQ, 2)
sage: H.centralizer_basis(H)

[z]
```

```sage
sage: # needs sage.combinat sage.groupssage.modules
sage: D = DescentAlgebra(QQ, 4).D()
sage: L = LieAlgebra(associative=D)
sage: L.centralizer_basis(L)

[D{}, D{1} + D{1, 2} + D{2, 3} + D{3}, D{1, 2, 3} + D{1, 3} + D{2}]
```

chevalley_eilenberg_complex(\(M=\text{None}, \ dual=\text{False}, \ sparse=\text{True}, \ ncpus=\text{None}\))
Return the Chevalley-Eilenberg complex of \(self\).

Let \(g\) be a Lie algebra and \(M\) be a right \(g\)-module. The **Chevalley-Eilenberg complex** is the chain complex

\[
C_\bullet(g, M) = M \otimes \bigwedge \bullet g,
\]

where the differential is given by

\[
d(m \otimes g_1 \land \cdots \land g_p) = \sum_{i=1}^{p} (-1)^{i+1} (mg_i) \otimes g_1 \land \cdots \land \hat{g}_i \land \cdots \land g_p + \sum_{1 \leq i < j \leq p} (-1)^{i+j} m \otimes [g_i, g_j] \land g_1 \land \cdots \land \hat{g}_i \land \cdots \land \hat{g}_j \land \cdots \land g_p.
\]

**INPUT:**
- \(M\) – (default: the trivial 1-dimensional module) one of the following:
  - a module \(M\) with an action of \(self\)
  - a dictionary whose keys are basis elements and values are matrices representing a Lie algebra homomorphism defining the representation
- \(\text{dual}\) – (default: \(\text{False}\)) if \(\text{True}\), causes the dual of the complex to be computed
- \(\text{sparse}\) – (default: \(\text{True}\)) whether to use sparse or dense matrices
EXAMPLES:

```
sage: # needs sage.combinat sage.modules
sage: L = lie_algebras.sl(ZZ, 2)
sage: C = L.chevalley_eilenberg_complex(); C
Chain complex with at most 4 nonzero terms over Integer Ring
sage: ascii_art(C)
   [-2  0  0]  [0]
   [ 0  1  0]  [0]
   [ 0  0  0]  [0  0 -2]  [0]
0 <-- C_0 <-------- C_1 <-------- C_2 <---- C_3 <-- 0
```

```
sage: # needs sage.combinat sage.modules
sage: L = LieAlgebra(QQ, cartan_type=['C',2])
sage: C = L.chevalley_eilenberg_complex()  # long time
sage: [C.free_module_rank(i) for i in range(11)]  # long time
[1, 10, 45, 120, 210, 252, 210, 120, 45, 10, 1]
```

```
sage: # needs sage.combinat sage.modules
sage: g = lie_algebras.sl(QQ, 2)
sage: E, F, H = g.basis()
sage: n = g.subalgebra([F, H])
sage: ascii_art(n.chevalley_eilenberg_complex())
   [ 0]
   [0 0]
   [0 0 0]
   [-2]
0 <-- C_0 <------ C_1 <----- C_2 <-- 0
```

```
sage: L.<x,y> = LieAlgebra(QQ, {(x,y): {y:1}})
sage: f = ({x: Matrix([[1,0],[0,0]]), y: Matrix([[0,1],[0,0]])})
sage: C = L.chevalley_eilenberg_complex(f); C
Chain complex with at most 3 nonzero terms over Rational Field
sage: ascii_art(C)
   [ 0 -1]
   [ 2  0]
   [1 0 0 1]  [0  0]
   [0 0 0 0]  [ 0 1]
0 <-- C_0 <-------- C_1 <-------- C_2 <-- 0
```

REFERENCES:

- Wikipedia article Lie_algebra_cohomology#Chevalley-Eilenberg_complex
- [Wei1994] Chapter 7

cohomology (deg=None, M=None, sparse=True, ncpus=None)

Return the Lie algebra cohomology of self.

The Lie algebra cohomology is the cohomology of the Chevalley-Eilenberg cochain complex (which is the dual of the Chevalley-Eilenberg chain complex).

Let g be a Lie algebra and M a left g-module. It is known that $H^0(g; M)$ is the subspace of g-invariants.
of $M$:

$$H^0(g; M) = M^0 = \{ m \in M \mid gm = 0 \text{ for all } g \in g \}.$$  

Additionally, $H^1(g; M)$ is the space of derivations $g \to M$ modulo the space of inner derivations, and $H^2(g; M)$ is the space of equivalence classes of Lie algebra extensions of $g$ by $M$.

**INPUT:**
- `deg` – the degree of the homology (optional)
- `M` – (default: the trivial module) a right module of self
- `sparse` – (default: True) whether to use sparse matrices for the Chevalley-Eilenberg chain complex
- `ncpus` – (optional) how many cpus to use when computing the Chevalley-Eilenberg chain complex

**EXAMPLES:**

```python
sage: # needs sage.combinat sage.modules
sage: L = lie_algebras.so(QQ, 4)
sage: L.cohomology()
{0: Vector space of dimension 1 over Rational Field,
 1: Vector space of dimension 0 over Rational Field,
 2: Vector space of dimension 0 over Rational Field,
 3: Vector space of dimension 2 over Rational Field,
 4: Vector space of dimension 0 over Rational Field,
 5: Vector space of dimension 0 over Rational Field,
 6: Vector space of dimension 1 over Rational Field}

sage: # needs sage.combinat sage.modules
sage: L = lie_algebras.Heisenberg(QQ, 2)
sage: L.cohomology()
{0: Vector space of dimension 1 over Rational Field,
 1: Vector space of dimension 4 over Rational Field,
 2: Vector space of dimension 5 over Rational Field,
 3: Vector space of dimension 5 over Rational Field,
 4: Vector space of dimension 4 over Rational Field,
 5: Vector space of dimension 1 over Rational Field}

sage: # needs sage.combinat sage.modules
sage: d = {('x', 'y'): {y: 2}}
sage: L.<x,y> = LieAlgebra(ZZ, d)
sage: L.cohomology()
{0: Z, 1: Z, 2: C2}
```

**See also:**

`chevalley_eilenberg_complex()`

**REFERENCES:**
- Wikipedia article Lie_algebra_cohomology

**derivations_basis()**

Return a basis for the Lie algebra of derivations of `self` as matrices.

A derivation $D$ of an algebra is an endomorphism of $A$ such that

$$D([a, b]) = [D(a), b] + [a, D(b)]$$

for all $a, b \in A$. The set of all derivations form a Lie algebra.

**EXAMPLES:**

We construct the derivations of the Heisenberg Lie algebra:
We construct the derivations of \( \mathfrak{sl}_2 \):

```python
sage: # needs sage.combinat sage.modules
sage: sl2 = lie_algebras.sl(QQ, 2)
sage: sl2.derivations_basis()
\[
\begin{bmatrix}
1 & 0 & 0 \\
0 & 0 & -1/2 \\
0 & -1
\end{bmatrix}, \begin{bmatrix}
0 & 0 & 0 \\
0 & -2 & 0
\end{bmatrix}
\]
```

We verify these are derivations:

```python
sage: # needs sage.combinat sage.modules
sage: D = [sl2.module_morphism(matrix=M, codomain=sl2) for M in sl2.derivations_basis()]
sage: all(d(a.bracket(b)) == d(a).bracket(b) + a.bracket(d(b))
    for a in sl2.basis() for b in sl2.basis() for d in D)
True
```

REFERENCES:

Wikipedia article Derivation_(differential_algebra)

derived_series()

Return the derived series \( (\mathfrak{g}^{(i)}) \), of \texttt{self} where the rightmost \( \mathfrak{g}^{(k)} = \mathfrak{g}^{(k+1)} = \cdots \).

We define the derived series of a Lie algebra \( \mathfrak{g} \) recursively by \( \mathfrak{g}^{(0)} := \mathfrak{g} \) and

\[
\mathfrak{g}^{(k+1)} = [\mathfrak{g}^{(k)}, \mathfrak{g}^{(k)}]
\]

and recall that \( \mathfrak{g}^{(k)} \supseteq \mathfrak{g}^{(k+1)} \). Alternatively we can express this as

\[
\mathfrak{g} \supseteq [\mathfrak{g}, \mathfrak{g}] \supseteq [[\mathfrak{g}, \mathfrak{g}], [\mathfrak{g}, \mathfrak{g}]] \supseteq [[[[[\mathfrak{g}, \mathfrak{g}], \mathfrak{g}], \mathfrak{g}], [\mathfrak{g}, \mathfrak{g}]], [\mathfrak{g}, \mathfrak{g}]]] \supseteq \cdots.
\]

EXAMPLES:

```python
sage: # needs sage.combinat sage.modules
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()
sage: L.derived_series()
An example of a finite dimensional Lie algebra with basis: the 3-dimensional abelian Lie algebra over Rational Field,
An example of a finite dimensional Lie algebra with basis: the 0-dimensional abelian Lie algebra over Rational Field with basis matrix: []
```

4.52. Finite Dimensional Lie Algebras With Basis 417
### derived_subalgebra()

Return the derived subalgebra of self.

**EXAMPLES:**

```python
sage: # needs sage.combinat sage.modules
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()
sage: L.derived_subalgebra()
```

An example of a finite dimensional Lie algebra with basis:
the 0-dimensional abelian Lie algebra over Rational Field
with basis matrix:
[]

If self is semisimple, then the derived subalgebra is self:

```python
sage: # needs sage.combinat sage.modules
sage: s3 = LieAlgebra(QQ, cartan_type=['A', 2])
sage: s3.derived_subalgebra()
```

Lie algebra of ['A', 2] in the Chevalley basis
sage: s3 is s3.derived_subalgebra()
```

True
```

### from_vector(v, order=None)

Return the element of self corresponding to the vector v in self.module().

Implement this if you implement module(); see the documentation of sage.categories.
lie_algebras.LieAlgebras.module() for how this is to be done.

**EXAMPLES:**

```python
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()  #-- needs sage.modules
sage: u = L.from_vector(vector(QQ, (1, 0, 0))); u                      #-- needs sage.modules
(1, 0, 0)

sage: parent(u) is L                                                 #-- needs sage.modules
True
```

### homology (deg=None, M=None, sparse=True, ncpus=None)

Return the Lie algebra homology of self.

The Lie algebra homology is the homology of the Chevalley-Eilenberg chain complex.

**INPUT:**

- `deg` – the degree of the homology (optional)
- `M` – (default: the trivial module) a right module of self
• **sparse** – (default: True) whether to use sparse matrices for the Chevalley-Eilenberg chain complex
• **ncpus** – (optional) how many cpus to use when computing the Chevalley-Eilenberg chain complex

**EXAMPLES:**

```python
sage: # needs sage.combinat sage.modules
sage: L = lie_algebras.cross_product(QQ)
sage: L.homology()
{0: Vector space of dimension 1 over Rational Field,
  1: Vector space of dimension 0 over Rational Field,
  2: Vector space of dimension 0 over Rational Field,
  3: Vector space of dimension 1 over Rational Field}

sage: # needs sage.combinat sage.modules
sage: L = lie_algebras.pwitt(GF(5), 5)
sage: L.homology()
{0: Vector space of dimension 1 over Finite Field of size 5,
  1: Vector space of dimension 0 over Finite Field of size 5,
  2: Vector space of dimension 0 over Finite Field of size 5,
  3: Vector space of dimension 1 over Finite Field of size 5,
  4: Vector space of dimension 0 over Finite Field of size 5,
  5: Vector space of dimension 1 over Finite Field of size 5}

sage: # needs sage.combinat sage.modules
d = {(x, y): {y: 2}}
sage: L.<x,y> = LieAlgebra(ZZ, d)
sage: L.homology()
{0: Z, 1: Z x C2, 2: 0}
```

**See also:**

`chevalley_eilenberg_complex()`

### ideal(*gens, **kwds)*

Return the ideal of `self` generated by `gens`.

**INPUT:**
- **gens** – a list of generators of the ideal
- **category** – (optional) a subcategory of subobjects of finite dimensional Lie algebras with basis

**EXAMPLES:**

```python
sage: # needs sage.combinat sage.modules
sage: H = lie_algebras.Heisenberg(QQ, 2)
sage: p1, p2, q1, q2, z = H.basis()
sage: I = H.ideal([p1 - p2, q1 - q2])
sage: I.basis().list()
[-p1 + p2, -q1 + q2, z]
sage: I.reduce(p1 + p2 + q1 + q2 + z)
2*p1 + 2*q1
```

**Passing an extra category to an ideal:**

```python
sage: # needs sage.combinat sage.modules
sage: L.<x,y,z> = LieAlgebra(QQ, abelian=True)
sage: C = LieAlgebras(QQ).FiniteDimensional().WithBasis()
sage: C = C.Subobjects().Graded().Stratified()
sage: I = L.ideal(x, y, category=C)
sage: I.homogeneous_component_basis(1).list()
[x, y]
```
inner_derivations_basis()

Return a basis for the Lie algebra of inner derivations of self as matrices.

EXAMPLES:
```
sage: # needs sage.combinat sage.modules
sage: H = lie_algebras.Heisenberg(QQ, 1)
sage: H.inner_derivations_basis()
([0 0 0] [0 0 0]
 [0 0 0] [0 0 0]
 [1 0 0], [0 1 0])
```

is_abelian()

Return if self is an abelian Lie algebra.

EXAMPLES:
```
sage: # needs sage.combinat sage.modules
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()
sage: L.is_abelian()
True
```
```
sage: # needs sage.combinat sage.modules
sage: L.<x,y> = LieAlgebra(QQ, {'x':1})
sage: L.is_abelian()
False
```

is_ideal(A)

Return if self is an ideal of A.

EXAMPLES:
```
sage: # needs sage.combinat sage.modules
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()
sage: a, b, c = L.lie_algebra_generators()
sage: I = L.ideal([2*a - c, b + c])
sage: I.is_ideal(L)
True
```
```
sage: # needs sage.combinat sage.modules
sage: L.<x,y> = LieAlgebra(QQ, {'x':1})
```
```
˓→ needs sage.combinat sage.modules
sage: L.is_ideal(L)
˓→ needs sage.combinat sage.modules
True
```
```
sage: F = LieAlgebra(QQ, 'F', representation='polynomial')
˓→ needs sage.combinat sage.modules
sage: L.is_ideal(F)
˓→ needs sage.combinat sage.modules
Traceback (most recent call last):
NotImplementedError: A must be a finite dimensional Lie algebra with basis
```

is_nilpotent()

Return if self is a nilpotent Lie algebra.
A Lie algebra is nilpotent if the lower central series eventually becomes 0.

EXAMPLES:

```python
sage: # needs sage.combinat sage.modules
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()
sage: L.is_nilpotent()
True
```

`is_semisimple()`

Return if `self` is a semisimple Lie algebra.

A Lie algebra is semisimple if the solvable radical is zero. In characteristic 0, this is equivalent to saying the Killing form is non-degenerate.

EXAMPLES:

```python
sage: # needs sage.combinat sage.modules
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()
sage: L.is_semisimple()
False
```

`is_solvable()`

Return if `self` is a solvable Lie algebra.

A Lie algebra is solvable if the derived series eventually becomes 0.

EXAMPLES:

```python
sage: # needs sage.combinat sage.modules
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()
sage: L.is_solvable()
True
```

`killing_form(x, y)`

Return the Killing form on `x` and `y`, where `x` and `y` are two elements of `self`.

The Killing form is defined as

\[ \langle x \mid y \rangle = \text{tr}(\text{ad}_x \circ \text{ad}_y). \]

EXAMPLES:

```python
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()  # needs sage.modules
sage: a, b, c = L.lie_algebra_generators()  # needs sage.modules
sage: L.killing_form(a, b)  # not implemented
0
```

`killing_form_matrix()`

Return the matrix of the Killing form of `self`. 

4.52. Finite Dimensional Lie Algebras With Basis 421
The rows and the columns of this matrix are indexed by the elements of the basis of \texttt{self} (in the order provided by \texttt{basis()}).

EXAMPLES:

```python
sage: # needs sage.modules
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()
sage: L.killing_form_matrix()
[0 0 0]
[0 0 0]
[0 0 0]
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example(0)
sage: m = L.killing_form_matrix(); m
[]
sage: parent(m)
Full MatrixSpace of 0 by 0 dense matrices over Rational Field
```

\texttt{killing\_matrix}(x, y)

Return the Killing matrix of \(x\) and \(y\), where \(x\) and \(y\) are two elements of \texttt{self}.

The Killing matrix is defined as the matrix corresponding to the action of \(\text{ad}_x \circ \text{ad}_y\) in the basis of \texttt{self}.

EXAMPLES:

```python
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()  # needs sage.modules
sage: a, b, c = L.lie_algebra_generators()  # needs sage.modules
sage: L.killing_matrix(a, b)  # needs sage.modules
[0 0 0]
[0 0 0]
[0 0 0]
sage: L.<x,y> = LieAlgebra(QQ, {(x,y): {x:1}})  # needs sage.combinat sage.modules
sage: L.killing_matrix(y, x)  # needs sage.combinat sage.modules
[ 0 -1]
[ 0 0]
```

\texttt{lower\_central\_series}(\texttt{submodule=False})

Return the lower central series \((g_i)\), of \texttt{self} where the rightmost \(g_k = g_{k+1} = \cdots\).

INPUT:

• \texttt{submodule} = (default: \texttt{False}) if \texttt{True}, then the result is given as submodules of \texttt{self}

We define the lower central series of a Lie algebra \(g\) recursively by \(g_0 := g\) and

\[ g_{k+1} = [g, g_k] \]

and recall that \(g_k \supseteq g_{k+1}\). Alternatively we can express this as

\[ g \supseteq [g, g] \supseteq [[g, g], g] \supseteq \cdots. \]
The lower central series as submodules:

```sage
# needs sage.combinat sage.modules
sage: L.<x,y> = LieAlgebra(QQ, {('x','y'): {'x':1}})
sage: L.lower_central_series()  # not implemented
```

```sage
sage: # needs sage.combinat sage.modules
sage: L.<x,y> = LieAlgebra(QQ, {('x','y'): {'x':1}})
```

```
Sparse vector space of dimension 2 over Rational Field,
Vector space of degree 2 and dimension 1 over Rational Field
Basis matrix: [1 0]
```

```
Module (R=None)

Return a dense free module associated to self over R.

EXAMPLES:

```sage
L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()  #...
```

```
# needs sage.modules
sage: L._dense_free_module()  #...
```

```
Vector space of dimension 3 over Rational Field
```

```
morphism (on_generators=codomain=None, base_map=None, check=True)

Return a Lie algebra morphism defined by images of a Lie generating subset of self.

INPUT:

- **on_generators** – dictionary \{X: Y\} of the images \(Y\) in \texttt{codomain}\ of elements \(X\) of \texttt{domain}\n- **codomain** – a Lie algebra (optional); this is inferred from the \texttt{values}\ of \texttt{on_generators}\ if not given
- **base_map** – a homomorphism from the base ring to something coercing into the \texttt{codomain}\n- **check** – (default: True) boolean; if False the \texttt{values}\ on the Lie brackets implied by \texttt{on_generators}\ will not be checked for contradictory values

Note: The keys of \texttt{on_generators}\ need to generate \texttt{domain}\ as a Lie algebra.

See also:

```
sage.algebras.lie_algebras.morphism.LieAlgebraMorphism_from_generators
```

EXAMPLES:
A quotient type Lie algebra morphism

```sage
# needs sage.combinat sage.modules
L.<X,Y,Z,W> = LieAlgebra(QQ, {('X','Y'): {'Z': 1},
....: ('X','Z'): {'W': 1}})
sage: K.<A,B> = LieAlgebra(QQ, abelian=True)
sage: L.morphism({X: A, Y: B})
```

The reverse map \( A \mapsto X, \, B \mapsto Y \) does not define a Lie algebra morphism, since \([A, B] = 0\), but \([X, Y] \neq 0\):

```sage
# needs sage.combinat sage.modules
K.morphism({A:X, B: Y})
```

However, it is still possible to create a morphism that acts nontrivially on the coefficients, even though it’s not a Lie algebra morphism (since it isn’t linear):

```sage
# needs sage.combinat sage.modules sage.rings.number_fields
R.<x> = ZZ[]
sage: K.<i> = NumberField(x^2 + 1)
cc = K.hom([-i])
sage: L.<X,Y,Z,W> = LieAlgebra(K, {('X','Y'): {'Z': 1},
....: ('X','Z'): {'W': 1}})
sage: M.<A,B> = LieAlgebra(K, abelian=True)
sage: phi = L.morphism({X: A, Y: B}, base_map=cc)
sage: phi(X)
A
sage: phi(i*X)
-i*A
```

**product_space** (\(L, \text{submodule=False}\))

Return the product space \([self, L]\).

**INPUT:**

- \(L\) — a Lie subalgebra of \(self\)
- \(\text{submodule} \quad (\text{default: False})\) if True, then the result is forced to be a submodule of \(self\)

**EXAMPLES:**

```sage
# needs sage.combinat sage.modules
L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()
sage: a,b,c = L.lie_algebra_generators()
sage: X = L.subalgebra([a, b + c])
sage: L.product_space(X)
An example of a finite dimensional Lie algebra with basis: the 0-dimensional abelian Lie algebra over Rational Field with basis matrix: []
sage: Y = L.subalgebra([a, 2*b - c])
```
An example of a finite dimensional Lie algebra with basis:
the 0-dimensional abelian Lie algebra over Rational Field
with basis matrix: []

```python
sage: # needs sage.combinat sage.modules
sage: H = lie_algebras.Heisenberg(ZZ, 4)
sage: Hp = H.product_space(H, submodule=True).basis()
sage: [H.from_vector(v) for v in Hp]
[z]
```

```python
sage: # needs sage.combinat sage.modules
sage: L.<x,y> = LieAlgebra(QQ, {'x', 'y'}: {'x': 1})
sage: Lp = L.product_space(L)
```

```python
Subalgebra generated of
Lie algebra on 2 generators (x, y) over Rational Field
with basis: (x,)

sage: Lp.product_space(L)
```

```python
Subalgebra generated of
Lie algebra on 2 generators (x, y) over Rational Field
with basis: ()
```

```python
quotient (I, names=None, category=None)
```

Return the quotient of self by the ideal I.

A quotient Lie algebra.

**INPUT:**
- I – an ideal or a list of generators of the ideal
- names – (optional) a string or a list of strings; names for the basis elements of the quotient. If names is a string, the basis will be named names_1,...,"names_n".

**EXAMPLES:**

The Engel Lie algebra as a quotient of the free nilpotent Lie algebra of step 3 with 2 generators:

```python
sage: # needs sage.combinat sage.modules
sage: L.<X,Y,Z,W,U> = LieAlgebra(QQ, 2, step=3)
sage: E = L.quotient(U); E
```

Lie algebra quotient L/I of dimension 4 over Rational Field where
L: Free Nilpotent Lie algebra on 5 generators (X, Y, Z, W, U)
over Rational Field
I: Ideal (U)

sage: E.basis().list()
[X, Y, Z, W]

sage: E(X).bracket(E(Y))
Z

sage: Y.bracket(Z)
```

(continues on next page)
Quotients when the base ring is not a field are not implemented:

```python
sage: # needs sage.combinat sage.modules
sage: L = lie_algebras.Heisenberg(ZZ, 1)
sage: L.quotient(L.an_element())
Traceback (most recent call last):
  ...  
NotImplementedError: quotients over non-fields not implemented
```

**structure_coefficients**(include_zeros=False)

Return the structure coefficients of self.

**INPUT:**
- include_zeros - (default: False) if True, then include the \([x, y] = 0\) pairs in the output.

**OUTPUT:**
A dictionary whose keys are pairs of basis indices \((i, j)\) with \(i < j\), and whose values are the corresponding elements \([b_i, b_j]\) in the Lie algebra.

**EXAMPLES:**

```python
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()  #...  
# needs sage.modules
sage: L.structure_coefficients()  #...  
# needs sage.modules
Finite family {}  
sage: L.structure_coefficients(True)  #...  
# needs sage.modules
Finite family {(0, 1): (0, 0, 0), (0, 2): (0, 0, 0), (1, 2): (0, 0, 0)}
```

```python
sage: # needs sage.combinat sage.groups sage.modules
sage: G = SymmetricGroup(3)  
sage: S = GroupAlgebra(G, QQ)  
sage: L = LieAlgebra(associative=S)  
sage: L.structure_coefficients()  
Finite family {((2,3), (1,2)): (1,2,3) - (1,3,2),  
((2,3), (1,3)): -(1,2,3) + (1,3,2),  
((1,2,3), (2,3)): -(1,2) + (1,3),  
((1,2,3), (1,2)): (2,3) - (1,3),  
((1,2,3), (1,3)): -(2,3) + (1,2),  
((1,3,2), (2,3)): (1,2) - (1,3),  
((1,3,2), (1,2)): -(2,3) + (1,3),  
((1,3,2), (1,3)): (2,3) - (1,2),  
((1,3), (1,2)): -(1,2,3) + (1,3,2)}
```

**subalgebra**(gens, **kwds)

Return the subalgebra of self generated by gens.

**INPUT:**
- gens - a list of generators of the subalgebra
- category - (optional) a subcategory of subobjects of finite dimensional Lie algebras with basis
EXAMPLES:

```python
sage: # needs sage.combinat sage.modules
sage: H = lie_algebras.Heisenberg(QQ, 2)
sage: p1,p2,q1,q2,z = H.basis()
sage: S = H.subalgebra([p1, q1])
sage: S.basis().list()
[p1, q1, z]
sage: S.basis_matrix()
[1 0 0 0 0]
[0 0 1 0 0]
[0 0 0 1 0]
```

Passing an extra category to a subalgebra:

```python
sage: # needs sage.combinat sage.modules
sage: L = LieAlgebra(QQ, 3, step=2)
sage: x,y,z = L.homogeneous_component_basis(1)
sage: C = LieAlgebras(QQ).FiniteDimensional().WithBasis()
sage: C = C.Subobjects().Graded().Stratified()
sage: S = L.subalgebra([x, y], category=C)
sage: S.homogeneous_component_basis(2).list()
[X_12]
```

```
universal_commutative_algebra()

Return the universal commutative algebra associated to self.

Let \( I \) be the index set of the basis of self. Let \( P = \{P_{a,i,j}\}_{a,i,j \in I} \) denote the universal polynomials of a Lie algebra \( L \). The universal commutative algebra associated to \( L \) is the quotient ring \( \mathbb{R}[X_{ij}]_{i,j \in I} / (P) \).

EXAMPLES:

```python
sage: # needs sage.combinat sage.modules
sage: L.<x,y> = LieAlgebra(QQ, {(x,y): {x:1}})
sage: A = L.universal_commutative_algebra()
sage: a, b, c, d = A.gens()
sage: a, b, c, d
(X00bar, X01bar, 0, X11bar)
sage: a*d - a
0
```
```
universal_polynomials()

Return the family of universal polynomials of self.

The universal polynomials of a Lie algebra \( L \) with basis \( \{e_i\}_{i \in I} \) and structure coefficients \([e_i, e_j] = \tau_{ij}^a e_a\) is given by

\[
P_{aij} = \sum_{u \in I} \tau_{ij}^u X_{au} - \sum_{s,t \in I} \tau_{st}^a X_{si} X_{tj},
\]

where \( a,i,j \in I \).

REFERENCES:

• [AM2020]

EXAMPLES:

```python
sage: # needs sage.combinat sage.modules
sage: L.<x,y> = LieAlgebra(QQ, {(x,y): {x:1}})
(continues on next page)
```
sage: L.universal_polynomials()
Finite family {'x', 'x', 'y'}: X01*X10 - X00*X11 + X00,
                 {'y', 'x', 'y'}: X10

sage: # needs sage.combinat sage.modules
sage: L = LieAlgebra(QQ, cartan_type=['A', 1])
sage: list(L.universal_polynomials())
[-2*X01*X10 + 2*X00*X11 - 2*X00,
 -2*X02*X10 + 2*X00*X12 + X01,
 -2*X02*X11 + 2*X01*X12 - 2*X02,
 X01*X20 - X00*X21 - 2*X10,
 X02*X20 - X00*X22 + X11,
 X02*X21 - X01*X22 - 2*X12,
 -2*X11*X20 + 2*X10*X21 - 2*X20,
 -2*X12*X20 + 2*X10*X22 + X21,
 -2*X12*X21 + 2*X11*X22 - 2*X22]

sage: # long time, needs sage.combinat sage.modules
sage: L = LieAlgebra(QQ, cartan_type=['B', 2])
sage: al = RootSystem(['B', 2]).root_lattice().simple_roots()
sage: k = list(L.basis().keys())[0]
sage: UP = L.universal_polynomials()
sage: len(UP)
450
sage: UP[al[2], al[1], -al[1]]
X0_7*X4_1 - X0_1*X4_7 - 2*X0_7*X5_1 + 2*X0_1*X5_7 + X2_7*X7_1
    - X2_1*X7_7 - X3_7*X8_1 + X3_1*X8_7 + X0_4

class Subobjects (category, *args)
Bases: SubobjectsCategory
A category for subalgebras of a finite dimensional Lie algebra with basis.

class ParentMethods
Bases: object

ambient()
Return the ambient Lie algebra of self.

EXAMPLES:

sage: # needs sage.combinat sage.modules
sage: C = LieAlgebras(QQ).FiniteDimensional().WithBasis()
sage: L = C.example()
sage: a, b, c = L.lie_algebra_generators()
sage: S = L.subalgebra([2*a + b, b + c])
sage: S.ambient() == L
True

basis_matrix()
Return the basis matrix of self.

EXAMPLES:

sage: # needs sage.combinat sage.modules
sage: C = LieAlgebras(QQ).FiniteDimensional().WithBasis()
sage: L = C.example()
example \( (n=3) \)

Return an example of a finite dimensional Lie algebra with basis as per `Category.example`.

EXAMPLES:

```python
sage: C = LieAlgebras(QQ).FiniteDimensional().WithBasis()
sage: C.example()  # needs sage.modules
An example of a finite dimensional Lie algebra with basis:
the 3-dimensional abelian Lie algebra over Rational Field
```

Other dimensions can be specified as an optional argument:

```python
sage: C.example(5)  # needs sage.modules
An example of a finite dimensional Lie algebra with basis:
the 5-dimensional abelian Lie algebra over Rational Field
```

4.53 Finite dimensional modules with basis

class `sage.categories.finite_dimensional_modules_with_basis.FiniteDimensionalModulesWithBasis`

Bases: `CategoryWithAxiom_over_base_ring`

The category of finite dimensional modules with a distinguished basis

EXAMPLES:

```python
sage: C = FiniteDimensionalModulesWithBasis(ZZ); C
Category of finite dimensional modules with basis over Integer Ring
sage: sorted(C.super_categories(), key=str)
[Category of finite dimensional modules over Integer Ring, 
 Category of modules with basis over Integer Ring]
sage: C is Modules(ZZ).WithBasis().FiniteDimensional()
True
```

class `ElementMethods`

Bases: `object`

`dense_coefficient_list (order=None)`

Return a list of all coefficients of `self`.

By default, this list is ordered in the same way as the indexing set of the basis of the parent of `self`.

INPUT:

- `order` – (optional) an ordering of the basis indexing set

EXAMPLES:
```python
sage: # needs sage.modules
sage: v = vector([0, -1, -3])
sage: v.dense_coefficient_list()
[0, -1, -3]
sage: v.dense_coefficient_list([2,1,0])
[-3, -1, 0]
sage: sorted(v.coefficients())
[-3, -1]
```

class MorphismMethods
Bases: object

```python
image()
```

Return the image of `self` as a submodule of the codomain.

EXAMPLES:

```python
sage: SGA = SymmetricGroupAlgebra(QQ, 3)
# needs sage.groups sage.modules
sage: f = SGA.module_morphism(lambda x: SGA(x**2), codomain=SGA)
# needs sage.groups sage.modules
sage: f.image()
# needs sage.groups sage.modules
Free module generated by {0, 1, 2} over Rational Field
```

```python
image_basis()
```

Return a basis for the image of `self` in echelon form.

EXAMPLES:

```python
sage: SGA = SymmetricGroupAlgebra(QQ, 3)
# needs sage.groups sage.modules
sage: f = SGA.module_morphism(lambda x: SGA(x**2), codomain=SGA)
# needs sage.groups sage.modules
sage: f.image_basis()
# needs sage.groups sage.modules
([1, 2, 3], [2, 3, 1], [3, 1, 2])
```

```python
kernel()
```

Return the kernel of `self` as a submodule of the domain.

EXAMPLES:

```python
sage: # needs sage.groups sage.modules
sage: SGA = SymmetricGroupAlgebra(QQ, 3)
# needs sage.groups sage.modules
sage: f = SGA.module_morphism(lambda x: SGA(x**2), codomain=SGA)
# needs sage.groups sage.modules
sage: K = f.kernel()
sage: K
Free module generated by {0, 1, 2} over Rational Field
sage: K.ambient()
Symmetric group algebra of order 3 over Rational Field
```

```python
kernel_basis()
```

Return a basis of the kernel of `self` in echelon form.

EXAMPLES:
```
sage: SGA = SymmetricGroupAlgebra(QQ, 3)  # needs sage.groups sage.modules
sage: f = SGA.module_morphism(lambda x: SGA(x*x*2), codomain=SGA)  # needs sage.groups sage.modules
sage: f.kernel_basis()
# needs sage.groups sage.modules
([1, 2, 3] - [3, 2, 1], [1, 3, 2] - [3, 2, 1], [2, 1, 3] - [3, 2, 1])
```

**matrix** *(base_ring=None, side='left')*

Return the matrix of this morphism in the distinguished bases of the domain and codomain.

**INPUT:**
- **base_ring** — A ring (default: None, meaning the base ring of the codomain)
- **side** — “left” or “right” (default: “left”)

If **side** is “left”, this morphism is considered as acting on the left; i.e. each column of the matrix represents the image of an element of the basis of the domain.

The order of the rows and columns matches with the order in which the bases are enumerated.

**See also:**
- Modules.WithBasis.ParentMethods.module_morphism()

**EXAMPLES:**
```
sage: # needs sage.modules
sage: X = CombinatorialFreeModule(ZZ, [1,2]); x = X.basis()
sage: Y = CombinatorialFreeModule(ZZ, [3,4]); y = Y.basis()
sage: phi = X.module_morphism(on_basis={1: y[3] + 3*y[4],
                                  ....: 2: 2*y[3] + 5*y[4]}.__getitem__,
                                  ....: codomain=Y)
sage: phi.matrix()
[1 2]
[3 5]
sage: phi.matrix(side="right")
[1 3]
[2 5]
```

The resulting matrix is immutable:
```
sage: phi.matrix().is_mutable()  # needs sage.modules
False
```

The zero morphism has a zero matrix:
```
sage: Hom(X, Y).zero().matrix()  # needs sage.modules
[0 0]
[0 0]
```

4.53. Finite dimensional modules with basis 431
Todo: Add support for morphisms where the codomain has a different base ring than the domain:

```
sage: Y = CombinatorialFreeModule(QQ, [3,4]); y = Y.basis()  # needs sage.modules
sage: phi = X.module_morphism(on_basis={1: y[3] + 3*y[4],  # needs sage.modules
......: 2: 2*y[3] + 5/2*y[4]}.__getitem__,
......: codomain=Y)
sage: phi.matrix().parent()  # not implemented  # needs sage.modules
Full MatrixSpace of 2 by 2 dense matrices over Rational Field
```

This currently does not work because, in this case, the morphism is just in the category of commutative additive groups (i.e. the intersection of the categories of modules over \( Z \) and over \( Q \)):

```
sage: phi.parent().homset_category()  # needs sage.modules
Category of commutative additive semigroups
sage: phi.parent().homset_category()  # not implemented, needs sage.modules
Category of finite dimensional modules with basis over Integer Ring
```

class ParentMethods

Bases: object

\texttt{annihilator}(S, action=\texttt{<built-in function mul>}, side='right', category=None)

Return the annihilator of a finite set.

INPUT:

- \( S \) – a finite set
- \texttt{action} – a function (default: \texttt{operator.mul})
- \texttt{side} – 'left' or 'right' (default: 'right')
- \texttt{category} – a category

Assumptions:

- \texttt{action} takes elements of \( S \) as first argument and elements of \( S \) as second argument;
- The codomain is any vector space, and \texttt{action} is linear on its first argument; typically it is bilinear;
- If \texttt{side} is 'left', this is reversed.

OUTPUT:

The subspace of the elements \( x \) of \( S \) such that \( \texttt{action}(x, s) = 0 \) for all \( s \in S \). If \texttt{side} is 'left' replace the above equation by \( \texttt{action}(s, x) = 0 \).

If \( self \) is a ring, \texttt{action} an action of \( self \) on a module \( M \) and \( S \) is a subset of \( M \), we recover the Wikipedia article Annihilator_%28ring_theory%29. Similarly this can be used to compute torsion or orthogonals.

See also:

\texttt{annihilator_basis()} for lots of examples.

EXAMPLES:

```
sage:  # needs sage.modules
sage: F = FiniteDimensionalAlgebrasWithBasis(QQ).example(); F
An example of a finite dimensional algebra with basis:
the path algebra of the Kronecker quiver
```
containing the arrows \( a:x \rightarrow y \) and \( b:x \rightarrow y \) over Rational Field

\[
sage: \ x, \ y, \ a, \ b = F.basis()
\]

\[
sage: A = F.annihilator([a + 3*b + 2*y]); A
\]
Free module generated by \( \{0\} \) over Rational Field

\[
sage: \ [b.lift() \ \text{for} \ b \ \text{in} \ A.basis()]
\]
\([-1/2*a - 3/2*b + x]\)

The category can be used to specify other properties of this subspace, like that this is a subalgebra:

\[
\text{sage: } \ # \text{ needs sage.modules}
\text{sage: center = F.annihilator(F.basis(), F.bracket,
\text{....:} \quad \text{category=Algebras(QQ).Subobjects()})}
\text{sage: } \ (e,) = \text{center.basis()}
\text{sage: e.lift()}
\text{x + y}
\text{sage: e * e == e}
\text{True}
\]

Taking annihilator is order reversing for inclusion:

\[
\text{sage: } \ # \text{ needs sage.graphs sage.modules}
\text{sage: A } = \text{F.annihilator([]); A.rename("A")}
\text{sage: Ax } = \text{F.annihilator([x]); Ax.rename("Ax")}
\text{sage: Ay } = \text{F.annihilator([y]); Ay.rename("Ay")}
\text{sage: Axy } = \text{F.annihilator([x,y]); Axy.rename("Axy")}
\text{sage: P = Poset(([A, Ax, Ay, Axy], attrcall("is_submodule")))}
\text{# needs sage.combinat sage.graphs}
\text{sage: sorted(P.cover_relations(), key=str)}
\text{# needs sage.combinat sage.graphs}
\]
\[
\left[ [Ax, A], \ [Axy, Ax], \ [Axy, Ay], \ [Ay, A]\right]
\]

\textit{annihilator\_basis} \( (S, \text{ action=<built-in function mul>, side='right'} \)

Return a basis of the annihilator of a finite set of elements.

\textbf{INPUT:}

- \( S \) – a finite set of objects
- \( \text{action} \) – a function (default: \text{operator.mul})
- \( \text{side} \) – `left` or `right` (default: `right`): on which side of \text{self} the elements of \( S \) acts.

\textbf{See }\text{annihilator()}\text{ for the assumptions and definition of the annihilator.}

\textbf{EXAMPLES:}

By default, the action is the standard * operation. So our first example is about an algebra:

\[
\text{sage: } \ # \text{ needs sage.graphs sage.modules}
\text{sage: F = FiniteDimensionalAlgebrasWithBasis(QQ).example(); F}
\text{An example of a finite dimensional algebra with basis:}
\text{the path algebra of the Kronecker quiver}
\text{(containing the arrows } a:x \rightarrow y \text{ and } b:x \rightarrow y \text{) over Rational Field}
\text{sage: x,y,a,b = F.basis()}
\]

In this algebra, multiplication on the right by \( x \) annihilates all basis elements but \( x \):

\[
\text{sage: } \ x^*x, \ y^*x, \ a^*x, \ b^*x
\text{# needs sage.graphs sage.modules}
\]
\[
(x, \ 0, \ 0, \ 0)
\]

So the annihilator is the subspace spanned by \( y, a, \) and \( b \):
The same holds for $a$ and $b$: $\text{sage: } x*a, y*a, a*a, b*a$

On the other hand, $y$ annihilates only $x$: $\text{sage: } F.annihilator_basis([y])$

Here is a non trivial annihilator: $\text{sage: } F.annihilator_basis([a + 3*b + 2*y])$

Let's check it: $\text{sage: } (-1/2*a - 3/2*b + x) * (a + 3*b + 2*y)$

Doing the same calculations on the left exchanges the roles of $x$ and $y$:

By specifying an inner product, this method can be used to compute the orthogonal of a subspace:

By specifying the standard Lie bracket as action, one can compute the commutator of a subspace of $F$: 

```python
sage: x,y,a,b = F.basis()
sage: def scalar(u,v):
    ....:     return vector([sum(u[i]*v[i] for i in F.basis().keys())])
sage: F.annihilator_basis([x + y, a + b], scalar)
```
In particular one can compute a basis of the center of the algebra. In our example, it is reduced to the identity:

```
sage: F.annihilator_basis(F.algebra_generators(), action=F.bracket)  # needs sage.graphs sage.modules
(x + y,)
```

But see also `FiniteDimensionalAlgebrasWithBasis.ParentMethods.center_basis()`.

**echelon_form**(elements, row_reduced=False, order=None)

Return a basis in echelon form of the subspace spanned by a finite set of elements.

**INPUT:**
- elements – a list or finite iterable of elements of self
- row_reduced – (default: False) whether to compute the basis for the row reduced echelon form
- order – (optional) either something that can be converted into a tuple or a key function

**OUTPUT:**
A list of elements of self whose expressions as vectors form a matrix in echelon form. If `base_ring` is specified, then the calculation is achieved in this base ring.

**EXAMPLES:**

```
sage: # needs sage.modules
sage: X = CombinatorialFreeModule(QQ, range(3), prefix="x")
sage: x = X.basis()
sage: V = X.echelon_form([x[0]-x[1], x[0]-x[2], x[1]-x[2]]); V
[ x[0] - x[2], x[1] - x[2]]
sage: matrix(list(map(vector, V)))
[ 1 0 -1]
[ 0 1 -1]
```

```
sage: # needs sage.modules
sage: F = CombinatorialFreeModule(ZZ, [1,2,3,4])
sage: B = F.basis()
sage: F.echelon_form(elements)
```

```
sage: # needs sage.modules
sage: a,b,c = F.basis()  # needs sage.modules
sage: F.echelon_form([8*a+b+10*c, -3*a+b-c, a-b-c])  # needs sage.modules
[B['a'] + B['c'], B['b'] + 2*B['c']]
```

```
sage: R.<x,y> = QQ[]
sage: C = CombinatorialFreeModule(R, range(3), prefix='x')  # needs sage.modules
```

(continues on next page)
sage: x = C.basis()  # needs sage.modules
sage: C.echelon_form([x[0] - x[1], 2*x[1] - 2*x[2], x[0] - x[2]])  # needs sage.modules sage.rings.function_field
[x[0] - x[2], x[1] - x[2]]

sage: M = MatrixSpace(QQ, 3, 3)  # needs sage.modules
sage: A = M([[0, 0, 2], [0, 0, 0], [0, 0, 0]])  # needs sage.modules
sage: M.echelon_form([A, A])  # needs sage.modules
[[0 0 1]
 [0 0 0]
 [0 0 0]]

from_vector(vector, order=None, coerce=True)

Build an element of self from a vector.

EXAMPLES:

sage: # needs sage.modules
sage: p_mult = matrix([[0,0,0], [0,0,-1], [0,0,0]])

sage: q_mult = matrix([[0,0,1], [0,0,0], [0,0,0]])

sage: A = algebras.FiniteDimensional(QQ, [p_mult, q_mult, matrix(QQ, 3, 3)], p,q,z)

sage: A.from_vector(vector([1,0,2]))
p + 2*z

gens()

Return the generators of self.

OUTPUT:

A tuple containing the basis elements of self.

EXAMPLES:

sage: F = CombinatorialFreeModule(ZZ, ['a', 'b', 'c'])  # needs sage.modules
sage: F.gens()  # needs sage.modules
(B['a'], B['b'], B['c'])

invariant_module(S, action=<built-in function mul>, action_on_basis=None, side='left', **kwargs)

Return the submodule of self invariant under the action of $S$.

For a semigroup $S$ acting on a module $M$, the invariant submodule is given by

$$M^S = \{ m \in M : s \cdot m = m, \forall s \in S \}.$$  

INPUT:

- $S$ – a finitely-generated semigroup  
- action – a function (default: operator.mul)  
- side – 'left' or 'right' (default: 'right'); which side of self the elements of $S$ acts
• action_on_basis – (optional) define the action of $S$ on the basis of self

OUTPUT:
• FiniteDimensionalInvariantModule

EXAMPLES:

We build the invariant module of the permutation representation of the symmetric group:

```python
sage: # needs sage.groups sage.modules
sage: G = SymmetricGroup(3); G.rename('S3')
sage: M = FreeModule(ZZ, [1,2,3], prefix='M'); M.rename('M')
sage: action = lambda g, x: M.term(g(x))
sage: I = M.invariant_module(G, action_on_basis=action); I
(S3)-invariant submodule of M
sage: I.basis()
Finite family {0: B[0]}
sage: [I.lift(b) for b in I.basis()]
sage: G.rename(); M.rename() # reset the names
```

We can construct the invariant module of any module that has an action of $S$. In this example, we consider the dihedral group $G = D_4$ and the subgroup $H < G$ of all rotations. We construct the $H$-invariant module of the group algebra $\mathbb{Q}[G]$:

```python
sage: # needs sage.groups
sage: G = groups.permutation.Dihedral(4)
sage: H = G.subgroup(G.gen(0))
sage: H
Subgroup generated by [(1,2,3,4)]
  of (Dihedral group of order 8 as a permutation group)
sage: H.cardinality()
4
sage: # needs sage.groups sage.modules
sage: A = G.algebra(QQ)
sage: I = A.invariant_module(H)
sage: [I.lift(b) for b in I.basis()]
[(0) + (1,2,3,4) + (1,3)(2,4) + (1,4,3,2),
 (2,4) + (1,2)(3,4) + (1,3) + (1,4)(2,3)]
sage: all(h * I.lift(b) == I.lift(b) for h in H)
True
```

`twisted_invariant_module` ($G$, $\chi$, action=<$\text{mul}$>, action_on_basis=None, side='left', **kwargs)

Create the isotypic component of the action of $G$ on self with irreducible character given by $\chi$.

See also:

- FiniteDimensionalTwistedInvariantModule

INPUT:
• $G$ – a finitely-generated group
• $\chi$ – a list/tuple of character values or an instance of ClassFunction_gap
• action – a function (default: operator.mul)
• action_on_basis – (optional) define the action of $g$ on the basis of self
• side – 'left' or 'right' (default: 'right'); which side of self the elements of $S$ acts

OUTPUT:
• FiniteDimensionalTwistedInvariantModule

4.53. Finite dimensional modules with basis 437
### EXAMPLES:

```python
class TensorProducts (category, *args)
Bases: TensorProductsCategory

effective_super_categories ()
    Implement the fact that a (finite) tensor product of finite dimensional modules is a finite dimensional module.

EXAMPLES:

```python
C = ModulesWithBasis(ZZ).FiniteDimensional().TensorProducts()
C.effective_super_categories()  # Category of finite dimensional modules with basis over Integer Ring
C.FiniteDimensional()  # Category of tensor products of finite dimensional modules with basis over Integer Ring
```

### 4.54 Finite Dimensional Nilpotent Lie Algebras With Basis

**AUTHORS:**
- Eero Hakavuori (2018-08-16): initial version

```python
class sage.categories.finite_dimensional_nilpotent_lie_algebras_with_basis.FiniteDimensionalNilpotentLieAlgebrasWithBasis
Bases: CategoryWithAxiom_over_base_ring
Category of finite dimensional nilpotent Lie algebras with basis.

class ParentMethods
Bases: object

is_nilpotent ()
    Return True since self is nilpotent.

EXAMPLES:

```python
L = LieAlgebra(QQ, {('x','y'): {'z': 1}}, nilpotent=True)  # needs sage.combinat sage.modules
L.is_nilpotent()  # needs sage.combinat sage.modules
True
```
**lie_group** (*name='G', **kwds*)

Return the Lie group associated to self.

**INPUT:**

- name – string (default: 'G'); the name (symbol) given to the Lie group

**EXAMPLES:**

We define the Heisenberg group:

```sage
sage: L = lie_algebras.Heisenberg(QQ, 1)
# needs sage.combinat sage.modules
sage: G = L.lie_group('G'); G
# needs sage.combinat sage.modules sage.symbolic
Lie group G of Heisenberg algebra of rank 1 over Rational Field
```

We test multiplying elements of the group:

```sage
sage: p, q, z = L.basis()
sage: g = G.exp(p); g
exp(p1)
sage: h = G.exp(q); h
exp(q1)
sage: g * h
exp(p1 + q1 + 1/2*z)
```

We extend an element of the Lie algebra to a left-invariant vector field:

```sage
sage: X = G.left_invariant_extension(2*p + 3*q, name='X'); X
# needs sage.combinat sage.modules sage.symbolic
Vector field X on the Lie group G of Heisenberg algebra of rank 1 over Rational Field
sage: X.at(G.one()).display()
# needs sage.combinat sage.modules sage.symbolic
X = 2 ∂/∂x_0 + 3 ∂/∂x_1
sage: X.display()
# needs sage.combinat sage.modules sage.symbolic
X = 2 ∂/∂x_0 + 3 ∂/∂x_1 + (3/2*x_0 - x_1) ∂/∂x_2
```

See also:

- NilpotentLieGroup

**step()**

Return the nilpotency step of self.

**EXAMPLES:**

```sage
sage: L = LieAlgebra(QQ, {'X': 'Y': {'Z': 1}}, nilpotent=True)
sage: L.step()
2
sage: sc = {'X': 'Y': {'Z': 1}, {'X': 'Z': {'W': 1}}
sage: LieAlgebra(QQ, sc, nilpotent=True).step()
3
```
4.55 Finite dimensional semisimple algebras with basis

class sage.categories.finite_dimensional_semisimple_algebras_with_basis.FiniteDimensionalSemisimpleAlgebrasWithBasis

Bases: CategoryWithAxiom_over_base_ring

The category of finite dimensional semisimple algebras with a distinguished basis

EXAMPLES:

```python
sage: from sage.categories.finite_dimensional_semisimple_algebras_with_basis...
˓→ import FiniteDimensionalSemisimpleAlgebrasWithBasis
sage: C = FiniteDimensionalSemisimpleAlgebrasWithBasis(QQ); C
Category of finite dimensional semisimple algebras with basis over Rational Field
```

This category is best constructed as:

```python
sage: D = Algebras(QQ).Semisimple().FiniteDimensional().WithBasis(); D
Category of finite dimensional semisimple algebras with basis over Rational Field
sage: D is C
True
```

class Commutative(base_category)

Bases: CategoryWithAxiom_over_base_ring

class ParentMethods

Bases: object

central_orthogonal_idempotents()

Return the central orthogonal idempotents of this semisimple commutative algebra.

Those idempotents form a maximal decomposition of the identity into primitive orthogonal idempotents.

OUTPUT:

A list of orthogonal idempotents of self.

EXAMPLES:

```python
sage: # needs sage.groups sage.modules
sage: A4 = SymmetricGroup(4).algebra(QQ)
sage: Z4 = A4.center()
sage: idempotents = Z4.central_orthogonal_idempotents()
sage: idempotents
1/6*B[0] + 1/6*B[2] - 1/12*B[3],
```

Lifting those idempotents from the center, we recognize among them the sum and alternating sum of all permutations:

```python
sage: [e.lift() for e in idempotents]  #...
˓→ needs sage.groups sage.modules
[1/24*() + 1/24*(3,4) + 1/24*(2,3) + 1/24*(2,3,4) + 1/24*(2,4,3)
(continues on next page)
+ 1/24*(2,4) + 1/24*(1,2) + 1/24*(1,2)(3,4) + 1/24*(1,2,3)
+ 1/24*(1,2,3,4) + 1/24*(1,2,4,3) + 1/24*(1,2,4) + 1/24*(1,3,2)
+ 1/24*(1,3,2,4) + 1/24*(1,4,3,2) + 1/24*(1,4,2) + 1/24*(1,4,3)
+ 1/24*(1,4) + 1/24*(1,4,2,3) + 1/24*(1,4)(2,3),
...
1/24*(3,4) - 1/24*(2,3) + 1/24*(2,3,4) + 1/24*(2,4,3)
- 1/24*(2,4) - 1/24*(1,2) + 1/24*(1,2)(3,4) + 1/24*(1,2,3)
- 1/24*(1,2,3,4) - 1/24*(1,2,4,3) + 1/24*(1,2,4) + 1/24*(1,3,2)
- 1/24*(1,3,2,4) - 1/24*(1,4,3,2) + 1/24*(1,4,2) + 1/24*(1,4,3)
- 1/24*(1,4) - 1/24*(1,4,2,3) + 1/24*(1,4)(2,3)

We check that they indeed form a decomposition of the identity of \( Z_4 \) into orthogonal idempotents:

```python
sage: Z4.is_identity_decomposition_into_orthogonal_idempotents(idempotents)  # needs sage.groups sage.modules
True
```

```python
class ParentMethods
    Bases: object

central_orthogonal_idempotents()

    Return a maximal list of central orthogonal idempotents of self.

    Central orthogonal idempotents of an algebra \( A \) are idempotents \((e_1, \ldots, e_n)\) in the center of \( A \) such that \( e_ie_j = 0 \) whenever \( i \neq j \).

    With the maximality condition, they sum up to 1 and are uniquely determined (up to order).

    EXAMPLES:

    For the algebra of the (abelian) alternating group \( A_3 \), we recover three idempotents corresponding to the three one-dimensional representations \( V_i \) on which \((1,2,3)\) acts on \( V_i \) as multiplication by the \( i \)-th power of a cube root of unity:

    ```python
    sage: # needs sage.groups sage.rings.number_field
    sage: R = CyclotomicField(3)
    sage: A3 = AlternatingGroup(3).algebra(R)
    sage: idempotents = A3.central_orthogonal_idempotents()
    sage: idempotents
    (1/3*(1,2,3) + 1/3*(1,3,2),
     1/3*(1,2,3) - (1/3*zeta3+1/3)*(1,2,3) - (-1/3*zeta3)*(1,3,2),
     1/3*(1,2,3) - (-1/3*zeta3)*(1,2,3) - (1/3*zeta3+1/3)*(1,3,2))
    sage: A3.is_identity_decomposition_into_orthogonal_idempotents(idempotents)
    True
    ```

    For the semisimple quotient of a quiver algebra, we recover the vertices of the quiver:

    ```python
    sage: # needs sage.graphs sage.modules
    sage: A = FiniteDimensionalAlgebrasWithBasis(QQ).example(); A
    An example of a finite dimensional algebra with basis:
    the path algebra of the Kronecker quiver (containing the arrows a:x->y and b:x->y) over Rational Field
    sage: Aquo = A.semisimple_quotient()
    sage: Aquo.central_orthogonal_idempotents()
    (B['x'], B['y'])
    ```

4.55. Finite dimensional semisimple algebras with basis
radical_basis (**keywords)

Return a basis of the Jacobson radical of this algebra.
• keywords – for compatibility; ignored.
OUTPUT: the empty list since this algebra is semisimple.

EXAMPLES:

```python
sage: A = SymmetricGroup(4).algebra(QQ)  # needs sage.groups sage.modules
sage: A.radical_basis()  # needs sage.groups sage.modules
()```

4.56 Finite Enumerated Sets

class sage.categories.finite_enumerated_sets.FiniteEnumeratedSets (base_category)

Bases: CategoryWithAxiom_singleton

The category of finite enumerated sets

EXAMPLES:

```python
sage: FiniteEnumeratedSets()
Category of finite enumerated sets
sage: FiniteEnumeratedSets().super_categories()
[Category of enumerated sets, Category of finite sets]
sage: FiniteEnumeratedSets().all_super_categories()
[Category of finite enumerated sets,
  Category of enumerated sets,
  Category of finite sets,
  Category of sets,
  Category of sets with partial maps,
  Category of objects]
```

Todo: sage.combinat.debruijn_sequence.DeBruijnSequences should not inherit from this class. If that is solved, then FiniteEnumeratedSets shall be turned into a subclass of Category_singleton.

class CartesianProducts (category, *args)

Bases: CartesianProductsCategory

class ParentMethods

Bases: object

cardinality()

Return the cardinality of self.

EXAMPLES:

```python
sage: E = FiniteEnumeratedSet([1,2,3])
sage: C = cartesian_product([E, SymmetricGroup(4)])  # needs sage.groups
sage: C.cardinality()
```
needs sage.groups
72

sage: E = FiniteEnumeratedSet([])
sage: C = cartesian_product([E, ZZ, QQ])
sage: C.cardinality()
0

sage: C = cartesian_product([ZZ, QQ])
sage: C.cardinality()
+Infinity

sage: cartesian_product([GF(5), Permutations(10)]).cardinality()
18144000
sage: cartesian_product([GF(71)]*20).cardinality() == 71**20
True

last()

Return the last element

EXAMPLES:

sage: C = cartesian_product([Zmod(42), Partitions(10), #...
needs sage.combinat
....: IntegerRange(5)])
sage: C.last() #...
needs sage.combinat
(41, [1, 1, 1, 1, 1, 1, 1, 1, 1, 1], 4)

random_element(*args)

Return a random element of this Cartesian product.

The extra arguments are passed down to each of the factors of the Cartesian product.

EXAMPLES:

sage: C = cartesian_product([Permutations(10)]*5)
sage: C.random_element() # random
([2, 9, 4, 7, 1, 8, 6, 10, 5, 3],
 [8, 6, 5, 7, 1, 4, 9, 3, 10, 2],
 [5, 10, 3, 8, 2, 9, 1, 4, 7, 6],
 [9, 6, 10, 3, 2, 1, 5, 8, 7, 4],
 [8, 5, 2, 9, 10, 3, 7, 1, 4, 6])

sage: C = cartesian_product([ZZ]**10)
sage: c1 = C.random_element() # random
(3, 1, 4, 1, 1, -3, 0, -4, -17, 2)
sage: c2 = C.random_element(4,7)
sage: c2 # random
(6, 5, 6, 4, 5, 6, 6, 4, 5, 5)
sage: all(4 <= i < 7 for i in c2)
True

rank(x)

Return the rank of an element of this Cartesian product.

4.56. Finite Enumerated Sets
The rank of \( x \) is its position in the enumeration. It is an integer between 0 and \( n-1 \) where \( n \) is the cardinality of this set.

See also:

- `EnumeratedSets.ParentMethods.rank()`
- `unrank()`

EXAMPLES:

```python
sage: C = cartesian_product([GF(2), GF(11), GF(7)])
sage: C.rank(C((1,2,5)))
96
sage: C.rank(C((0,0,0)))
0

sage: for c in C: print(C.rank(c))
0
1
2
3
4
5
...
150
151
152
153

sage: # needs sage.combinat
sage: F1 = FiniteEnumeratedSet('abcdefgh')
sage: F2 = IntegerRange(250)
sage: F3 = Partitions(20)
sage: C = cartesian_product([F1, F2, F3])
sage: c = C((a, 86, [7,5,4,4]))
sage: C.rank(c)
54213
sage: C.unrank(54213)
('a', 86, [7, 5, 4, 4])
```

unrank \((i)\)

Return the \( i \)-th element of this Cartesian product.

INPUT:

- \( i \) – integer between 0 and \( n-1 \) where \( n \) is the cardinality of this set.

See also:

- `EnumeratedSets.ParentMethods.unrank()`
- `rank()`

EXAMPLES:

```python
sage: C = cartesian_product([GF(3), GF(11), GF(7), GF(5)])
sage: c = C.unrank(123); c
(0, 3, 3, 3)
sage: C.rank(c)
123
sage: c = C.unrank(857); c
(continues on next page)
```
(continued from previous page)

```python
sage: C.rank(c)
857

sage: C.unrank(2500)
Traceback (most recent call last):
  ... IndexError: index i (=2) is greater than the cardinality
```

### extra_super_categories()

A Cartesian product of finite enumerated sets is a finite enumerated set.

**EXAMPLES:**

```python
sage: C = FiniteEnumeratedSets().CartesianProducts()
sage: C.extra_super_categories()
[Category of finite enumerated sets]
```

### class IsomorphicObjects(category, *args)

**Bases:** IsomorphicObjectsCategory

#### class ParentMethods

**Bases:** object

#### cardinality()

Returns the cardinality of `self` which is the same as that of the ambient set `self` is isomorphic to.

**EXAMPLES:**

```python
sage: A = FiniteEnumeratedSets().IsomorphicObjects().example(); A
The image by some isomorphism of An example of a finite enumerated set:
\rightarrow \{1,2,3\}
sage: A.cardinality()
3
```

#### example()

Returns an example of isomorphic object of a finite enumerated set, as per `Category.example`.

**EXAMPLES:**

```python
sage: FiniteEnumeratedSets().IsomorphicObjects().example()
The image by some isomorphism of An example of a finite enumerated set: \rightarrow \{1,2,3\}
```

### class ParentMethods

**Bases:** object

#### cardinality(*ignored_args, **ignored_kwds)

Return the cardinality of `self`.

This brute force implementation of `cardinality()` iterates through the elements of `self` to count them.

**EXAMPLES:**

---

4.56. Finite Enumerated Sets 445
sage: C = FiniteEnumeratedSets().example(); C
An example of a finite enumerated set: {1,2,3}
sage: C._cardinality_from_iterator()
3

iterator_range (start=None, stop=None, step=None)
Iterate over the range of elements of self starting at start, ending at stop, and stepping by step.

See also:
unrank(), unrank_range()

EXAMPLES:
sage: F = FiniteEnumeratedSet([1,2,3])
sage: list(F.iterator_range(1))
[2, 3]
sage: list(F.iterator_range(stop=2))
[1, 2]
sage: list(F.iterator_range(stop=2, step=2))
[1]
sage: list(F.iterator_range(start=1, step=2))
[2]
sage: list(F.iterator_range(start=1, stop=2))
[2]
sage: list(F.iterator_range(start=0, stop=1))
[1]
sage: list(F.iterator_range(start=0, stop=3, step=2))
[1, 3]
sage: list(F.iterator_range(stop=-1))
[1, 2]
sage: F = FiniteEnumeratedSet([1,2,3,4])
sage: list(F.iterator_range(start=1, stop=3))
[2, 3]
sage: list(F.iterator_range(stop=10))
[1, 2, 3, 4]

last ()
The last element of self.

self.last() returns the last element of self.

This is the default (brute force) implementation from the category FiniteEnumeratedSet() which can be used when the method __iter__ is provided. Its complexity is $O(n)$ where $n$ is the size of self.

EXAMPLES:
sage: C = FiniteEnumeratedSets().example()
sage: C.last()
3
sage: C._last_from_iterator()
3

random_element ()
A random element in self.

self.random_element() returns a random element in self with uniform probability.
This is the default implementation from the category `EnumeratedSet()` which uses the method `unrank`.

**EXAMPLES:**

```
sage: C = FiniteEnumeratedSets().example()
sage: n = C.random_element()
sage: n in C
True

sage: n = C._random_element_from_unrank()
sage: n in C
True
```

**TODO:** implement `_test_random` which checks uniformness.

**tuple()**

Return a tuple of the elements of `self`.

**EXAMPLES:**

```
sage: C = FiniteEnumeratedSets().example()
sage: C.tuple()
(1, 2, 3)
sage: C.tuple() is C.tuple()
True
```

**unrank_range**(start=None, stop=None, step=None)

Return the range of elements of `self` starting at `start`, ending at `stop`, and stepping by `step`.

See also `unrank()`.

**EXAMPLES:**

```
sage: F = FiniteEnumeratedSet([1,2,3])
sage: F.unrank_range(1)
[2, 3]
sage: F.unrank_range(stop=2)
[1, 2]
sage: F.unrank_range(stop=2, step=2)
[1]
sage: F.unrank_range(start=1, step=2)
[2]
sage: F.unrank_range(stop=-1)
[1, 2]
sage: F = FiniteEnumeratedSet([1,2,3,4])
sage: F.unrank_range(stop=10)
[1, 2, 3, 4]
```
4.57 Finite fields

class sage.categories.finite_fields.FiniteFields(base_category):
    Bases: CategoryWithAxiom_singleton
    The category of finite fields.

    EXAMPLES:

    sage: K = FiniteFields(); K
    Category of finite enumerated fields

    A finite field is a finite monoid with the structure of a field; it is currently assumed to be enumerated:

    sage: K = FiniteFields(); K
    Category of finite enumerated fields

    Some examples of membership testing and coercion:

    sage: FiniteField(17) in K
    True
    sage: RationalField() in K
    False
    sage: K(RationalField())
    Traceback (most recent call last):
    ...
    TypeError: unable to canonically associate a finite field to Rational Field

    class ElementMethods
        Bases: object
    class ParentMethods
        Bases: object

    extra_super_categories()
    Any finite field is assumed to be endowed with an enumeration.

4.58 Finite groups

class sage.categories.finite_groups.FiniteGroups(base_category):
    Bases: CategoryWithAxiom_singleton
    The category of finite (multiplicative) groups.

    EXAMPLES:

    sage: C = FiniteGroups(); C
    Category of finite groups
    sage: C.super_categories()
    [Category of finite monoids, Category of groups]
    sage: C.example()
    General Linear Group of degree 2 over Finite Field of size 3
class Algebras(category, *args)
    Bases: AlgebrasCategory

class ParentMethods
    Bases: object
    extra_super_categories()
    Implement Maschke’s theorem.

    In characteristic 0 all finite group algebras are semisimple.

    EXAMPLES:

        sage: FiniteGroups().Algebras(QQ).is_subcategory(Algebras(QQ).Semisimple())
        True
        sage: FiniteGroups().Algebras(FiniteField(7)).is_subcategory(Algebras(FiniteField(7)).Semisimple())
        False
        sage: FiniteGroups().Algebras(ZZ).is_subcategory(Algebras(ZZ).Semisimple())
        False
        sage: FiniteGroups().Algebras(Fields()).is_subcategory(Algebras(Fields()).Semisimple())
        False

        sage: Cat = CommutativeAdditiveGroups().Finite()
        sage: Cat.Algebras(QQ).is_subcategory(Algebras(QQ).Semisimple())
        True
        sage: Cat.Algebras(GF(7)).is_subcategory(Algebras(GF(7)).Semisimple())
        False
        sage: Cat.Algebras(ZZ).is_subcategory(Algebras(ZZ).Semisimple())
        False
        sage: Cat.Algebras(Fields()).is_subcategory(Algebras(Fields()).Semisimple())
        False

    class ElementMethods
        Bases: object

    class ParentMethods
        Bases: object
        cardinality()

            Returns the cardinality of self, as per EnumeratedSets.ParentMethods.cardinality().

            This default implementation calls order() if available, and otherwise resorts to _cardinality_from_iterator(). This is for backward compatibility only. Finite groups should override this method instead of order().

            EXAMPLES:

            We need to use a finite group which uses this default implementation of cardinality:

                sage: G = groups.misc.SemimonomialTransformation(GF(5), 3); G
                Semimonomial transformation group over Finite Field of size 5 of degree 3
                sage: G.cardinality.__module__
                'sage.categories.finite_groups'

                (continues on next page)
cayley_graph_disabled (connecting_set=None)

 AUTHORS:
• Bobby Moretti (2007-08-10)
• Robert Miller (2008-05-01): editing

 conjugacy_classes()

 Return a list with all the conjugacy classes of the group.

 This will eventually be a fall-back method for groups not defined over GAP. Right now, it just raises a
 Not Implemented Error, until we include a non-GAP way of listing the conjugacy classes representatives.

 EXAMPLES:

 sage: G = SymmetricGroup(3)
 sage: G.conjugacy_classes_representatives()
 [(), (1,2), (1,2,3)]

 monoid_generators()

 Return monoid generators for self.

 For finite groups, the group generators are also monoid generators. Hence, this default implementation
calls group_generators().

 EXAMPLES:

 sage: A = AlternatingGroup(4)
 sage: A.monoid_generators()
 Family ((2,3,4), (1,2,3))

 semigroup_generators()

 Returns semigroup generators for self.

 For finite groups, the group generators are also semigroup generators. Hence, this default implementation
calls group_generators().

 EXAMPLES:

 sage: A = AlternatingGroup(4)
 sage: A.semigroup_generators()
 Family ((2,3,4), (1,2,3))
some_elements()

Return some elements of self.

EXAMPLES:

```
sage: A = AlternatingGroup(4)
sage: A.some_elements()
Family ((2,3,4), (1,2,3))
```

element()

Return an example of finite group, as per Category.example().

EXAMPLES:

```
sage: G = FiniteGroups().example(); G
General Linear Group of degree 2 over Finite Field of size 3
```

### 4.59 Finite lattice posets

class sage.categories.finite_lattice_posets.FiniteLatticePosets(base_category)

Bases: CategoryWithAxiom

The category of finite lattices, i.e. finite partially ordered sets which are also lattices.

EXAMPLES:

```
sage: FiniteLatticePosets()
Category of finite lattice posets
sage: FiniteLatticePosets().super_categories()
[Category of lattice posets, Category of finite posets]
sage: FiniteLatticePosets().example()
NotImplemented
```

See also:

FinitePosets, LatticePosets, FiniteLatticePoset

class ParentMethods

Bases: object

irreducibles_poset()

Return the poset of meet- or join-irreducibles of the lattice.

A join-irreducible element of a lattice is an element with exactly one lower cover. Dually a
meet-irreducible element has exactly one upper cover.

This is the smallest poset with completion by cuts being isomorphic to the lattice. As a special case this
returns one-element poset from one-element lattice.

See also:

completion_by_cuts().

EXAMPLES:
is_lattice_morphism\( (f, \text{codomain}) \)

Return whether \(f\) is a morphism of posets from \(\text{self}\) to \(\text{codomain}\).

A map \(f : P \to Q\) is a poset morphism if

\[
x \leq y \Rightarrow f(x) \leq f(y)
\]

for all \(x, y \in P\).

**INPUT:**

- \(f\) – a function from \(\text{self}\) to \(\text{codomain}\)
- \(\text{codomain}\) – a lattice

**EXAMPLES:**

We build the boolean lattice of \(\{2, 2, 3\}\) and the lattice of divisors of 60, and check that the map \(b \mapsto 5 \prod_{x \in b} x\) is a morphism of lattices:

```python
sage: D = LatticePoset((divisors(60), attrcall("divides")))  # needs sage.graphs sage.modules
sage: B = LatticePoset((Subsets([2,2,3]), attrcall("issubset")))  # needs sage.graphs sage.modules
sage: def f(b):
...     return D(5*prod(b))
... 
sage: B.is_lattice_morphism(f, D)  # needs sage.graphs sage.modules
True
```

We construct the boolean lattice \(B_2\):

```python
sage: B = posets.BooleanLattice(2)  # needs sage.graphs
sage: B.cover_relations()  # needs sage.graphs
[[0, 1], [0, 2], [1, 3], [2, 3]]
```

And the same lattice with new top and bottom elements numbered respectively \(-1\) and \(3\):

```python
sage: G = DiGraph({[-1:0], 0:[1,2], 1:[3], 2:[3], 3:[4]})  # needs sage.graphs
sage: L = LatticePoset(G)  # needs sage.graphs sage.modules
sage: L.cover_relations()  # needs sage.graphs sage.modules
[[-1, 0], [0, 1], [0, 2], [1, 3], [2, 3], [3, 4]]
```

```python
sage: f = {B(0): L(0), B(1): L(1), B(2): L(2), B(3): L(3)}.__getitem__  # needs sage.graphs sage.modules
sage: B.is_lattice_morphism(f, L)  # needs sage.graphs sage.modules
```

(continues on next page)
True

```python
sage: f = {B(0): L(-1), B(1): L(1), B(2): L(2), B(3): L(3)}.__getitem__  #-
     __needs sage.graphs sage.modules
sage: B.is_lattice_morphism(f, L)  #-
     __needs sage.graphs sage.modules
False

sage: f = {B(0): L(0), B(1): L(1), B(2): L(2), B(3): L(4)}.__getitem__  #-
     __needs sage.graphs sage.modules
sage: B.is_lattice_morphism(f, L)  #-
     __needs sage.graphs sage.modules
False
```

See also:

- `is_poset_morphism()`

### join_irreducibles()

Return the join-irreducible elements of this finite lattice.

A **join-irreducible element** of `self` is an element `x` that is not minimal and that cannot be written as the join of two elements different from `x`.

**EXAMPLES:**

```python
sage: L = LatticePoset({0:[1,2], 1:[3], 2:[3,4], 3:[5], 4:[5]})  #-
     __needs sage.graphs sage.modules
sage: L.join_irreducibles()  #-
     __needs sage.graphs sage.modules
[1, 2, 4]
```

See also:

- Dual function: `meet_irreducibles()`
- Other: `double_irreducibles()`, `join_irreducibles_poset()`

### join_irreducibles_poset()

Return the poset of join-irreducible elements of this finite lattice.

A **join-irreducible element** of `self` is an element `x` that is not minimal and cannot be written as the join of two elements different from `x`.

**EXAMPLES:**

```python
sage: L = LatticePoset({0:[1,2,3], 1:[4], 2:[4], 3:[4]})  #-
     __needs sage.graphs sage.modules
sage: L.join_irreducibles_poset()  #-
     __needs sage.graphs sage.modules
Finite poset containing 3 elements
```

See also:

- Dual function: `meet_irreducibles_poset()`
- Other: `join_irreducibles()`

### meet_irreducibles()

Return the meet-irreducible elements of this finite lattice.
A \textit{meet-irreducible element} of \texttt{self} is an element \(x\) that is not maximal and that can not be written as the meet of two elements different from \(x\).

**EXAMPLES:**

```python
sage: L = LatticePoset({0:[1,2], 1:[3], 2:[3,4], 3:[5], 4:[5]})  # needs sage.graphs sage.modules
sage: L.meet_irreducibles()  # needs sage.graphs sage.modules
[1, 3, 4]
```

See also:

- Dual function: \texttt{join_irreducibles()}
- Other: \texttt{double_irreducibles(), meet_irreducibles_poset()}

### meet_irreducibles_poset()

Return the poset of join-irreducible elements of this finite lattice.

A \textit{meet-irreducible element} of \texttt{self} is an element \(x\) that is not maximal and can not be written as the meet of two elements different from \(x\).

**EXAMPLES:**

```python
sage: L = LatticePoset({0:[1,2,3], 1:[4], 2:[4], 3:[4]})  # needs sage.graphs sage.modules
sage: L.join_irreducibles_poset()  # needs sage.graphs sage.modules
Finite poset containing 3 elements
```

See also:

- Dual function: \texttt{join_irreducibles_poset()}
- Other: \texttt{meet_irreducibles()}

### 4.60 Finite monoids

**class** `sage.categories.finite_monoids.FiniteMonoids`(\texttt{base_category})

Bases: \texttt{CategoryWithAxiom_singleton}

The category of finite (multiplicative) monoids.

A finite monoid is a \textit{finite sets} endowed with an associative unital binary operation \(*\).

**EXAMPLES:**

```python
sage: FiniteMonoids()
Category of finite monoids
sage: FiniteMonoids().super_categories()
[Category of monoids, Category of finite semigroups]
```

**class** `ElementMethods`

Bases: \texttt{object}

**pseudo_order()**

Return the pair \([k, j]\) with \(k\) minimal and \(0 \leq j < k\) such that \(\texttt{self}^k = \texttt{self}^j\).

Note that \(j\) is uniquely determined.
EXAMPLES:

```python
sage: M = FiniteMonoids().example(); M
An example of a finite multiplicative monoid: the integers modulo 12

sage: x = M(2)
sage: [ x^i for i in range(7) ]
[1, 2, 4, 8, 4, 8, 4]
sage: x.pseudo_order()
[4, 2]

sage: x = M(3)
sage: [ x^i for i in range(7) ]
[1, 3, 9, 3, 9, 3, 9]
sage: x.pseudo_order()
[3, 1]

sage: x = M(4)
sage: [ x^i for i in range(7) ]
[1, 4, 4, 4, 4, 4, 4]
sage: x.pseudo_order()
[2, 1]

sage: x = M(5)
sage: [ x^i for i in range(7) ]
[1, 5, 1, 5, 1, 5, 1]
sage: x.pseudo_order()
[2, 0]
```

Todo: more appropriate name? see, for example, Jean-Eric Pin’s lecture notes on semigroups.

```python
class ParentMethods
    Bases: object

    nerve()
    The nerve (classifying space) of this monoid.

    OUTPUT:
    the nerve $BG$ (if $G$ denotes this monoid), as a simplicial set. The $k$-dimensional simplices of this object
    are indexed by products of $k$ elements in the monoid:

    $a_1 \ast a_2 \ast \cdots \ast a_k$

    The 0th face of this is obtained by deleting $a_1$, and the $k$-th face is obtained by deleting $a_k$. The other
    faces are obtained by multiplying elements: the 1st face is

    $(a_1 \ast a_2) \ast \cdots \ast a_k$

    and so on. See Wikipedia article Nerve_(category_theory), which describes the construction of the nerve
    as a simplicial set.

    A simplex in this simplicial set will be degenerate if in the corresponding product of $k$ elements, one of
    those elements is the identity. So we only need to keep track of the products of non-identity elements.
    Similarly, if a product $a_{i-1} a_i$ is the identity element, then the corresponding face of the simplex will be
    a degenerate simplex.

    EXAMPLES:
```

4.60. Finite monoids 455
The nerve (classifying space) of the cyclic group of order 2 is infinite-dimensional real projective space.

```sage
sage: Sigma2 = groups.permutation.Cyclic(2)  # needs sage.groups
sage: BSigma2 = Sigma2.nerve()  # needs sage.groups
sage: BSigma2.cohomology(4, base_ring=GF(2))  # needs sage.groups sage.modules
Vector space of dimension 1 over Finite Field of size 2
```

The $k$-simplices of the nerve are named after the chains of $k$ non-unit elements to be multiplied. The group $\Sigma_2$ has two elements, written $()$ (the identity element) and $(1,2)$ in Sage. So the 1-cells and 2-cells in $B\Sigma_2$ are:

```sage
sage: BSigma2.n_cells(1)  # needs sage.groups
[(1,2)]
sage: BSigma2.n_cells(2)  # needs sage.groups
[(1,2) * (1,2)]
```

Another construction of the group, with different names for its elements:

```sage
sage: # needs sage.groups
sage: C2 = groups.misc.MultiplicativeAbelian([2])
sage: BC2 = C2.nerve()
sage: BC2.n_cells(0)  # needs sage.groups
[1]
sage: BC2.n_cells(1)  # needs sage.groups
[f]
sage: BC2.n_cells(2)  # needs sage.groups
[f * f]
```

With mod $p$ coefficients, $B\Sigma_p$ should have its first nonvanishing homology group in dimension $p$:

```sage
sage: Sigma3 = groups.permutation.Symmetric(3)  # needs sage.groups
sage: BSigma3 = Sigma3.nerve()  # needs sage.groups
sage: BSigma3.homology(range(4), base_ring=GF(3))  # needs sage.groups
{0: Vector space of dimension 0 over Finite Field of size 3,
 1: Vector space of dimension 0 over Finite Field of size 3,
 2: Vector space of dimension 0 over Finite Field of size 3,
 3: Vector space of dimension 1 over Finite Field of size 3}
```

Note that we can construct the $n$-skeleton for $B\Sigma_2$ for relatively large values of $n$, while for $B\Sigma_3$, the complexes get large pretty quickly:

```sage
sage: # needs sage.groups
sage: Sigma2.nerve().n_skeleton(14)
Simplicial set with 15 non-degenerate simplices
sage: BSigma3 = Sigma3.nerve()
sage: BSigma3.n_skeleton(3)
Simplicial set with 156 non-degenerate simplices
sage: BSigma3.n_skeleton(4)
Simplicial set with 781 non-degenerate simplices
```
Finally, note that the classifying space of the order $p$ cyclic group is smaller than that of the symmetric group on $p$ letters, and its first homology group appears earlier:

```python
sage: # needs sage.groups
sage: C3 = groups.misc.MultiplicativeAbelian([3])
sage: list(C3)
[1, f, f^2]
sage: BC3 = C3.nerve()
sage: BC3.n_cells(1)
[f, f^2]
sage: len(BC3.n_cells(2))
25
sage: len(BC3.n_cells(3))
8
sage: BC5 = groups.permutation.Cyclic(5).nerve()
sage: BC5.homology(range(4), base_ring=GF(5))
{0: Vector space of dimension 0 over Finite Field of size 5,
 1: Vector space of dimension 1 over Finite Field of size 5,
 2: Vector space of dimension 1 over Finite Field of size 5,
 3: Vector space of dimension 1 over Finite Field of size 5}
```

**rhodes_radical_congruence** *(base_ring=None)*

Return the Rhodes radical congruence of the semigroup.

The Rhodes radical congruence is the congruence induced on $S$ by the map $S \to kS \to kS/rad kS$ with $k$ a field.

**INPUT:**
- `base_ring` *(default: **Q**)* a field

**OUTPUT:**
- A list of couples $(m, n)$ with $m \neq n$ in the lexicographic order for the enumeration of the monoid `self`.

**EXAMPLES:**

```python
sage: M = Monoids().Finite().example()
sage: M.rhodes_radical_congruence()  # needs sage.modules
[(0, 6), (2, 8), (4, 10)]
sage: from sage.monoids.hecke_monoid import HeckeMonoid
sage: H3 = HeckeMonoid(SymmetricGroup(3))
sage: H3.repr_element_method(style="reduced")
sage: H3.rhodes_radical_congruence()
((([1, 2], [2, 1]), ([1, 2], [1, 2, 1]), ([2, 1], [1, 2, 1]))
```

By Maschke’s theorem, every group algebra over **Q** is semisimple hence the Rhodes radical of a group must be trivial:

4.60. Finite monoids 457
REFERENCES:

• [Rho69]

4.61 Finite Permutation Groups

class sage.categories.finite_permutation_groups.FinitePermutationGroups(base_category):

Bases: CategoryWithAxiom

The category of finite permutation groups, i.e. groups concretely represented as groups of permutations acting on a finite set.

It is currently assumed that any finite permutation group comes endowed with a distinguished finite set of generators (method group_generators); this is the case for all the existing implementations in Sage.

EXAMPLES:

```python
sage: C = PermutationGroups().Finite(); C
Category of finite enumerated permutation groups
sage: C.super_categories()
[Category of permutation groups, Category of finite groups, Category of finite finitely generated semigroups]

sage: C.example()
Dihedral group of order 6 as a permutation group
```

class ElementMethods

    bases: object

class ParentMethods

    bases: object

cycle_index(parent=None)

    Return the cycle index of self.

    INPUT:
    • self - a permutation group \( G \)
    • parent - a free module with basis indexed by partitions, or behave as such, with a term and sum method (default: the symmetric functions over the rational field in the \( p \) basis)

    The cycle index of a permutation group \( G \) (Wikipedia article Cycle_index) is a gadget counting the elements of \( G \) by cycle type, averaged over the group:

    \[
P = \frac{1}{|G|} \sum_{g \in G} p_{\text{cycle type}(g)}
    \]

    EXAMPLES:

    Among the permutations of the symmetric group \( S_4 \), there is the identity, 6 cycles of length 2, 3 products of two cycles of length 2, 8 cycles of length 3, and 6 cycles of length 4:
```
sage: S4 = SymmetricGroup(4)
sage: P = S4.cycle_index()
sage: 24 * P
p[1, 1, 1, 1] + 6*p[2, 2, 1] + 3*p[2, 1, 2] + 8*p[2, 1, 1, 1] + 6*p[3, 1]
```

If $l = (l_1, \ldots, l_k)$ is a partition, $|G|$ $P(l)$ is the number of elements of $G$ with cycles of length $(p_1, \ldots, p_k)$:

```
sage: 24 * P[ Partition([3,1]) ]
8
```

The cycle index plays an important role in the enumeration of objects modulo the action of a group (Pólya enumeration), via the use of symmetric functions and plethysms. It is therefore encoded as a symmetric function, expressed in the powersum basis:

```
sage: P.parent()
Symmetric Functions over Rational Field in the powersum basis
```

This symmetric function can have some nice properties; for example, for the symmetric group $S_n$, we get the complete symmetric function $h_n$:

```
sage: S = SymmetricFunctions(QQ); h = S.h()
sage: h( P )
h[4]
```

**Todo:** Add some simple examples of Pólya enumeration, once it will be easy to expand symmetric functions on any alphabet.

Here are the cycle indices of some permutation groups:

```
sage: 6 * CyclicPermutationGroup(6).cycle_index()
p[1, 1, 1, 1, 1] + 6*p[2, 2, 1] + 3*p[2, 1, 2] + 8*p[2, 1, 1, 1] + 6*p[3, 1]
sage: 60 * AlternatingGroup(5).cycle_index()
sage: for G in TransitiveGroups(5):  # long time
    ....:    G.cardinality() * G.cycle_index()
p[1, 1, 1, 1, 1] + 4*p[5]
p[1, 1, 1, 1, 1] + 5*p[2, 2, 1] + 4*p[5]
p[1, 1, 1, 1, 1] + 5*p[2, 2, 1] + 10*p[4, 1] + 4*p[5]
```

Permutation groups with arbitrary domains are supported (see [github issue #22765](https://github.com/sagemath/sage/issues/22765)):

```
sage: G = PermutationGroup([['b','c','a']], domain=['a','b','c'])
sage: G.cycle_index()
1/3*p[1, 1, 1] + 2/3*p[3]
```

One may specify another parent for the result:

```
sage: F = CombinatorialFreeModule(QQ, Partitions())
sage: P = CyclicPermutationGroup(6).cycle_index(parent = F)
```

(continues on next page)
This parent should be a module with basis indexed by partitions:

```
sage: P.parent() is F
True
```

REFERENCES:
- [Ke1991]

AUTHORS:
- Nicolas Borie and Nicolas M. Thiéry

**profile** *(n, using_polya=True)*

Return the value in *n* of the profile of the group *self*.

Optional argument `using_polya` allows to change the default method.

**INPUT:**
- *n* – a nonnegative integer
- `using_polya` (optional) – a boolean: if `True` (default), the computation uses Pólya enumeration (and all values of the profile are cached, so this should be the method used in case several of them are needed); if `False`, uses the GAP interface to compute the orbit.

**OUTPUT:**
- A nonnegative integer that is the number of orbits of *n*-subsets under the action induced by *self* on the subsets of its domain (i.e. the value of the profile of *self* in *n*)

See also:
- `profile_series()`

**EXAMPLES:**

```
sage: C6 = CyclicPermutationGroup(6)
sage: C6.profile(2)
3
sage: C6.profile(3)
4
sage: D8 = DihedralGroup(8)
sage: D8.profile(4, using_polya=False)
8
```

**profile_polynomial** *(variable='z')*

Return the (finite) generating series of the (finite) profile of the group.

The profile of a permutation group *G* is the counting function that maps each nonnegative integer *n* onto the number of orbits of the action induced by *G* on the *n*-subsets of its domain. If *f* is the profile of *G*, *f*(n) is thus the number of orbits of *n*-subsets of *G*.

**INPUT:**
- `variable` – a variable, or variable name as a string (default: 'z')

**OUTPUT:**
- A polynomial in `variable` with nonnegative integer coefficients. By default, a polynomial in *z* over ZZ.
profile_series \(\text{variable}='z'\)

Return the (finite) generating series of the (finite) profile of the group.

The profile of a permutation group \(G\) is the counting function that maps each nonnegative integer \(n\) onto the number of orbits of the action induced by \(G\) on the \(n\)-subsets of its domain. If \(f\) is the profile of \(G\), \(f(n)\) is thus the number of orbits of \(n\)-subsets of \(G\).

INPUT:
- \text{variable} – a variable, or variable name as a string (default: ’z’)

OUTPUT:
- A polynomial in \text{variable} with nonnegative integer coefficients. By default, a polynomial in \(z\) over \(\mathbb{Z}\).

See also:
- \text{profile()}
EXAMPLES:

```python
sage: G = FinitePermutationGroups().example(); G
Dihedral group of order 6 as a permutation group
```

```python
extra_super_categories()
```

Any permutation group is assumed to be endowed with a finite set of generators.

## 4.62 Finite posets

Here is some terminology used in this file:

- An **order filter** (or **upper set**) of a poset $P$ is a subset $S$ of $P$ such that if $x \leq y$ and $x \in S$ then $y \in S$.
- An **order ideal** (or **lower set**) of a poset $P$ is a subset $S$ of $P$ such that if $x \leq y$ and $y \in S$ then $x \in S$.

```python
class sage.categories.finite_posets.FinitePosets(base_category)
Bases: CategoryWithAxiom

The category of finite posets i.e. finite sets with a partial order structure.

EXAMPLES:

```python
sage: FinitePosets()
Category of finite posets
sage: FinitePosets().super_categories()
[Category of posets, Category of finite sets]
sage: FinitePosets().example()
NotImplemented
```

See also:

*Posets*, Poset()

```python
class ParentMethods
Bases: object

antichains()
```

Return all antichains of self.

EXAMPLES:

```python
sage: A = posets.PentagonPoset().antichains(); A
Set of antichains of Finite lattice containing 5 elements
sage: list(A)
[[], [0], [1], [1, 2], [1, 3], [2], [3], [4]]
```

```python
birational_free_labelling(linear_extension=None, prefix='x', base_field=None,
reduced=False, addvars=None, labels=None, min_label=None,
max_label=None)
```

Return the birational free labelling of self.

Let us hold back defining this, and introduce birational toggles and birational rowmotion first. These notions have been introduced in [EP2013] as generalizations of the notions of toggles (order_ideal_toggle()) and rowmotion on order ideals of a finite poset. They have been studied further in [GR2013].
Let $K$ be a field, and $P$ be a finite poset. Let $\hat{P}$ denote the poset obtained from $P$ by adding a new element $1$ which is greater than all existing elements of $P$, and a new element $0$ which is smaller than all existing elements of $P$ and $1$. Now, a $K$-labelling of $P$ will mean any function from $\hat{P}$ to $K$. The image of an element $v$ of $\hat{P}$ under this labelling will be called the label of this labelling at $v$. The set of all $K$-labellings of $P$ is clearly $K^{\hat{P}}$.

For any $v \in P$, we now define a rational map $T_v : K^{\hat{P}} \rightarrow K^{\hat{P}}$ as follows: For every $f \in K^{\hat{P}}$, the image $T_v f$ should send every element $u \in \hat{P}$ distinct from $v$ to $f(u)$ (so the labels at all $u \neq v$ don't change), while $v$ is sent to

$$\frac{1}{f(v)} \cdot \sum_{u < v} f(u) \cdot \frac{1}{\sum_{u > v} f(u)}$$

(both sums are over all $u \in \hat{P}$ satisfying the respectively given conditions). Here, $<$ and $>$ mean (respectively) "covered by" and "covers", interpreted with respect to the poset $\hat{P}$. This rational map $T_v$ is an involution and is called the (birational) $v$-toggle; see birational_toggle() for its implementation.

Now, birational rowmotion is defined as the composition $T_{v_n} \circ T_{v_{n-1}} \circ \cdots \circ T_{v_1}$, where $(v_1, v_2, \ldots, v_n)$ is a linear extension of $P$ (written as a linear ordering of the elements of $P$). This is a rational map $K^{\hat{P}} \rightarrow K^{\hat{P}}$ which does not depend on the choice of the linear extension; it is denoted by $R$. See birational_rowmotion() for its implementation.

The definitions of birational toggles and birational rowmotion extend to the case of $K$ being any semifield rather than necessarily a field (although it becomes less clear what constitutes a rational map in this generality). The most useful case is that of the tropical semiring, in which case birational rowmotion relates to classical constructions such as promotion of rectangular semistandard Young tableaux (page 5 of [EP2013b] and future work, via the related notion of birational promotion) and rowmotion on order ideals of the poset ([EP2013]).

The birational free labelling is a special labelling defined for every finite poset $P$ and every linear extension $(v_1, v_2, \ldots, v_n)$ of $P$. It is given by sending every element $v_i$ in $P$ to $x_i$, sending the element $0$ of $\hat{P}$ to $a$, and sending the element $1$ of $\hat{P}$ to $b$, where the ground field $K$ is the field of rational functions in $n + 2$ indeterminates $a, x_1, x_2, \ldots, x_n, b$ over $\mathbb{Q}$.

In Sage, a labelling $f$ of a poset $P$ is encoded as a 4-tuple $(K, d, u, v)$, where $K$ is the ground field of the labelling (i.e., its target), $d$ is the dictionary containing the values of $f$ at the elements of $P$ (the keys being the respective elements of $P$), $u$ is the label of $f$ at $0$, and $v$ is the label of $f$ at $1$.

**Warning:** The dictionary $d$ is labelled by the elements of $P$. If $P$ is a poset with facade option set to False, these might not be what they seem to be! (For instance, if $P == \text{Poset}([1: [2, 3]], \text{facade}=\text{False})$, then the value of $d$ at $1$ has to be accessed by $d[P(1)]$, not by $d[1]$.)

**Warning:** Dictionaries are mutable. They do compare correctly, but are not hashable and need to be cloned to avoid spooky action at a distance. Be careful!

**INPUT:**
- linear_extension – (default: the default linear extension of self) a linear extension of self (as a linear extension or as a list), or more generally a list of all elements of all elements of self each occurring exactly once
- prefix – (default: ‘x’) the prefix to name the indeterminates corresponding to the elements of self in the labelling (so, setting it to ‘frog’ will result in these indeterminates being called frog1, frog2, ..., frogn rather than x1, x2, ..., xn).
• base_field – (default: QQ) the base field to be used instead of \( \mathbb{Q} \) to define the rational function field over; this is not going to be the base field of the labelling, because the latter will have indeterminates adjoined!

• reduced – (default: False) if set to True, the result will be the reduced birational free labelling, which differs from the regular one by having 0 and 1 both sent to 1 instead of \( a \) and \( b \) (the indeterminates \( a \) and \( b \) then also won’t appear in the ground field)

• addvars – (default: '') a string containing names of extra variables to be adjoined to the ground field (these don’t have an effect on the labels)

• labels – (default: 'x') Either a function that takes an element of the poset and returns a name for the indeterminate corresponding to that element, or a string containing a comma-separated list of indeterminates that will be assigned to elements in the order of linear_extension. If the list contains more indeterminates than needed, the excess will be ignored. If it contains too few, then the needed indeterminates will be constructed from prefix.

• min_label – (default: 'a') a string to be used as the label for the element 0 of \( \hat{P} \)

• max_label – (default: 'b') a string to be used as the label for the element 1 of \( \hat{P} \)

OUTPUT:

The birational free labelling of the poset self and the linear extension linear_extension. Or, if reduced is set to True, the reduced birational free labelling.

EXAMPLES:

We construct the birational free labelling on a simple poset:

```python
sage: P = Poset({1: [2, 3]})
sage: l = P.birational_free_labelling(); l
(Fraction Field of Multivariate Polynomial Ring in a, x1, x2, x3, b over Rational Field, {...}, a, b)
sage: sorted(l[1].items())
[(1, x1), (2, x2), (3, x3)]

sage: l = P.birational_free_labelling(linear_extension=[1, 3, 2]); l
(Fraction Field of Multivariate Polynomial Ring in a, x1, x2, x3, b over Rational Field, {...}, a, b)
sage: sorted(l[1].items())
[(1, x1), (2, x3), (3, x2)]

sage: l = P.birational_free_labelling(linear_extension=[1, 3, 2], reduced=True, addvars="spam, eggs"); l
(Fraction Field of Multivariate Polynomial Ring in x1, x2, x3, spam, eggs over Rational Field, {...}, 1, 1)
sage: sorted(l[1].items())
[(1, x1), (2, x3), (3, x2)]

sage: l = P.birational_free_labelling(linear_extension=[1, 3, 2], prefix="wut", reduced=True, addvars="spam, eggs"); l
(Fraction Field of Multivariate Polynomial Ring in wut1, wut2, wut3, spam, eggs over Rational Field, {...},)
```

(continues on next page)
Illustrating labelling with a function:

```
sage: P = posets.ChainPoset(2).product(posets.ChainPoset(2))
sage: l = P.birational_free_labelling(labels=lambda e : 'x_' + str(e[0]) + str(e[1]), min_label="lambda", max_label="mu")
sage: sorted(l[1].items())
[((0, 0), x_00), ((0, 1), x_01), ((1, 0), x_10), ((1, 1), x_11)]
sage: l[2]
lambda
sage: l[3]
mu
```

Illustrating labelling with a comma separated list of labels:

```
sage: l = P.birational_free_labelling(labels='w,x,y,z')
sage: sorted(l[1].items())
[((0, 0), w), ((0, 1), x), ((1, 0), y), ((1, 1), z)]
sage: l = P.birational_free_labelling(labels='w,x,y,z,m')
sage: sorted(l[1].items())
[((0, 0), w), ((0, 1), x), ((1, 0), y), ((1, 1), z)]
sage: l = P.birational_free_labelling(labels='w')
sage: sorted(l[1].items())
[((0, 0), w), ((0, 1), x1), ((1, 0), x2), ((1, 1), x3)]
```

Illustrating the warning about facade:

```
sage: P = Poset({1: [2, 3]}, facade=False)
sage: l = P.birational_free_labelling(linear_extension=[1, 3, 2], reduced=False, addvars="spam, eggs"); l
(Fraction Field of Multivariate Polynomial Ring in a, x1, x2, x3, b, spam, spam)
```

(continues on next page)
eggs over Rational Field,
(...),
a,
b)
sage: l[1][2]
Traceback (most recent call last):
...
KeyError: 2
sage: l[1][P(2)]
x3

Another poset:

sage: P = posets.SSTPoset([2,1])
sage: ext = sorted(P)
sage: l = P.birational_free_labelling(linear_extension=ext, addvars="ohai ...")
sage: l
(Fraction Field of Multivariate Polynomial Ring in a, x1, x2, x3, x4, x5,...
→x6, x7, x8, b, ohai over Rational Field,
(...),
a,
b)
sage: sorted(l[1].items())
[(\[[1, 1], [2]\], x1), (\[[1, 1], [3]\], x2), (\[[1, 2], [2]\], x3), (\[[1, 2],...
→\[3]\], x4),
(\[[1, 3], [2]\], x5), (\[[1, 3], [3]\], x6), (\[[2, 2], [3]\], x7), (\[[2, 3],...
→\[3]\], x8)]

See \texttt{birational_rowmotion()}, \texttt{birational_toggle()} and \texttt{birational_toggles()} for more substantial examples of what one can do with the birational free labelling.

\textbf{birational_rowmotion (labelling)}

Return the result of applying birational rowmotion to the \(K\)-labelling \texttt{labelling} of the poset \texttt{self}.

See the documentation of \texttt{birational_free_labelling()} for a definition of birational rowmotion and \(K\)-labellings and for an explanation of how \(K\)-labellings are to be encoded to be understood by Sage. This implementation allows \(K\) to be a semifield, not just a field. Birational rowmotion is only a rational map, so an exception (most likely, \texttt{ZeroDivisionError}) will be thrown if the denominator is zero.

\textbf{INPUT}:

- \texttt{labelling} – a \(K\)-labelling of \texttt{self} in the sense as defined in the documentation of \texttt{birational_free_labelling()}

\textbf{OUTPUT}:

The image of the \(K\)-labelling \(f\) under birational rowmotion.

\textbf{EXAMPLES}:

sage: P = Poset({1: [2, 3], 2: [4], 3: [4]})
sage: lex = [1, 2, 3, 4]
sage: t = P.birational_free_labelling(linear_extension=lex); t
(Fraction Field of Multivariate Polynomial Ring in a, x1, x2, x3, x4, b...
→over Rational Field,
(...),
a,
A result of [GR2013] states that applying birational rowmotion $n + m$ times to a $K$-labelling $f$ of the poset $[n] \times [m]$ gives back $f$. Let us check this:

```
sage: def test_rectangle_periodicity(n, m, k):
    ....:     P = posets.ChainPoset(n).product(posets.ChainPoset(m))
    ....:     t0 = P.birational_free_labelling(P)
    ....:     t = t0
    ....:     for i in range(k):
    ....:         t = P.birational_rowmotion(t)
    ....:     return t == t0
sage: test_rectangle_periodicity(2, 2, 4)
True
sage: test_rectangle_periodicity(2, 2, 2)
False
sage: test_rectangle_periodicity(2, 3, 5)  # long time
True
```

While computations with the birational free labelling quickly run out of memory due to the complexity of the rational functions involved, it is computationally cheap to check properties of birational rowmotion on examples in the tropical semiring:

```
sage: def test_rectangle_periodicity_tropical(n, m, k):
    ....:     P = posets.ChainPoset(n).product(posets.ChainPoset(m))
    ....:     TT = TropicalSemiring(ZZ)
    ....:     t0 = (TT, {v: TT(randint(0, 99)) for v in P}, TT(0), TT(124))
    ....:     t = t0
    ....:     for i in range(k):
    ....:         t = P.birational_rowmotion(t)
    ....:     return t == t0
sage: test_rectangle_periodicity_tropical(7, 6, 13)
True
```

Tropicalization is also what relates birational rowmotion to classical rowmotion on order ideals. In fact, if $T$ denotes the tropical semiring of $\mathbb{Z}$ and $P$ is a finite poset, then we can define an embedding $\phi$ from the set $J(P)$ of all order ideals of $P$ into the set $T^P$ of all $T$-labellings of $P$ by sending every $I \in J(P)$ to the indicator function of $I$ extended by the value 1 at the element 0 and the value 0 at the element 1. This map $\phi$ has the property that $R \circ \phi = \phi \circ r$, where $R$ denotes birational rowmotion, and $r$ denotes classical rowmotion on $J(P)$. An example:

```
sage: P = posets.IntegerPartitions(5)
sage: TT = TropicalSemiring(ZZ)
sage: def indicator_labelling(I):
    ....:     # send order ideal `I` to a `TT`-labelling of `P`.
```

(continues on next page)
....:    dct = {v: TT(v in I) for v in P}
....:    return (TT, dct, TT(1), TT(0))
sage: all(indicator_labelling(P.rowmotion(I))
....:     == P.birational_rowmotion(indicator_labelling(I))
....:     for I in P.order_ideals_lattice(facade=True))
True

**birational_toggle**(*v, labelling*)

Return the result of applying the birational *v*-toggle *T/sub*v/* to the *K*-labelling *labelling* of the poset *self*.

See the documentation of **birational_free_labelling()** for a definition of this toggle and of *K*-labellings as well as an explanation of how *K*-labellings are to be encoded to be understood by Sage. This implementation allows *K* to be a semifield, not just a field. The birational *v*-toggle is only a rational map, so an exception (most likely, **ZeroDivisionError**) will be thrown if the denominator is zero.

**INPUT:**

- *v* – an element of *self* (must have *self* as parent if *self* is a facade=False poset)
- *labelling* – a *K*-labelling of *self* in the sense as defined in the documentation of **birational_free_labelling()**

**OUTPUT:**

The *K*-labelling *T*v*f* of *self*, where *f* is *labelling*.

**EXAMPLES:**

Let us start with the birational free labelling of the “V”-poset (the three-element poset with Hasse diagram looking like a “V”):

```python
sage: V = Poset({1: [2, 3]})
sage: s = V.birational_free_labelling(); s
(Fraction Field of Multivariate Polynomial Ring in a, x1, x2, x3, b over...
   Rational Field,
   {...},
   a,
   b)
sage: sorted(s[1].items())
[(1, x1), (2, x2), (3, x3)]
```

The image of *s* under the 1-toggle *T*₁ is:

```python
sage: s1 = V.birational_toggle(1, s); s1
(Fraction Field of Multivariate Polynomial Ring in a, x1, x2, x3, b over...
   Rational Field,
   {...},
   a,
   b)
sage: sorted(s1[1].items())
[(1, a*x2*x3/(x1*x2 + x1*x3)), (2, x2), (3, x3)]
```

Now let us apply the 2-toggle *T*₂ (to the old *s*):

```python
sage: s2 = V.birational_toggle(2, s); s2
(Fraction Field of Multivariate Polynomial Ring in a, x1, x2, x3, b over...
   Rational Field,
   {...},
   a,
   b)
```

(continues on next page)
On the other hand, we can also apply $T_2$ to the image of $s$ under $T_1$:

```sage
s12 = V.birational_toggle(2, s1); s12
sage: sorted(s12[1].items())
[(1, a*x2*x3/(x1*x2 + x1*x3)), (2, a*x3*b/(x1*x2 + x1*x3)), (3, x3)]
```

Each toggle is an involution:

```sage
sage: all( V.birational_toggle(i, V.birational_toggle(i, s)) == s
      for i in V )
True
```

We can also start with a less generic labelling:

```sage
t = (QQ, {1: 3, 2: 6, 3: 7}, 2, 10)
t1 = V.birational_toggle(1, t); t1
sage: sorted(t1[1].items())
[(1, 28/13), (2, 6), (3, 7)]
```

However, labellings have to be sufficiently generic, lest denominators vanish:

```sage
t = (QQ, {1: 3, 2: 5, 3: -5}, 1, 15)
t1 = V.birational_toggle(1, t)
Traceback (most recent call last):
  ... ZeroDivisionError: rational division by zero
```

We don’t get into zero-division issues in the tropical semiring (unless the zero of the tropical semiring appears in the labelling):

```sage
TT = TropicalSemiring(QQ)
t = (TT, {1: TT(2), 2: TT(4), 3: TT(1)}, TT(6), TT(0))
t1 = V.birational_toggle(1, t)
```

(continues on next page)
We turn to more interesting posets. Here is the 6-element poset arising from the weak order on $S_3$:

```python
sage: P = posets.SymmetricGroupWeakOrderPoset(3)
sage: sorted(list(P))
['123', '132', '213', '231', '312', '321']
```

```python
sage: t = (TT, {'123': TT(4), '132': TT(2), '213': TT(3), '231': TT(1), ...
           '321': TT(1), '312': TT(2)}, TT(7), TT(1))
sage: t1 = P.birational_toggle('123', t); t1
(Tropical semiring over Rational Field, {...}, 7, 1)
sage: sorted(t1[1].items())
[(123, 6), (132, 2), (213, 3), (231, 1), (312, 2), (321, 1)]
```

```python
sage: t13 = P.birational_toggle('213', t1); t13
(Tropical semiring over Rational Field, {...}, 7, 1)
sage: sorted(t13[1].items())
[(123, 6), (132, 2), (213, 4), (231, 1), (312, 2), (321, 1)]
```

Let us verify on this example some basic properties of toggles. First of all, again let us check that $T_v$ is an involution for every $v$:

```python
sage: all( P.birational_toggle(v, P.birational_toggle(v, t)) == t ...
           ....: for v in P )
True
```

Furthermore, two toggles $T_v$ and $T_w$ commute unless one of $v$ or $w$ covers the other:

```python
sage: all( P.covers(v, w) or P.covers(w, v) ...
           ....: or P.birational_toggle(v, P.birational_toggle(w, t)) ...
           ....: == P.birational_toggle(w, P.birational_toggle(v, t)) ...
           ....: for v in P for w in P )
True
```

**birational_toggles** *(vs, labelling)*

Return the result of applying a sequence of birational toggles (specified by vs) to the K-labelling la-
beling of the poset self.

See the documentation of *birational_free_labelling()* for a definition of birational toggles
and K-labellings and for an explanation of how K-labellings are to be encoded to be understood by Sage.
This implementation allows K to be a semifield, not just a field. The birational $v$-toggle is only a rational
map, so an exception (most likely, *ZeroDivisionError*) will be thrown if the denominator is zero.

**INPUT:**

- vs – an iterable comprising elements of self (which must have self as parent if self is a
  facade=False poset)
- labelling – a K-labelling of self in the sense as defined in the documentation of *bira-
  tional_free_labelling()*

**OUTPUT:**

The K-labelling $T_{v_n} T_{v_{n-1}} \cdots T_{v_1} f$ of self, where $f$ is labelling and $(v_1, v_2, \ldots, v_n)$ is vs (writ-
ten as list).

**EXAMPLES:**

```python
sage: P = posets.SymmetricGroupBruhatOrderPoset(3)
sage: sorted(list(P))
```

(continues on next page)
\begin{verbatim}
\texttt{['123', '132', '213', '231', '312', '321']}
\texttt{sage: TT = TropicalSemiring(ZZ)}
\texttt{sage: t = (TT, ('123': TT(4), '132': TT(2), '213': TT(3), '231': TT(1), \rightarrow '312': TT(2), '321': TT(1)), TT(7), TT(1))}
\texttt{sage: tA = P.birational_toggles([123, 231, 312], t); tA}
\texttt{(Tropical semiring over Integer Ring, {...}, 7, 1)}
\texttt{sage: sorted(tA[1].items())}
\texttt{[(123, 6), (132, 2), (213, 3), (231, 2), (312, 1), (321, 1)]}
\texttt{sage: tAB = P.birational_toggles([132, 213, 321], tA); tAB}
\texttt{(Tropical semiring over Integer Ring, {...}, 7, 1)}
\texttt{sage: sorted(tAB[1].items())}
\texttt{[(123, 6), (132, 6), (213, 5), (231, 2), (312, 1), (321, 1)]}
\texttt{sage: P = Poset({1: [2, 3], 2: [4], 3: [4]})}
\texttt{sage: Qx = PolynomialRing(QQ, 'x').fraction_field()}
\texttt{sage: x = Qx.gen()}
\texttt{sage: t = (Qx, {1: 1, 2: x, 3: (x+1)/x, 4: x^2}, 1, 1)}
\texttt{sage: t1 = P.birational_toggles((i for i in range(1, 5)), t); t1}
\texttt{(Fraction Field of Univariate Polynomial Ring in x over Rational Field, {...}, 1, 1)}
\texttt{sage: sorted(t1[1].items())}
\texttt{[(1, (x^2 + x)/(x^2 + x + 1)), (2, (x^3 + x^2)/(x^2 + x + 1)), (3, x^4/(x^2 + x + 1)), (4, 1)]}
\texttt{sage: t2 = P.birational_toggles(reversed(range(1, 5)), t)}
\texttt{sage: sorted(t2[1].items())}
\texttt{[(1, 1/x^2), (2, (x^2 + x + 1)/x^4), (3, (x^2 + x + 1)/(x^3 + x^2)), (4, \rightarrow (x^2 + x + 1)/x^3)]}
\texttt{Facadesetto\texttt{False}works:}
\texttt{sage: P = Poset({x: [y, w], y: [z], w: [z]}, facade=\texttt{False})}
\texttt{sage: lex = [x, y, w, z]}
\texttt{sage: t = P.birational_free_labelling(linear_extension=lex)}
\texttt{sage: sorted(P.birational_toggles([P(x), P(y)], t)[1].items())}
\texttt{[(x, a*x2*x3/(x1*x2 + x1*x3)), (y, a*x3*x4/(x1*x2 + x1*x3)), (w, x3), (z, \rightarrow x4)]}
\texttt{directed_subsets(\texttt{direction})}
\texttt{Returntheorderfilters(resp. orderideals)of \texttt{self}, aslists.}
\texttt{If \texttt{direction} is ‘up’,returns the order filters (upper sets).}
\texttt{If \texttt{direction} is ‘down’,returns the order ideals (lower sets).}
\texttt{INPUT:}
\texttt{• \texttt{direction} – ‘up’ or ‘down’}
\texttt{EXAMPLES:}
\texttt{sage: P = Poset((divisors(12), attrcall("divides")), facade=\texttt{True})}
\texttt{sage: A = P.directed_subsets(‘up’)}
\texttt{sage: sorted(list(A))}
\texttt{[[], [1, 2, 4, 3, 6, 12], [2, 4, 3, 6, 12], [2, 4, 6, 12], [3, 6, 12], [4, \rightarrow 3, 6, 12], [4, 6, 12], [4, 12], [6, 12], [12]]}
\texttt{is_lattice()}
\texttt{Returnwhether the poset is a lattice.}
\end{verbatim}
A poset is a lattice if all pairs of elements have both a least upper bound ("join") and a greatest lower bound ("meet") in the poset.

**EXAMPLES:**

```python
sage: P = Poset([[1, 3, 2], [4], [4, 5, 6], [6], [7], [7], [7], []])
sage: P.is_lattice()
True

sage: P = Poset([[1, 2], [3], [3], []])
sage: P.is_lattice()
True

sage: P = Poset({0: [2, 3], 1: [2, 3]})
sage: P.is_lattice()
False

sage: P = Poset({1: [2, 3, 4], 2: [5, 6], 3: [5, 7], 4: [6, 7], 5: [8, 9],
             6: [8, 10], 7: [9, 10], 8: [11], 9: [11], 10: [11]})
sage: P.is_lattice()
False
```

**See also:**

- Weaker properties: `is_join_semilattice()`, `is_meet_semilattice()`

**is_poset_isomorphism** *(f, codomain)*

Return whether *f* is an isomorphism of posets from *self* to *codomain*.

**INPUT:**

- *f* – a function from *self* to *codomain*
- *codomain* – a poset

**EXAMPLES:**

We build the poset *D* of divisors of 30, and check that it is isomorphic to the boolean lattice *B* of the subsets of {2, 3, 5} ordered by inclusion, via the reverse function *f*: *B* → *D*, *b* ↦ ∏ᵢ∈*b* *x*:  

```python
sage: D = Poset((divisors(30), attrcall("divides")))
sage: B = Poset({[frozenset(s) for s in Subsets([2, 3, 5])], attrcall("issubset")})
sage: def f(b):
    return D(prod(b))
sage: B.is_poset_isomorphism(f, D)
True
```

On the other hand, *f* is not an isomorphism to the chain of divisors of 30, ordered by usual comparison:

```python
sage: P = Poset((divisors(30), operator.le))
sage: def f(b):
    return P(prod(b))
sage: B.is_poset_isomorphism(f, P)
False
```

A non surjective case:

```python
sage: B = Poset({[frozenset(s) for s in Subsets([2, 3])], attrcall("issubset")})
sage: def f(b):
    return D(prod(b))
sage: B.is_poset_isomorphism(f, D)
False
```

A non injective case:
sage: B = Poset({[frozenset(s) for s in Subsets([2,3,5,6])], attrcall("issubset")})
sage: def f(b): return D(gcd(prod(b), 30))
sage: B.is_poset_isomorphism(f, D)
False

Note: since $D$ and $B$ are not facade posets, $f$ is responsible for the conversions between integers and subsets to elements of $D$ and $B$ and back.

See also:

`FiniteLatticePosets.ParentMethods.is_lattice_morphism()`

`is_poset_morphism(f, codomain)`

Return whether $f$ is a morphism of posets from `self` to `codomain`, that is

$$x \leq y \implies f(x) \leq f(y)$$

for all $x$ and $y$ in `self`.

INPUT:

- `f` - a function from `self` to `codomain`
- `codomain` - a poset

EXAMPLES:

We build the boolean lattice of the subsets of $\{2, 3, 5, 6\}$ and the lattice of divisors of 30, and check that the map $b \mapsto \gcd(\prod_{x \in b} x, 30)$ is a morphism of posets:

sage: D = Poset((divisors(30), attrcall("divides")))
sage: B = Poset({[frozenset(s) for s in Subsets([2,3,5,6])], attrcall("issubset")})
sage: def f(b): return D(gcd(prod(b), 30))
sage: B.is_poset_morphism(f, D)
True

Note: since $D$ and $B$ are not facade posets, $f$ is responsible for the conversions between integers and subsets to elements of $D$ and $B$ and back.

$f$ is also a morphism of posets to the chain of divisors of 30, ordered by usual comparison:

sage: P = Poset((divisors(30), operator.le))
sage: def f(b): return P(gcd(prod(b), 30))
sage: B.is_poset_morphism(f, P)
True

FIXME: should this be `is_order_preserving_morphism`?

See also:

`is_poset_isomorphism()`

`is_self_dual()`

Return whether the poset is `self-dual`.

A poset is self-dual if it is isomorphic to its dual poset.

EXAMPLES:
sage: P = Poset({1: [3, 4], 2: [3, 4]})
sage: P.is_self_dual()
True
sage: P = Poset({1: [2, 3]})
sage: P.is_self_dual()
False

See also:

- Stronger properties: is_orthocomplemented() (for lattices)
- Other: dual()

order_filter_generators (filter)

Generators for an order filter

INPUT:

- filter – an order filter of self, as a list (or iterable)

EXAMPLES:

sage: P = Poset((Subsets([1,2,3]), attrcall("issubset")))
sage: I = P.order_filter([Set([1,2]), Set([2,3]), Set([1])])
sage: sorted(sorted(p) for p in I)
[[1], [1, 2], [1, 2, 3], [1, 3], [2, 3]]
sage: gen = P.order_filter_generators(I)
sage: sorted(sorted(p) for p in gen)
[[1], [2, 3]]

See also:

order_ideal_generators()

order_ideal_complement_generators (antichain, direction='up')

Return the Panyushev complement of the antichain antichain.

Given an antichain \(A\) of a poset \(P\), the Panyushev complement of \(A\) is defined to be the antichain consisting of the minimal elements of the order filter \(B\), where \(B\) is the (set-theoretic) complement of the order ideal of \(P\) generated by \(A\).

Setting the optional keyword variable direction to 'down' leads to the inverse Panyushev complement being computed instead of the Panyushev complement. The inverse Panyushev complement of an antichain \(A\) is the antichain whose Panyushev complement is \(A\). It can be found as the antichain consisting of the maximal elements of the order ideal \(C\), where \(C\) is the (set-theoretic) complement of the order filter of \(P\) generated by \(A\).

panyushev_complement() is an alias for this method.

Panyushev complementation is related (actually, isomorphic) to rowmotion (rowmotion()).

INPUT:

- antichain – an antichain of self, as a list (or iterable), or, more generally, generators of an order ideal (resp. order filter)
- direction – 'up' or 'down' (default: 'up')

OUTPUT:

- the generating antichain of the complement order filter (resp. order ideal) of the order ideal (resp. order filter) generated by the antichain antichain

EXAMPLES:
Warning: This is a brute force implementation, building the order ideal generated by the antichain, and searching for order filter generators of its complement.

```python
sage: P = Poset( ( [1,2,3], [ [1,3], [2,3] ] ) )
sage: P.order_ideal_complement_generators([1])
{2}
sage: P.order_ideal_complement_generators([3])
set()
sage: P.order_ideal_complement_generators([1,2])
{3}
sage: P.order_ideal_complement_generators([1,2,3])
set()
sage: P.order_ideal_complement_generators([1], direction="down")
{2}
sage: P.order_ideal_complement_generators([3], direction="down")
{1, 2}
sage: P.order_ideal_complement_generators([1,2], direction="down")
set()
sage: P.order_ideal_complement_generators([1,2,3], direction="down")
set()
```

### order_ideal_generators (ideal, direction='down')
Return the antichain of (minimal) generators of the order ideal (resp. order filter) `ideal`.

**INPUT:**
- `ideal` – an order ideal $I$ (resp. order filter) of `self`, as a list (or iterable); this should be an order ideal if `direction` is set to 'down', and an order filter if `direction` is set to 'up'.
- `direction` – 'up' or 'down' (default: 'down').

The antichain of (minimal) generators of an order ideal $I$ in a poset $P$ is the set of all minimal elements of $P$. In the case of an order filter, the definition is similar, but with “maximal” used instead of “minimal”.

**EXAMPLES:**

We build the boolean lattice of all subsets of $\{1, 2, 3\}$ ordered by inclusion, and compute an order ideal there:

```python
sage: P = Poset((Subsets([1,2,3]), attrcall("issubset")))
sage: I = P.order_ideal([Set([1,2]), Set([2,3]), Set([1])])
sage: sorted(sorted(p) for p in I)
[[], [1], [1, 2], [2], [2, 3], [3]]
```

Then, we retrieve the generators of this ideal:

```python
sage: gen = P.order_ideal_generators(I)
sage: sorted(sorted(p) for p in gen)
[[1, 2], [2, 3]]
```

If `direction` is ‘up’, then this instead computes the minimal generators for an order filter:

```python
sage: I = P.order_filter([Set([1,2]), Set([2,3]), Set([1])])
sage: sorted(sorted(p) for p in I)
[[1], [1, 2], [1, 2, 3], [1, 3], [2, 3]]
sage: gen = P.order_ideal_generators(I, direction='up')
sage: sorted(sorted(p) for p in gen)
[[1], [2, 3]]
```
Complexity: \( O(n + m) \) where \( n \) is the cardinality of \( I \), and \( m \) the number of upper covers of elements of \( I \).

**order Ideals Lattice** *(as ideals=True, facade=None)*

Return the lattice of order ideals of a poset `self`, ordered by inclusion.

The lattice of order ideals of a poset \( P \) is usually denoted by \( J(P) \). Its underlying set is the set of order ideals of \( P \), and its partial order is given by inclusion.

The order ideals of \( P \) are in a canonical bijection with the antichains of \( P \). The bijection maps every order ideal to the antichain formed by its maximal elements. By setting the `as ideals` keyword variable to `False`, one can make this method apply this bijection before returning the lattice.

**INPUT:**
- `as ideals` – Boolean, if `True` (default) returns a poset on the set of order ideals, otherwise on the set of antichains
- `facade` – Boolean or `None` (default). Whether to return a facade lattice or not. By default return facade lattice if the poset is a facade poset.

**EXAMPLES:**

```python
sage: P = posets.PentagonPoset()
sage: P.cover_relations()
[[0, 1], [0, 2], [1, 4], [2, 3], [3, 4]]
sage: J = P.order_ideals_lattice(); J
Finite lattice containing 8 elements
sage: sorted(sorted(e) for e in J)
[[], [0], [0, 1], [0, 1, 2], [0, 1, 2, 3], [0, 1, 2, 3, 4], [0, 2], [0, 2, 3], [0, 2, 3, 4]]
```

As a lattice on antichains:

```python
sage: J2 = P.order_ideals_lattice(False); J2
Finite lattice containing 8 elements
sage: sorted(J2)
[(), (0,), (1,), (1, 2), (1, 3), (2,), (3,), (4,)]
```

**panyushev_complement** *(antichain, direction='up')*

Return the Panyushev complement of the antichain `antichain`.

Given an antichain \( A \) of a poset \( P \), the Panyushev complement of \( A \) is defined to be the antichain consisting of the minimal elements of the order filter \( B \), where \( B \) is the (set-theoretic) complement of the order ideal of \( P \) generated by \( A \).

Setting the optional keyword variable `direction` to 'down' leads to the inverse Panyushev complement being computed instead of the Panyushev complement. The inverse Panyushev complement of an antichain \( A \) is the antichain whose Panyushev complement is \( A \). It can be found as the antichain consisting of the maximal elements of the order ideal \( C \), where \( C \) is the (set-theoretic) complement of the order filter of \( P \) generated by \( A \).

`panyushev_complement()` is an alias for this method.

Panyushev complementation is related (actually, isomorphic) to rowmotion (`rowmotion()`).

**INPUT:**
- `antichain` – an antichain of `self`, as a list (or iterable), or, more generally, generators of an order ideal (resp. order filter)
- `direction` – 'up' or 'down' (default: 'up')

**OUTPUT:**
- the generating antichain of the complement order filter (resp. order ideal) of the order ideal (resp. order filter) generated by the antichain `antichain`
EXAMPLES:

```python
sage: P = Poset( ( [1,2,3], [ [1,3], [2,3] ] ) )
sage: P.order_ideal_complement_generators([1])
{2}
sage: P.order_ideal_complement_generators([3])
set()
sage: P.order_ideal_complement_generators([1,2])
{3}
sage: P.order_ideal_complement_generators([1,2,3])
set()
sage: P.order_ideal_complement_generators([1], direction="down")
{2}
sage: P.order_ideal_complement_generators([3], direction="down")
{1, 2}
sage: P.order_ideal_complement_generators([1,2], direction="down")
set()
sage: P.order_ideal_complement_generators([1,2,3], direction="down")
set()
```

**Warning:** This is a brute force implementation, building the order ideal generated by the antichain, and searching for order filter generators of its complement.

`panyushev_orbit_iter` *(antichain, element_constructor=\<class 'set'>, stop=True, check=True)*

Iterate over the Panyushev orbit of an antichain `antichain` of `self`.

The Panyushev orbit of an antichain is its orbit under Panyushev complementation (see `panyushev_complement()`).

**INPUT:**
- `antichain` – an antichain of `self`, given as an iterable.
- `element_constructor` (defaults to `set`) – a type constructor (`set`, `tuple`, `list`, `frozenset`, `iter`, etc.) which is to be applied to the antichains before they are yielded.
- `stop` – a Boolean (default: `True`) determining whether the iterator should stop once it completes its cycle (this happens when it is set to `True`) or go on forever (this happens when it is set to `False`).
- `check` – a Boolean (default: `True`) determining whether `antichain` should be checked for being an antichain.

**OUTPUT:**
- an iterator over the orbit of the antichain `antichain` under Panyushev complementation.

This iterator `I` has the property that `I[0] == antichain` and each `i` satisfies `self.order_ideal_complement_generators(I[i]) == I[i+1]`, where `I[i+1]` has to be understood as `I[0]` if it is undefined. The entries `I[i]` are sets by default, but depending on the optional keyword variable `element_constructors` they can also be tuples, lists etc.

**EXAMPLES:**

```python
sage: P = Poset( ( [1,2,3], [ [1,3], [2,3] ] ) )
sage: list(P.panyushev_orbit_iter(set([1, 2])))
[(1, 2), (3), set()]
sage: list(P.panyushev_orbit_iter([1, 2]))
[(1, 2), (3), set()]
sage: list(P.panyushev_orbit_iter([1, 2]))
[(1, 2), (3), set()]
sage: list(P.panyushev_orbit_iter([1, 2], element_constructor=list))
[[1, 2], [3], []]
```

(continues on next page)
sage: list(P.panyushev_orbit_iter(set([1, 2]), element_constructor=frozenset))
[frozenset({1, 2}), frozenset({3}), frozenset({})]

sage: list(P.panyushev_orbit_iter(set([1, 2]), element_constructor=tuple))
[(1, 2), (3,), ()]

sage: P = Poset( {} )

sage: list(P.panyushev_orbit_iter([]))
[set()]

sage: P = Poset({ 1: [2, 3], 2: [4], 3: [4], 4: [] })

sage: Piter = P.panyushev_orbit_iter([2], stop=False)

sage: next(Piter)
{2}

sage: next(Piter)
{3}

sage: next(Piter)
{2}

sage: next(Piter)
{3}

panyushev_orbits(element_constructor=<class 'set'>)

Return the Panyushev orbits of antichains in self.

The Panyushev orbit of an antichain is its orbit under Panyushev complementation (see panyu-
shev_complement()).

INPUT:

• element_constructor (defaults to set) – a type constructor (set, tuple, list, frozenset, iter, etc.) which is to be applied to the antichains before they are returned.

OUTPUT:

• the partition of the set of all antichains of self into orbits under Panyushev complementa-
tion. This is returned as a list of lists L such that for each L and i, cyclically: self.
order_ideal_complement_generators(L[i]) == L[i+1]. The entries L[i] are sets by default, but depending on the optional keyword variable element_constructors they can also be tuples, lists etc.

EXAMPLES:

sage: P = Poset( ( [1,2,3], [ [1, 3], [2, 3] ] ) )

sage: orb = P.panyushev_orbits()

sage: sorted(sorted(o) for o in orb)
[[set(), {1, 2}, {3}], [{2}, {1}]]

sage: orb = P.panyushev_orbits(element_constructor=list)

sage: sorted(sorted(o) for o in orb)
[[[], [1, 2], [3]], [[1], [2]]]

sage: orb = P.panyushev_orbits(element_constructor=frozenset)

sage: sorted(sorted(o) for o in orb)
[[frozenset(), frozenset({{1, 2}}), frozenset({3})],
[frozenset({{2}}), frozenset({{1}})]]

sage: orb = P.panyushev_orbits(element_constructor=tuple)

sage: sorted(sorted(o) for o in orb)
[[(), (1, 2), (3,)], [(1,), (2,)], [(0,)]]

sage: P = Poset( {} )

sage: P.panyushev_orbits()
[[set()]]

rowmotion(order_ideal)
The image of the order ideal order_ideal under rowmotion in self.

Rowmotion on a finite poset $P$ is an automorphism of the set $J(P)$ of all order ideals of $P$. One way to define it is as follows: Given an order ideal $I \in J(P)$, we let $F$ be the set-theoretic complement of $I$ in $P$. Furthermore we let $A$ be the antichain consisting of all minimal elements of $F$. Then, the rowmotion of $I$ is defined to be the order ideal of $P$ generated by the antichain $A$ (that is, the order ideal consisting of each element of $P$ which has some element of $A$ above it).

Rowmotion is related (actually, isomorphic) to Panyushev complementation (panyushev_complement()).

INPUT:

- order_ideal – an order ideal of self, as a set

OUTPUT:

- the image of order_ideal under rowmotion, as a set again

EXAMPLES:

```python
sage: P = Poset( {1: [2, 3], 2: [], 3: [], 4: [8], 5: [], 6: [5], 7: [1, -4], 8: []} )
sage: I = Set({2, 6, 1, 7})
sage: P.rowmotion(I)
{1, 3, 4, 5, 6, 7}
sage: P = Poset( {} )
sage: I = Set({})
sage: P.rowmotion(I)
{}
```

[rowmotion_orbit_iter (oidel, element_constructor=<class 'set'>, stop=True, check=True)]

Iterate over the rowmotion orbit of an order ideal oideal of self.

The rowmotion orbit of an order ideal is its orbit under rowmotion (see rowmotion()).

INPUT:

- oideal – an order ideal of self, given as an iterable.
- element_constructor (defaults to set) – a type constructor (set, tuple, list, frozenset, iter, etc.) which is to be applied to the order ideals before they are yielded.
- stop – a Boolean (default: True) determining whether the iterator should stop once it completes its cycle (this happens when it is set to True) or go on forever (this happens when it is set to False).
- check – a Boolean (default: True) determining whether oideal should be checked for being an order ideal.

OUTPUT:

- an iterator over the orbit of the order ideal oideal under rowmotion. This iterator $I$ has the property that $I[0] == oideal$ and that every $i$ satisfies self.rowmotion($I[i]$) == $I[i+1]$, where $I[i+1]$ has to be understood as $I[0]$ if it is undefined. The entries $I[i]$ are sets by default, but depending on the optional keyword variable element_constructors they can also be tuples, lists etc.

EXAMPLES:

```python
sage: P = Poset( ( [1,2,3], [ [1,3], [2,3] ] ) )
sage: list(P.rowmotion_orbit_iter(set([1, 2])))
[(1, 2), (1, 2, 3), set()]
sage: list(P.rowmotion_orbit_iter([1, 2]))
[(1, 2), (1, 2, 3), set()]
sage: list(P.rowmotion_orbit_iter([2, 1]))
[(1, 2), (1, 2, 3), set()]
```

(continues on next page)
rowmotion_orbits (element_constructor=<class 'set'>)

Return the rowmotion orbits of order ideals in self.

The rowmotion orbit of an order ideal is its orbit under rowmotion (see rowmotion()).

INPUT:

• element_constructor (defaults to set) – a type constructor (set, tuple, list, frozenset, iter, etc.) which is to be applied to the antichains before they are returned.

OUTPUT:

• the partition of the set of all order ideals of self into orbits under rowmotion. This is returned as a list of lists L such that for each L and i, cyclically: self.rowmotion(L[i]) == L[i+1]. The entries L[i] are sets by default, but depending on the optional keyword variable element_constructors they can also be tuples, lists etc.

EXAMPLES:

```python
sage: P = Poset({ 1: [4], 2: [4, 5], 3: [5] })
sage: list(P.rowmotion_orbit_iter([1, 2], element_constructor=list))
[[1, 2], [1, 2, 3, 4], [2, 3, 5], [1], [2, 3], [1, 2, 3, 5], [1, 2, 4], [3]]
```
rowmotion_orbits_plots()

Return plots of the rowmotion orbits of order ideals in self.

The rowmotion orbit of an order ideal is its orbit under rowmotion (see rowmotion()).

EXAMPLES:

```
sage: P = Poset( {1: [2, 3], 2: [], 3: [], 4: [2]} )
sage: P.rowmotion_orbits_plots()
Graphics Array of size 2 x 5
sage: P = Poset({})
sage: P.rowmotion_orbits_plots()
Graphics Array of size 1 x 1
```

toggling_orbit_iter (vs, oideal, element_constructor=<class 'set'>, stop=True, check=True)

Iterate over the orbit of an order ideal oideal of self under the operation of toggling the vertices vs[0], vs[1], ... in this order.

See order_ideal_toggle() for a definition of toggling.

Warning: The orbit is that under the composition of toggles, not under the single toggles themselves. Thus, for example, if vs == [1, 2], then the orbit has the form (I, T₂T₁I, T₂T₁I, T₂T₁T₂T₁I,...) (where I denotes oideal and Tᵢ means toggling at i) rather than (I, T₁I, T₂I, T₁T₂T₁I,...).

INPUT:

• vs: a list (or other iterable) of elements of self (but since the output depends on the order, sets should not be used as vs).
• oideal – an order ideal of self, given as an iterable.
• element_constructor (defaults to set) – a type constructor (set, tuple, list, frozenset, iter, etc.) which is to be applied to the order ideals before they are yielded.
• stop – a Boolean (default: True) determining whether the iterator should stop once it completes its cycle (this happens when it is set to True) or go on forever (this happens when it is set to False).
• check – a Boolean (default: True) determining whether oideal should be checked for being an order ideal.

OUTPUT:

• an iterator over the orbit of the order ideal oideal under toggling the vertices in the list vs in this order. This iterator I has the property that I[0] == oideal and that every i satisfies self.order_ideal_toggles(I[i], vs) == I[i+1], where I[i+1] has to be understood as I[0] if it is undefined. The entries I[i] are sets by default, but depending on the optional keyword variable element_constructors they can also be tuples, lists etc.

EXAMPLES:

```
sage: P = Poset( ( [1,2,3], [ [1,3], [2,3] ] ) )
sage: list(P.toggling_orbit_iter([1, 3, 1], set([1, 2])))
[(1, 2), (1, 2, 3)]
sage: list(P.toggling_orbit_iter([1, 2, 3], set([1, 2])))
[(1, 2), (1, 2, 3)]
sage: list(P.toggling_orbit_iter([3, 2, 1], set([1, 2])))
[(1, 2), (1, 2, 3)]
sage: list(P.toggling_orbit_iter([3, 2, 1], set([1, 2]), element_constructor=list))
[[1, 2], [1, 2, 3], []]
sage: list(P.toggling_orbit_iter([3, 2, 1], set([1, 2]), element_constructor=frozenset))
[frozenset({1, 2}), frozenset({1, 2, 3}), frozenset({})]
```

(continues on next page)
toggling_orbits \( \text{(vs, element\_constructor=\text{<class} 'set'>)} \)

Return the orbits of order ideals in \( \text{self} \) under the operation of toggling the vertices \( \text{vs}[0], \text{vs}[1], \ldots \) in this order.

See \text{order\_ideal\_toggle()} for a definition of toggling.

**Warning:** The orbits are those under the composition of toggles, not under the single toggles themselves. Thus, for example, if \( \text{vs} == [1,2] \), then the orbits have the form \((I, T_2 T_1 I, T_2 T_1 T_2 T_1 I, \ldots) \) (where \( I \) denotes an order ideal and \( T_i \) means toggling at \( i \)) rather than \((I, T_1 I, T_2 T_1 I, T_1 T_2 T_1 I, \ldots) \).

**INPUT:**
- \( \text{vs} \): a list (or other iterable) of elements of \( \text{self} \) (but since the output depends on the order, sets should not be used as \( \text{vs} \)).

**OUTPUT:**
- a partition of the order ideals of \( \text{self} \), as a list of sets \( L \) such that for each \( L \) and \( i \), cyclically:
  \( \text{self.order\_ideal\_toggles}(L[i], \text{vs}) == L[i+1] \).

**EXAMPLES:**

```python
sage: P = Poset({ 1: [2, 4], 2: [], 3: [4], 4: [] })
sage: sorted(len(o) for o in P.toggling_orbits([1, 2]))
[2, 3, 3]
sage: P = Poset({ 1: [3], 2: [1, 4], 3: [], 4: [3] })
sage: sorted(len(o) for o in P.toggling_orbits([1, 2, 4, 3]))
[3, 3]
```

toggling_orbits\_plots(\text{vs})

Return plots of the orbits of order ideals in \( \text{self} \) under the operation of toggling the vertices \( \text{vs}[0], \text{vs}[1], \ldots \) in this order.

See \text{toggling\_orbits()} for more information.
EXAMPLES:

```python
sage: P = Poset( {1: [2, 3], 2: [], 3: [], 4: [2]} )
sage: P.toggling_orbits_plots([1,2,3,4])
Graphics Array of size 2 x 5
sage: P = Poset({})
sage: P.toggling_orbits_plots([])
Graphics Array of size 1 x 1
```

4.63 Finite semigroups

```python
class sage.categories.finite_semigroups.FiniteSemigroups(base_category):
    Bases: CategoryWithAxiom_singleton

    The category of finite (multiplicative) semigroups.

    A finite semigroup is a finite set endowed with an associative binary operation *.

    Warning: Finite semigroups in Sage used to be automatically endowed with an enumerated set structure; the default enumeration is then obtained by iteratively multiplying the semigroup generators. This forced any finite semigroup to either implement an enumeration, or provide semigroup generators; this was often inconvenient.

    Instead, finite semigroups that provide a distinguished finite set of generators with semigroup_generators() should now explicitly declare themselves in the category of finitely generated semigroups:

    ```python
    sage: Semigroups().FinitelyGenerated()
    Category of finitely generated semigroups
    ```
    This is a backward incompatible change.
```

EXAMPLES:

```python
sage: C = FiniteSemigroups(); C
Category of finite semigroups
sage: C.super_categories()
[Category of semigroups, Category of finite sets]
sage: sorted(C.axioms())
['Associative', 'Finite']
sage: C.example()
An example of a finite semigroup: the left regular band generated by ('a', 'b', 'c', 'd')
```

```python
class ParentMethods
    Bases: object

    idempotents()

    Returns the idempotents of the semigroup

    EXAMPLES:
```

```python
sage: S = FiniteSemigroups().example(alphabet=('x', 'y'))
sage: sorted(S.idempotents())
['x', 'xy', 'y', 'yx']
```
j_classes()
Returns the \( J \)-classes of the semigroup.

Two elements \( u \) and \( v \) of a monoid are in the same \( J \)-class if \( u \) divides \( v \) and \( v \) divides \( u \).

OUTPUT:
All the \( J \)-classes of self, as a list of lists.

EXAMPLES:

```sage
S = FiniteSemigroups().example(alphabet=('a','b', 'c'))
sage: sorted(map(sorted, S.j_classes()))
[['a'], ['ab', 'ba'], ['abc', 'acb', 'bac', 'bca', 'cab', 'cba'],
 ['ac', 'ca'], ['bc'], ['cb'], ['c']]
```

j_classes_of_idempotents()
Returns all the idempotents of self, grouped by \( J \)-class.

OUTPUT:
a list of lists.

EXAMPLES:

```sage
S = FiniteSemigroups().example(alphabet=('a','b', 'c'))
sage: sorted(map(sorted, S.j_classes_of_idempotents()))
[['a'], ['ab', 'ba'], ['abc', 'acb', 'bac', 'bca', 'cab', 'cba'],
 ['ac', 'ca'], ['bc'], ['cb'], ['c']]
```

j_transversal_of_idempotents()
Returns a list of one idempotent per regular \( J \)-class.

EXAMPLES:

```sage
S = FiniteSemigroups().example(alphabet=('a','b', 'c'))
sage: S.j_transversal_of_idempotents()
['a', 'ab', 'abc', 'ac', 'b', 'c', 'cb']
```

### 4.64 Finite sets

class sage.categories.finite_sets.FiniteSets(base_category)

Bases: CategoryWithAxiom_singleton

The category of finite sets.

EXAMPLES:

```sage
C = FiniteSets(); C
Category of finite sets
sage: C.super_categories()
[Category of sets]
```
sage: C.all_super_categories()
[Category of finite sets,
 Category of sets,
 Category of sets with partial maps,
 Category of objects]
sage: C.example()
NotImplemented

class Algebras\( (\text{category, } *\text{args}) \)
    Bases: AlgebrasCategory
    
    extra_super_categories()
    
    EXAMPLES:

```
sage: FiniteSets().Algebras(QQ).extra_super_categories()
[Category of finite dimensional vector spaces with basis over Rational\leftarrow Field]
```

This implements the fact that the algebra of a finite set is finite dimensional:

```
sage: FiniteMonoids().Algebras(QQ).is_subcategory(AlgebrasWithBasis(QQ).\leftarrow FiniteDimensional())
True
```

class ParentMethods
    Bases: object
    
    is_finite()
    
    Return True since self is finite.
    
    EXAMPLES:

```
sage: C = FiniteEnumeratedSets().example()
sage: C.is_finite()
True
```

class Subquotients\( (\text{category, } *\text{args}) \)
    Bases: SubquotientsCategory
    
    extra_super_categories()
    
    EXAMPLES:

```
sage: FiniteSets().Subquotients().extra_super_categories()
[Category of finite sets]
```

This implements the fact that a subquotient (and therefore a quotient or subobject) of a finite set is finite:

```
sage: FiniteSets().Subquotients().is_subcategory(FiniteSets())
True
sage: FiniteSets().Quotients().is_subcategory(FiniteSets())
True
sage: FiniteSets().Subobjects().is_subcategory(FiniteSets())
True
```

4.64. Finite sets
4.65 Finite Weyl Groups

class sage.categories.finite_weyl_groups.FiniteWeylGroups(base_category):
    Bases: CategoryWithAxiom
    The category of finite Weyl groups.

    EXAMPLES:
    
    sage: C = FiniteWeylGroups()
sage: C
    Category of finite Weyl groups
    sage: C.super_categories()
    [Category of finite Coxeter groups, Category of Weyl groups]
sage: C.example()
    The symmetric group on {0, ..., 3}

    class ElementMethods
        Bases: object
    
    class ParentMethods
        Bases: object

4.66 Finitely Generated Lambda bracket Algebras

AUTHORS:

• Reimundo Heluani (2020-08-21): Initial implementation.

class sage.categories.finitely_generated_lambda_bracket_algebras.FinitelyGeneratedLambdaBracketAlgebras(base_category):
    Bases: CategoryWithAxiom_over_base_ring
    The category of finitely generated lambda bracket algebras.

    EXAMPLES:
    
    sage: from sage.categories.lambda_bracket_algebras import LambdaBracketAlgebras
    sage: LambdaBracketAlgebras(QQbar).FinitelyGenerated()  #...
    Category of finitely generated lambda bracket algebras over Algebraic Field

    class Graded(base_category):
        Bases: GradedModulesCategory
        The category of H-graded finitely generated Lie conformal algebras.

        EXAMPLES:
        
        sage: LieConformalAlgebras(QQbar).FinitelyGenerated().Graded()  #...
        Category of H-graded finitely generated Lie conformal algebras over Algebraic Field
class ParentMethods
    Bases: object

gen(i)
    The i-th generator of this Lie conformal algebra.

    EXAMPLES:

    sage: # needs sage.combinat sage.modules
    sage: V = lie_conformal_algebras.Affine(QQ, 'A1')
    sage: V.gens()
    (B[alpha[1]], B[alphacheck[1]], B[-alpha[1]], B['K'])
    sage: V.gen(0)
    B[alpha[1]]
    sage: V.1
    B[alphacheck[1]]

ngens()
    The number of generators of this Lie conformal algebra.

    EXAMPLES:

    sage: Vir = lie_conformal_algebras.Virasoro(QQ)  # needs sage.combinat sage.modules
    sage: Vir.ngens()  # needs sage.combinat sage.modules
    2
    sage: V = lie_conformal_algebras.Affine(QQ, 'A2')  # needs sage.combinat sage.modules
    sage: V.ngens()  # needs sage.combinat sage.modules
    9

some_elements()
    Some elements of this Lie conformal algebra.

    This method returns a list with elements containing at least the generators.

    EXAMPLES:

    sage: V = lie_conformal_algebras.Affine(QQ, 'A1',  # needs sage.combinat sage.modules
    ....:
    names=('e', 'h', 'f'))
    sage: V.some_elements()  # needs sage.combinat sage.modules
    [e, h, f, K, ...]
    sage: all(v.parent() is V for v in V.some_elements())  # needs sage.combinat sage.modules
    True
4.67 Finitely Generated Lie Conformal Algebras

AUTHORS:

• Reimundo Heluani (2019-10-05): Initial implementation.

```python
class sage.categories.finitely_generated_lie_conformal_algebras.FinitelyGeneratedLieConformalAlgebras:
    #... from CategoryWithAxiom_over_base_ring
    Bases: CategoryWithAxiom_over_base_ring
    The category of finitely generated Lie conformal algebras.
    EXAMPLES:

    sage: LieConformalAlgebras(QQbar).FinitelyGenerated()  #...
    Category of finitely generated Lie conformal algebras over Algebraic Field

class Graded(base_category):
    Bases: GradedModulesCategory
    The category of H-graded finitely generated Lie conformal algebras.
    EXAMPLES:

    sage: LieConformalAlgebras(QQbar).FinitelyGenerated().Graded()  #...
    Category of H-graded finitely generated Lie conformal algebras over Algebraic Field

class ParentMethods:
    Bases: object
    some_elements():
    Some elements of this Lie conformal algebra.
    Returns a list with elements containing at least the generators.
    EXAMPLES:

    sage: V = lie_conformal_algebras.Affine(QQ, 'A1',  #...
    ....: name=names=('e', 'h', 'f'))
    sage: V.some_elements()  #...
    [e, h, f, K, ...]
    sage: all(v.parent() is V for v in V.some_elements())  #...
    True

class Super(base_category):
    Bases: SuperModulesCategory
    The category of super finitely generated Lie conformal algebras.
    EXAMPLES:
```
4.68 Finitely generated magmas

class sage.categories.finitely_generated_magmas.FinitelyGeneratedMagmas(base_category)

    Bases: CategoryWithAxiom_singleton

    The category of finitely generated (multiplicative) magmas.
    See Magmas.SubcategoryMethods.FinitelyGeneratedAsMagma() for details.

    EXAMPLES:

        sage: C = Magmas().FinitelyGeneratedAsMagma(); C
        Category of finitely generated magmas
        sage: C.super_categories()
        [Category of magmas]
        sage: sorted(C.axioms())
        ['FinitelyGeneratedAsMagma']

class ParentMethods

    Bases: object

    magma_generators()

        Return distinguished magma generators for self.

        OUTPUT: a finite family

        This method should be implemented by all finitely generated magmas.

        EXAMPLES:

            sage: S = FiniteSemigroups().example()
            sage: S.magma_generators()
            Family ('a', 'b', 'c', 'd')
4.69 Finitely generated semigroups

class sage.categories.finitely_generated_semigroups.FinitelyGeneratedSemigroups(base_category):

    Bases: CategoryWithAxiom_singleton

    The category of finitely generated (multiplicative) semigroups.

    A finitely generated semigroup is a semigroup endowed with a
distinguished finite set of generators (see
FinitelyGeneratedSemigroups.ParentMethods.semigroup_generators()). This
makes it into an enumerated set.

    EXAMPLES:

    sage: C = Semigroups().FinitelyGenerated(); C
    Category of finitely generated semigroups
    sage: C.super_categories()  
    [Category of semigroups,  
     Category of finitely generated magmas,  
     Category of enumerated sets]
    sage: sorted(C.axioms())
    ['Associative', 'Enumerated', 'FinitelyGeneratedAsMagma']
    sage: C.example()
    An example of a semigroup: the free semigroup generated
    by ('a', 'b', 'c', 'd')

class Finite(base_category):

    Bases: CategoryWithAxiom_singleton

    class ParentMethods

        Bases: object

        some_elements()

            Return an iterable containing some elements of the semigroup.

            OUTPUT: the ten first elements of the semigroup, if they exist.

            EXAMPLES:

            sage: S = FiniteSemigroups().example(alphabet=('x','y'))
            sage: sorted(S.some_elements())
            ['x', 'xy', 'y', 'yx']
            sage: S = FiniteSemigroups().example(alphabet=('x','y','z'))
            sage: X = S.some_elements()
            sage: len(X)
            10
            sage: all(x in S for x in X)
            True

class ParentMethods

    Bases: object

    ideal(gens, side='twosided')

        Return the side-sided ideal generated by gens.

        This brute force implementation recursively multiplies the
        elements of gens by the distinguished generators of this
        semigroup.
See also:

```
semigroup_generators()
```

**INPUT:**

- `gens` – a list (or iterable) of elements of `self`
- `side` – [default: “twosided”] “left”, “right” or “twosided”

**EXAMPLES:**

```
sage: S = FiniteSemigroups().example()
sage: sorted(S.ideal([S('cab')], side="left"))
['abc', 'abcd', 'acbd', 'acb', 'acdb', 'adbc',
 'adcb', 'bac', 'bacd', 'badc', 'bca', 'bcad', 'bcda',
 'bdac', 'bdca', 'cab', 'cabd', 'caba', 'cbda',
 'cbda', 'cdab', 'cdba', 'dabc', 'dacb', 'dbac', 'dbca',
 'dcab', 'dcba']
sage: list(S.ideal([S('cab')], side="right"))
['cab', 'cabd']
sage: sorted(S.ideal([S('cab')], side="twosided"))
['abc', 'abcd', 'acbd', 'acb', 'acdb', 'adbc',
 'adcb', 'bac', 'bacd', 'badc', 'bca', 'bcad', 'bcda',
 'bdac', 'bdca', 'cab', 'cabd', 'caba', 'cbda',
 'cbda', 'cdab', 'cdba', 'dabc', 'dacb', 'dbac', 'dbca',
 'dcab', 'dcba']
sage: sorted(S.ideal([S('cab')]))
['abc', 'abcd', 'acbd', 'acb', 'acdb', 'adbc',
 'adcb', 'bac', 'bacd', 'badc', 'bca', 'bcad', 'bcda',
 'bdac', 'bdca', 'cab', 'cabd', 'caba', 'cbda',
 'cbda', 'cdab', 'cdba', 'dabc', 'dacb', 'dbac', 'dbca',
 'dcab', 'dcba']
```

```
semigroup_generators()
```

Return distinguished semigroup generators for `self`.

**OUTPUT:** A finite family

This method should be implemented by all semigroups in `FinitelyGeneratedSemigroups`.

**EXAMPLES:**

```
sage: S = FiniteSemigroups().example()
sage: S.semigroup_generators()
Family ('a', 'b', 'c', 'd')
```

```
succ_generators (side='twosided')
```

Return the successor function of the `side`-sided Cayley graph of `self`.

This is a function that maps an element of `self` to all the products of `x` by a generator of this semigroup, where the product is taken on the left, right, or both sides.

**INPUT:**

- `side` – “left”, “right”, or “twosided”

**Todo:** Design choice:

- find a better name for this method
- should we return a set? a family?

**EXAMPLES:**
```python
sage: S = FiniteSemigroups().example()
sage: S.succ_generators("left")('ca')
('ac', 'bca', 'ca', 'dca')
sage: S.succ_generators("right")('ca')
('ca', 'cab', 'ca', 'cad')
sage: S.succ_generators("twosided")('ca')
('ac', 'bca', 'ca', 'dca', 'ca', 'cab', 'ca', 'cad')
```

**example()**

EXAMPLES:

```python
sage: Semigroups().FinitelyGenerated().example()
An example of a semigroup: the free semigroup generated by ('a', 'b', 'c', 'd')
```

**extra_super_categories()**

State that a finitely generated semigroup is endowed with a default enumeration.

EXAMPLES:

```python
sage: Semigroups().FinitelyGenerated().extra_super_categories()
[Category of enumerated sets]
```

### 4.70 Function fields

**class** `sage.categories.function_fields.FunctionFields`

Bases: `Category`

The category of function fields.

EXAMPLES:

```python
sage: C = FunctionFields()
sage: C
Category of function fields
```

**class** `ElementMethods`

Bases: `object`

**class** `ParentMethods`

Bases: `object`

**super_categories()**

Returns the Category of which this is a direct sub-Category For a list off all super categories see all_super_categories

EXAMPLES:

```python
sage: FunctionFields().super_categories()
[Category of fields]
```
4.71 G-Sets

class sage.categories.g_sets.GSets(G)
    Bases: Category

    The category of G-sets, for a group G.

    EXAMPLES:

    sage: S = SymmetricGroup(3)
    sage: GSets(S)
    # indirect doctest
    Category of G-sets for Symmetric group of order 3! as a permutation group

    TODO: should this derive from Category_over_base?

   classmethod an_instance()
    Returns an instance of this class.

    EXAMPLES:

    sage: GSets.an_instance()
    # indirect doctest
    Category of G-sets for Symmetric group of order 8! as a permutation group

    super_categories()
    EXAMPLES:

    sage: GSets(SymmetricGroup(8)).super_categories()
    [Category of sets]

4.72 Gcd domains

class sage.categories.gcd_domains.GcdDomains
    Bases: Category_singleton

    The category of gcd domains domains where gcd can be computed but where there is no guarantee of factorisation into irreducibles

    EXAMPLES:

    sage: GcdDomains()
    Category of gcd domains
    sage: GcdDomains().super_categories()
    [Category of integral domains]

    class ElementMethods
        Bases: object

    class ParentMethods
        Bases: object
additional_structure()

Return None.

Indeed, the category of gcd domains defines no additional structure: a ring morphism between two gcd domains is a gcd domain morphism.

See also:

Category.additional_structure()

EXAMPLES:

```
sage: GcdDomains().additional_structure()
```

super_categories()

EXAMPLES:

```
sage: GcdDomains().super_categories()
```

4.73 Generalized Coxeter Groups

class sage.categories.generalized_coxeter_groups.GeneralizedCoxeterGroups

Bases: Category_singleton

The category of generalized Coxeter groups.

A generalized Coxeter group is a group with a presentation of the following form:

\[ \langle s_i \mid s_i^{p_i}, s_i s_j \cdots = s_j s_i \cdots \rangle, \]

where \( p_i > 1, i \in I \), and the factors in the braid relation occur \( m_{ij} = m_{ji} \) times for all \( i \neq j \in I \).

EXAMPLES:

```
sage: from sage.categories.generalized_coxeter_groups import GeneralizedCoxeterGroups
sage: C = GeneralizedCoxeterGroups(); C
Category of generalized Coxeter groups
```

class Finite(base_category)

Bases: CategoryWithAxiom_singleton

The category of finite generalized Coxeter groups.

extra_super_categories()

Implement that a finite generalized Coxeter group is a well-generated complex reflection group.

EXAMPLES:

```
sage: from sage.categories.generalized_coxeter_groups import GeneralizedCoxeterGroups
sage: C = GeneralizedCoxeterGroups(); C
Category of generalized Coxeter groups
```

(continues on next page)
additional_structure()

Return None.

Indeed, all the structure generalized Coxeter groups have in addition to groups (simple reflections, ...) is already defined in the super category.

See also:

Category.additional_structure()

EXAMPLES:

sage: from sage.categories.generalized_coxeter_groups import GeneralizedCoxeterGroups
sage: GeneralizedCoxeterGroups().additional_structure()

super_categories()

EXAMPLES:

sage: from sage.categories.generalized_coxeter_groups import GeneralizedCoxeterGroups
sage: GeneralizedCoxeterGroups().super_categories()

[Category of complex reflection or generalized Coxeter groups]

4.74 Graded Algebras

class sage.categories.graded_algebras.GradedAlgebras(base_category)

Bases: GradedModulesCategory

The category of graded algebras

EXAMPLES:

sage: GradedAlgebras(ZZ)
Category of graded algebras over Integer Ring
sage: GradedAlgebras(ZZ).super_categories()
[Category of filtered algebras over Integer Ring, Category of graded modules over Integer Ring]

class ElementMethods

Bases: object

class ParentMethods

Bases: object

graded_algebra()

Return the associated graded algebra to self.

Since self is already graded, this just returns self.

EXAMPLES:
class SignedTensorProducts (category, *args)
Bases: SignedTensorProductsCategory

extra_super_categories()

EXAMPLES:

sage: Algebras(QQ).Graded().SignedTensorProducts().extra_super_categories()
[Category of graded algebras over Rational Field]
sage: Algebras(QQ).Graded().SignedTensorProducts().super_categories()
[Category of graded algebras over Rational Field]

Meaning: a signed tensor product of algebras is an algebra

class SubcategoryMethods
Bases: object

SignedTensorProducts ()

Return the full subcategory of objects of self constructed as signed tensor products.

See also:
• SignedTensorProductsCategory
• CovariantFunctorialConstruction

EXAMPLES:

sage: AlgebrasWithBasis(QQ).Graded().SignedTensorProducts()
Category of signed tensor products of graded algebras with basis over Rational Field

4.75 Graded algebras with basis

class sage.categories.graded_algebras_with_basis.GradedAlgebrasWithBasis (base_category)

Bases: GradedModulesCategory

The category of graded algebras with a distinguished basis

EXAMPLES:

sage: C = GradedAlgebrasWithBasis(ZZ); C
Category of graded algebras with basis over Integer Ring
sage: sorted(C.super_categories(), key=str)
[Category of filtered algebras with basis over Integer Ring,
 Category of graded algebras over Integer Ring,
 Category of graded modules with basis over Integer Ring]
class ElementMethods
    Bases: object

class ParentMethods
    Bases: object

completion()
    Return the completion of all formal linear combinations of self with finite linear combinations in each homogeneous degree (computed lazily).

EXAMPLES:

```sage
sage: # needs sage.combinat sage.modules
sage: NCSF = NonCommutativeSymmetricFunctions(QQ)
sage: S = NCSF.Complete()
sage: L = S.formal_series_ring()
sage: L
Lazy completion of Non-Commutative Symmetric Functions over
the Rational Field in the Complete basis
```

formal_series_ring()
    Return the completion of all formal linear combinations of self with finite linear combinations in each homogeneous degree (computed lazily).

EXAMPLES:

```sage
sage: # needs sage.combinat sage.modules
sage: NCSF = NonCommutativeSymmetricFunctions(QQ)
sage: S = NCSF.Complete()
sage: L = S.formal_series_ring()
sage: L
Lazy completion of Non-Commutative Symmetric Functions over
the Rational Field in the Complete basis
```

free_graded_module(generator_degrees, names=None)
    Create a finitely generated free graded module over self

INPUT:
    • generator_degrees – tuple of integers defining the number of generators of the module and their degrees
    • names – (optional) the names of the generators. If names is a comma-separated string like 'a, b, c', then those will be the names. Otherwise, for example if names is abc, then the names will be abc[d, i].

By default, if all generators are in distinct degrees, then the names of the generators will have the form g[d] where d is the degree of the generator. If the degrees are not distinct, then the generators will be called g[d, i] where d is the degree and i is its index in the list of generators in that degree.

See sage.modules.fp_graded.free_module for more examples and details.

EXAMPLES:

```sage
sage: # needs sage.combinat sage.modules
sage: Q = QuadraticForm(QQ, 3, [1,2,3,4,5,6])
sage: Cl = CliffordAlgebra(Q)
sage: M = Cl.free_graded_module((0, 2, 3))
sage: M.gens()
(g[0], g[2], g[3])
sage: N.<xy, z> = Cl.free_graded_module((1, 2))
```

(continues on next page)
sage: N.generators()
(xy, z)

graded_algebra()
Return the associated graded algebra to self.
This is self, because self is already graded. See graded_algebra() for the general behavior of
this method, and see AssociatedGradedAlgebra for the definition and properties of associated
graded algebras.
EXAMPLES:

sage: m = SymmetricFunctions(QQ).m()
# needs sage.combinat sage.modules
sage: m.graded_algebra() is m
# needs sage.combinat sage.modules
True

class SignedTensorProducts(category, *args)
Bases: SignedTensorProductsCategory
The category of algebras with basis constructed by signed tensor product of algebras with basis.
class ParentMethods
Bases: object
    Implements operations on tensor products of super algebras with basis.
    one_basis()
    Return the index of the one of this signed tensor product of algebras, as per
    AlgebrasWithBasis.ParentMethods.one_basis.
    It is the tuple whose operands are the indices of the ones of the operands, as returned by their
    one_basis() methods.
    EXAMPLES:
    
    sage: # needs sage.combinat sage.modules
    sage: A.<x,y> = ExteriorAlgebra(QQ)
    sage: A.one_basis()
    0
    sage: B = tensor((A, A, A))
    sage: B.one_basis()
    (0, 0, 0)
    sage: B.one()
    1 # 1 # 1

    product_on_basis(t0, t1)
The product of the algebra on the basis, as per AlgebrasWithBasis.ParentMethods.
    product_on_basis.
    EXAMPLES:
    Test the sign in the super tensor product:
    
    sage: # needs sage.combinat sage.modules
    sage: A = SteenrodAlgebra(3)
    sage: x = A.Q(0)
sage: y = x.coproduct()
sage: y^2
0

TODO: optimize this implementation!

extra_super_categories()

EXAMPLES:

sage: Cat = AlgebrasWithBasis(QQ).Graded()
sage: Cat.SignedTensorProducts().extra_super_categories()
[Category of graded algebras with basis over Rational Field]
sage: Cat.SignedTensorProducts().super_categories()
[Category of graded algebras with basis over Rational Field, Category of signed tensor products of graded algebras over Rational...-Field]

4.76 Graded bialgebras

sage.categories.graded_bialgebras.GradedBialgebras(base_ring)
The category of graded bialgebras

EXAMPLES:

sage: C = GradedBialgebras(QQ); C
Join of Category of graded algebras over Rational Field and Category of bialgebras over Rational Field and Category of graded coalgebras over Rational Field
sage: C is Bialgebras(QQ).Graded()
True

4.77 Graded bialgebras with basis

sage.categories.graded_bialgebras_with_basis.GradedBialgebrasWithBasis(base_ring)
The category of graded bialgebras with a distinguished basis

EXAMPLES:

sage: C = GradedBialgebrasWithBasis(QQ); C
Join of Category of ...

sage: sorted(C.super_categories(), key=str)
[Category of bialgebras with basis over Rational Field, Category of graded algebras with basis over Rational Field, Category of graded coalgebras with basis over Rational Field]
4.78 Graded Coalgebras

class sage.categories.graded_coalgebras.GradedCoalgebras (base_category)

   Bases: GradedModulesCategory

   The category of graded coalgebras

   EXAMPLES:

   sage: C = GradedCoalgebras(QQ); C
   Category of graded coalgebras over Rational Field
   sage: C is Coalgebras(QQ).Graded()
   True

class SignedTensorProducts (category, *args)

   Bases: SignedTensorProductsCategory

   extra_super_categories ()

   EXAMPLES:

   sage: Coalgebras(QQ).Graded().SignedTensorProducts().extra_super_categories()
   [Category of graded coalgebras over Rational Field]
   sage: Coalgebras(QQ).Graded().SignedTensorProducts().super_categories()
   [Category of graded coalgebras over Rational Field]

   Meaning: a signed tensor product of coalgebras is a coalgebra

class SubcategoryMethods

   Bases: object

   SignedTensorProducts ()

   Return the full subcategory of objects of self constructed as signed tensor products.

   See also:

   • SignedTensorProductsCategory
   • CovariantFunctorialConstruction

   EXAMPLES:

   sage: CoalgebrasWithBasis(QQ).Graded().SignedTensorProducts()
   Category of signed tensor products of graded coalgebras with basis over Rational Field

4.79 Graded coalgebras with basis

class sage.categories.graded_coalgebras_with_basis.GradedCoalgebrasWithBasis (base_category)

   Bases: GradedModulesCategory

   The category of graded coalgebras with a distinguished basis.

   EXAMPLES:
```
sage: C = GradedCoalgebrasWithBasis(QQ); C
Category of graded coalgebras with basis over Rational Field
sage: C is Coalgebras(QQ).WithBasis().Graded()
True

class SignedTensorProducts (category, *args)
    Bases: SignedTensorProductsCategory

    The category of coalgebras with basis constructed by signed tensor product of coalgebras with basis.

    extra_super_categories()

    EXAMPLES:

sage: Cat = CoalgebrasWithBasis(QQ).Graded()
sage: Cat.SignedTensorProducts().extra_super_categories()
[Category of graded coalgebras with basis over Rational Field]
sage: Cat.SignedTensorProducts().super_categories()
[Category of graded coalgebras with basis over Rational Field, Category of signed tensor products of graded coalgebras over Rational Field]
```

4.80 Graded Hopf algebras

```
sage.categories.graded_hopf_algebras.GradedHopfAlgebras (base_ring)

    The category of graded Hopf algebras.

    EXAMPLES:

sage: C = GradedHopfAlgebras(QQ); C
Join of Category of Hopf algebras over Rational Field and Category of graded algebras over Rational Field and Category of graded coalgebras over Rational Field
sage: C is HopfAlgebras(QQ).Graded()
True

Note: This is not a graded Hopf algebra as is typically defined in algebraic topology as the product in the tensor square \((x \otimes y)(a \otimes b) = (xa) \otimes (yb)\) does not carry an additional sign. For this, instead use super Hopf algebras.
```

4.81 Graded Hopf algebras with basis

```
class sage.categories.graded_hopf_algebras_with_basis.GradedHopfAlgebrasWithBasis (base_category)
    Bases: GradedModulesCategory

    The category of graded Hopf algebras with a distinguished basis.

    EXAMPLES:
```
sage: C = GradedHopfAlgebrasWithBasis(ZZ); C
Category of graded Hopf algebras with basis over Integer Ring
sage: C.super_categories()
[Category of filtered Hopf algebras with basis over Integer Ring,
 Category of graded algebras with basis over Integer Ring,
 Category of graded coalgebras with basis over Integer Ring]

sage: C is HopfAlgebras(ZZ).WithBasis().Graded()
True
sage: C is HopfAlgebras(ZZ).Graded().WithBasis()
False

class Connected(base_category)

    Bases: CategoryWithAxiom_over_base_ring

class ElementMethods

    Bases: object

class ParentMethods

    Bases: object

    antipode_on_basis(index)

        The antipode on the basis element indexed by index.
        INPUT:
        • index – an element of the index set
        For a graded connected Hopf algebra, we can define an antipode recursively by
        \[ S(x) := - \sum_{x^L \neq x} S(x^L) \times x^R \]
        when \(|x| > 0\), and by \(S(x) = x\) when \(|x| = 0\).

    counit_on_basis(i)

        The default counit of a graded connected Hopf algebra.
        INPUT:
        • i – an element of the index set
        OUTPUT:
        • an element of the base ring
        \[ c(i) := \begin{cases} 1 & \text{if } i \text{ indexes the 1 of the algebra} \\ 0 & \text{otherwise.} \end{cases} \]

    example()

        Return an example of a graded connected Hopf algebra with a distinguished basis.
class ElementMethods
Bases: object

class ParentMethods
Bases: object

class WithRealizations(category, *args)
Bases: WithRealizationsCategory

super_categories()

EXAMPLES:

```
sage: GradedHopfAlgebrasWithBasis(QQ).WithRealizations().super_categories()
[Join of Category of Hopf algebras over Rational Field
and Category of graded algebras over Rational Field
and Category of graded coalgebras over Rational Field]
```

eexample()
Return an example of a graded Hopf algebra with a distinguished basis.

4.82 Graded Lie Algebras

AUTHORS:

- Eero Hakavuori (2018-08-16): initial version

class sage.categories.graded_lie_algebras.GradedLieAlgebras(base_category)
Bases: GradedModulesCategory
Category of graded Lie algebras.

class Stratified(base_category)
Bases: CategoryWithAxiom_over_base_ring
Category of stratified Lie algebras.

A graded Lie algebra $L = \bigoplus_{k=1}^{M} L_k$ (where possibly $M = \infty$) is called stratified if it is generated by $L_1$; in other words, we have $L_{k+1} = [L_1, L_k]$.

class FiniteDimensional(base_category)
Bases: CategoryWithAxiom_over_base_ring
Category of finite dimensional stratified Lie algebras.

EXAMPLES:

```
sage: LieAlgebras(QQ).Graded().Stratified().FiniteDimensional()
Category of finite dimensional stratified Lie algebras over Rational Field
```

eextra_super_categories()
Implements the fact that a finite dimensional stratified Lie algebra is nilpotent.

EXAMPLES:
```
sage: C = LieAlgebras(QQ).Graded().Stratified().FiniteDimensional()
sage: C.extra_super_categories()
[Category of nilpotent Lie algebras over Rational Field]
sage: C is C.Nilpotent()
True
sage: C.is_subcategory(LieAlgebras(QQ).Nilpotent())
True
```

**class SubcategoryMethods**

Bases: object

```python
Stratified()
```

Return the full subcategory of stratified objects of `self`.

A Lie algebra is stratified if it is graded and generated as a Lie algebra by its component of degree one.

**EXAMPLES:**

```
sage: LieAlgebras(QQ).Graded().Stratified()
Category of stratified Lie algebras over Rational Field
```

### 4.83 Graded Lie Algebras With Basis

**class** `sage.categories.graded_lie_algebras_with_basis.GradedLieAlgebrasWithBasis(base_category)`

**Bases:** `GradedModulesCategory`

The category of graded Lie algebras with a distinguished basis.

**EXAMPLES:**

```
sage: C = LieAlgebras(ZZ).WithBasis().Graded(); C
Category of graded Lie algebras with basis over Integer Ring
sage: C.super_categories()
[Category of graded modules with basis over Integer Ring,
 Category of Lie algebras with basis over Integer Ring,
 Category of graded Lie algebras over Integer Ring]
sage: C is LieAlgebras(ZZ).WithBasis().Graded()
True
sage: C is LieAlgebras(ZZ).Graded().WithBasis()
False
```

**FiniteDimensional**

alias of `FiniteDimensionalGradedLieAlgebrasWithBasis`
4.84 Graded Lie Conformal Algebras

AUTHORS:

• Reimundo Heluani (2019-10-05): Initial implementation.

```python
class sage.categories.graded_lie_conformal_algebras.GradedLieConformalAlgebras(base_category):
    Bases: GradedLieConformalAlgebrasCategory
    The category of graded Lie conformal algebras.
    EXAMPLES:

    sage: C = LieConformalAlgebras(QQbar).Graded(); C
    Category of H-graded Lie conformal algebras over Algebraic Field
    sage: CS = LieConformalAlgebras(QQ).Graded().Super(); CS
    Category of H-graded super Lie conformal algebras over Rational Field
    sage: CS is LieConformalAlgebras(QQ).Super().Graded()
    True
```

```python
class sage.categories.graded_lie_conformal_algebras.GradedLieConformalAlgebrasCategory(base_category):
    Bases: GradedModulesCategory
    Super (base_ring=None)
    Return the super-analogue category of self.
    INPUT:
    • base_ring – this is ignored
    EXAMPLES:

    sage: # needs sage.rings.number_field
    sage: C = LieConformalAlgebras(QQbar)
    sage: C.Graded().Super() is C.Super().Graded()
    True
    sage: Cp = C.WithBasis()
    sage: Cp.Graded().Super() is Cp.Super().Graded()
    True
```

4.85 Graded modules

```python
class sage.categories.graded_modules.GradedModules(base_category):
    Bases: GradedModulesCategory
    The category of graded modules.
    We consider every graded module $M = \bigoplus_i M_i$ as a filtered module under the (natural) filtration given by
    $$F_i = \bigoplus_{j < i} M_j.$$
```

4.84. Graded Lie Conformal Algebras
EXAMPLES:

```python
sage: GradedModules(ZZ)
Category of graded modules over Integer Ring
sage: GradedModules(ZZ).super_categories()
[Category of filtered modules over Integer Ring]
```

The category of graded modules defines the graded structure which shall be preserved by morphisms:

```python
sage: Modules(ZZ).Graded().additional_structure()
Category of graded modules over Integer Ring
```

```python
class ElementMethods
    Bases: object

class ParentMethods
    Bases: object

class sage.categories.graded_modules.GradedModulesCategory(base_category)
    Bases: RegressiveCovariantConstructionCategory, Category_over_base_ring
```

EXAMPLES:

```python
sage: C = GradedAlgebras(QQ)
sage: C
Category of graded algebras over Rational Field
sage: C.base_category()
Category of algebras over Rational Field
sage: sorted(C.super_categories(), key=str)
[Category of filtered algebras over Rational Field,
Category of graded vector spaces over Rational Field]
sage: AlgebrasWithBasis(QQ).Graded().base_ring()
Rational Field
sage: GradedHopfAlgebrasWithBasis(QQ).base_ring()
Rational Field
```

```python
classmethod default_super_categories(category, *args)
    Return the default super categories of category.Graded().

    Mathematical meaning: every graded object (module, algebra, etc.) is a filtered object with the (implicit) filtration defined by
\[ F_i = \bigoplus_{j \leq i} G_j. \]

    INPUT:
    • cls -- the class GradedModulesCategory
    • category -- a category

    OUTPUT: a (join) category
    In practice, this returns category.Filtered(), joined together with the result of the method
    RegressiveCovariantConstructionCategory.default_super_categories() (that is the join of category.Filtered() and cat for each cat in the super categories of category).

    EXAMPLES:
    Consider category=Algebras(), which has cat=Modules() as super category. Then, a grading of an algebra \( G \) is also a filtration of \( G \):
```
This resulted from the following call:

```
sage: sage.categories.graded_modules.GradedModulesCategory.default_super_categories(Algebras(QQ))
Join of Category of filtered algebras over Rational Field and Category of graded vector spaces over Rational Field
```

## 4.86 Graded modules with basis

### class sage.categories.graded_modules_with_basis.GradedModulesWithBasis(base_category)

| Bases: | GradedModulesCategory |

The category of graded modules with a distinguished basis.

#### EXAMPLES:

```
sage: C = GradedModulesWithBasis(ZZ); C
Category of graded modules with basis over Integer Ring
sage: sorted(C.super_categories(), key=str)
[Category of filtered modules with basis over Integer Ring, Category of graded modules over Integer Ring]
sage: C is ModulesWithBasis(ZZ).Graded()
True
```

### class ElementMethods

| Bases: | object |

| degree_negation() |

Return the image of \(\text{self}\) under the degree negation automorphism of the graded module to which \(\text{self}\) belongs.

The degree negation is the module automorphism which scales every homogeneous element of degree \(k\) by \((-1)^k\) (for all \(k\)). This assumes that the module to which \(\text{self}\) belongs (that is, the module \(\text{self.parent()}\)) is \(\mathbb{Z}\)-graded.

#### EXAMPLES:

```
sage: E.<a,b> = ExteriorAlgebra(QQ)
# needs sage.modules
sage: ((1 + a) * (1 + b)).degree_negation()  # needs sage.modules
a*b - a - b + 1
sage: E.zero().degree_negation()  # needs sage.modules
0
sage: P = GradedModulesWithBasis(ZZ).example(); P  # needs sage.combinat sage.modules
An example of a graded module with basis:
the free module on partitions over Integer Ring
```

(continues on next page)
class ParentMethods

    Bases: object

    degree_negation(element)

    Return the image of element under the degree negation automorphism of the graded module self.

    The degree negation is the module automorphism which scales every homogeneous element of degree $k$
    by $(-1)^k$ (for all $k$). This assumes that the module self is $\mathbb{Z}$-graded.

    INPUT:
    • element – element of the module self

    EXAMPLES:

    sage: E.<a,b> = ExteriorAlgebra(QQ)  # needs sage.modules
    sage: E.degree_negation((1 + a) * (1 + b))  # needs sage.modules
    a*b - a - b + 1
    sage: E.degree_negation(E.zero())  # needs sage.modules
    0

    sage: P = GradedModulesWithBasis(ZZ).example(); P  # needs sage.combinat sage.modules
    An example of a graded module with basis:
    the free module on partitions over Integer Ring
    sage: pbp = lambda x: P.basis()[Partition(list(x))]  # needs sage.combinat sage.modules
    sage: p = pbp([3,1]) - 2 * pbp([2]) + 4 * pbp([1])  # needs sage.combinat sage.modules
    sage: P.degree_negation(p)  # needs sage.combinat sage.modules

    quotient_module(submodule, check=True, already_echelonized=False, category=None)

    Construct the quotient module self / submodule.

    INPUT:
    • submodule – a submodule with basis of self, or something that can be turned into one via
      self.submodule(submodule)
    • check, already_echelonized – passed down to ModulesWithBasis.
      ParentMethods.submodule()
    • category – (optional) the category of the quotient module

    Warning: At this point, this only supports quotients by free submodules admitting a basis in unitri-
    angular echelon form. In this case, the quotient is also a free module, with a basis consisting of the
    retract of a subset of the basis of self.

    EXAMPLES:
sage: # needs sage.combinat sage.modules
sage: E.<x,y,z> = ExteriorAlgebra(QQ)
sage: S = E.submodule([x + y, x*y - y*z, y])
sage: Q = E.quotient_module(S)
sage: Q.category()
Join of
    Category of quotients of graded modules with basis over Rational Field
    and
    Category of graded vector spaces with basis over Rational Field and
    Category of finite dimensional filtered modules with basis over Rational Field
See also:
• Modules.WithBasis.ParentMethods.submodule()
• Rings.ParentMethods.quotient()
• sage.modules.with_basis.subquotient.QuotientModuleWithBasis

submodule (gens, check=True, already_echelonized=False, unitriangular=False, support_order=None, category=None, *args, **opts)

Return the submodule spanned by a finite set of elements.

INPUT:
• gens – a list or family of elements of self
• check – (default: True) whether to verify that the elements of gens are in self
• already_echelonized – (default: False) whether the elements of gens are already in (not necessarily reduced) echelon form
• unitriangular – (default: False) whether the lift morphism is unitriangular
• support_order – (optional) either something that can be converted into a tuple or a key function
• category – (optional) the category of the submodule

If already_echelonized is False, then the generators are put in reduced echelon form using echelonize(), and reindexed by 0, 1,....

Warning: At this point, this method only works for finite dimensional submodules and if matrices can be echelonized over the base ring.

If in addition unitriangular is True, then the generators are made such that the coefficients of the pivots are 1, so that lifting map is unitriangular.

The basis of the submodule uses the same index set as the generators, and the lifting map sends \( y_i \) to \( \text{gens}[i] \).

See also:
• ModulesWithBasis.FiniteDimensional.ParentMethods.quotient_module()
• sage.modules.with_basis.subquotient.SubmoduleWithBasis

EXAMPLES:
A graded submodule of a graded module generated by homogeneous elements is naturally graded:

sage: # needs sage.combinat sage.modules
sage: E.<x,y,z> = ExteriorAlgebra(QQ)
sage: S = E.submodule([x + y, x*y - y*z])

(continues on next page)
We check on the echelonized basis:

```
sage: Sp = E.submodule([1, x + y + 5, x*y - y*z + x + y - 2])
# needs sage.combinat sage.modules
sage: Sp.category()
# needs sage.combinat sage.modules
Join of
  Category of graded vector spaces with basis over Rational Field and
  Category of subobjects of filtered modules with basis over Rational Field
  Category of finite dimensional filtered modules with basis over Rational Field
```

If it is generated by inhomogeneous elements, then it is filtered by default:

```
sage: F = E.submodule([x + y*z, x*z + y*x])
# needs sage.combinat sage.modules
sage: F.category()
# needs sage.combinat sage.modules
Join of
  Category of subobjects of filtered modules with basis over Rational Field
  Category of finite dimensional filtered modules with basis over Rational Field
  Category of filtered vector spaces with basis over Rational Field
```

If category is specified, then it does not give any extra structure to the submodule (we can think of this as applying the forgetful functor):

```
sage: # needs sage.combinat sage.modules
sage: SM = E.submodule([x + y, x*y - y*z],
  ....: category=ModulesWithBasis(QQ))
sage: SM.category()
Join of
  Category of finite dimensional vector spaces with basis over Rational Field
  Category of subobjects of sets
sage: FM = E.submodule([x + 1, x*y - x*y*z],
  ....: category=ModulesWithBasis(QQ))
sage: FM.category()
Join of
  Category of finite dimensional vector spaces with basis over Rational Field
  Category of subobjects of sets
```
If we have specified that this is a graded submodule of a graded module, then the echelonized elements must be homogeneous:

```python
cat = ModulesWithBasis(QQ).Graded().Subobjects()
cat
E.submodule([x + y, x*y - 1], category=cat) # needs sage.combinat sage.modules
Traceback (most recent call last):
  ... ValueError: all of the generators must be homogeneous
cat
E.submodule([x + y, x*y - x - y], category=cat) # needs sage.combinat sage.modules
Free module generated by {0, 1} over Rational Field
```

```python
class Quotients(category, *args)
Bases: QuotientsCategory
class ElementMethods
Bases: object
def degree()
    Return the degree of self.
    EXAMPLES:
        sage: # needs sage.combinat sage.modules
        sage: E.<x,y,z> = ExteriorAlgebra(QQ)
        sage: S = E.submodule([x + y, x*y - y*z, y])
        sage: Q = E.quotient_module(S)
        sage: B = Q.basis()
        sage: [B[i].lift() for i in Q.indices()]
        [1, z, x*z, y*z, x*y*z]
        sage: [B[i].degree() for i in Q.indices()]
        [0, 1, 2, 2, 3]
```

```python
class ParentMethods
Bases: object
def degree_on_basis(m)
    Return the degree of the basis element indexed by m in self.
    EXAMPLES:
        sage: # needs sage.combinat sage.modules
        sage: E.<x,y,z> = ExteriorAlgebra(QQ)
        sage: S = E.submodule([x + y, x*y - y*z, y])
        sage: Q = E.quotient_module(S)
        sage: B = Q.basis()
        sage: [B[i].lift() for i in Q.indices()]
        [1, z, x*z, y*z, x*y*z]
        sage: [Q.degree_on_basis(i) for i in Q.indices()]
        [0, 1, 2, 2, 3]
```

4.86. Graded modules with basis
4.87 Graphs

class sage.categories.graphs.Graphs
    Bases: Category_singleton
    The category of graphs.
    EXAMPLES:

    sage: from sage.categories.graphs import Graphs
    sage: C = Graphs(); C
    Category of graphs

class Connected(base_category)
    Bases: CategoryWithAxiom
    The category of connected graphs.
    EXAMPLES:

    sage: from sage.categories.graphs import Graphs
    sage: C = Graphs().Connected()
sage: TestSuite(C).run()

    extra_super_categories()
        Return the extra super categories of self.
        A connected graph is also a metric space.
    EXAMPLES:

    sage: from sage.categories.graphs import Graphs
    sage: Graphs().Connected().super_categories()  # indirect doctest
    [Category of connected topological spaces,
     Category of connected simplicial complexes,
     Category of graphs,
     Category of metric spaces]

class ParentMethods
    Bases: object

dimension()
        Return the dimension of self as a CW complex.
    EXAMPLES:

    sage: from sage.categories.graphs import Graphs
    sage: C = Graphs().example()
sage: C.dimension()
1

edges()
    Return the edges of self.
    EXAMPLES:
sage: from sage.categories.graphs import Graphs
sage: C = Graphs().example()
[(0, 1), (1, 2), (2, 3), (3, 4), (4, 0)]

faces()
Return the faces of self.

EXAMPLES:
sage: from sage.categories.graphs import Graphs
sage: C = Graphs().example()
sage: sorted(C.faces(), key=lambda x: (x.dimension(), x.value))
[0, 1, 2, 3, 4, (0, 1), (1, 2), (2, 3), (3, 4), (4, 0)]

facets()
Return the facets of self.

EXAMPLES:
sage: from sage.categories.graphs import Graphs
sage: C = Graphs().example()
sage: C.facets()
[(0, 1), (1, 2), (2, 3), (3, 4), (4, 0)]

vertices()
Return the vertices of self.

EXAMPLES:
sage: from sage.categories.graphs import Graphs
sage: C = Graphs().example()
sage: C.vertices()
[0, 1, 2, 3, 4]

super_categories()
EXAMPLES:
sage: from sage.categories.graphs import Graphs
sage: Graphs().super_categories()
[Category of simplicial complexes]
• Nicolas M. Thiéry (2010-2017), Travis Scrimshaw (2017): generalization to a covariant functorial construction for monoidal algebras, and beyond – see e.g. github issue #18700.

```python
class sage.categories.group_algebras.GroupAlgebras(category, *args)
    Bases: AlgebrasCategory

The category of group algebras over a given base ring.

EXAMPLES:

```
```
sage: C = Groups().Algebras(ZZ); C
Category of group algebras over Integer Ring
sage: C.super_categories()
[Category of Hopf algebras with basis over Integer Ring,
 Category of monoid algebras over Integer Ring]
```
```
We can also construct this category with:
```
```
sage: C is GroupAlgebras(ZZ)
True
```
```
Here is how to create the group algebra of a group $G$:
```
```
sage: G = DihedralGroup(5)  #...
sage: QG = G.algebra(QQ); QG
Algebra of Dihedral group of order 10 as a permutation group over Rational Field
```
```
and an example of computation:
```
```
sage: g = G.an_element(); g  #...
(1,4)(2,3)
sage: (QG.term(g) + 1)**3  #...
4*() + 4*(1,4)(2,3)
```
```
Todo:

• Check which methods would be better located in Monoid.Algebras or Groups.Finite.Algebras.
```
```
class ElementMethods
    Bases: object

    central_form()

    Return self expressed in the canonical basis of the center of the group algebra.

    INPUT:
    • self – an element of the center of the group algebra

    OUTPUT:
    • A formal linear combination of the conjugacy class representatives representing its coordinates in the canonical basis of the center. See Groups.Algebras.ParentMethods.center_basis() for details.
Warning:

- This method requires the underlying group to have a method `conjugacy_classes_representatives` (every permutation group has one, thanks GAP!).
- This method does not check that the element is indeed central. Use the method `Monoids.Algebras.ElementMethods.is_central()` for this purpose.
- This function has a complexity linear in the number of conjugacy classes of the group. One could easily implement a function whose complexity is linear in the size of the support of self.

EXAMPLES:

```python
sage: # needs sage.groups sage.modules
sage: QS3 = SymmetricGroup(3).algebra(QQ)
sage: A = QS3([[2,3,1]] + QS3([[3,1,2]])
sage: A.central_form()
B[(1,2,3)]
sage: QS4 = SymmetricGroup(4).algebra(QQ)
sage: B = sum(len(s.cycle_type()) * QS4(s) for s in Permutations(4))
sage: B.central_form()
4*B[()] + 3*B[(1,2)] + 2*B[(1,2)(3,4)] + 2*B[(1,2,3)] + B[(1,2,3,4)]
```

The following test fails due to a bug involving combinatorial free modules and the coercion system (see github issue #28544):

```python
sage: # needs sage.groups sage.modules
sage: G = PermutationGroup([[(1,2,3),(4,5)], [(3,4)]]
```

```python
sage: s = sum(QG.basis())
sage: s.central_form() # not tested
B[()] + B[(4,5)] + B[(3,4,5)] + B[(2,3)(4,5)]
+ B[(2,3,4,5)] + B[(1,2)(3,4,5)] + B[(1,2,3,4,5)]
```

See also:

- `Groups.Algebras.ParentMethods.center_basis()`
- `Monoids.Algebras.ElementMethods.is_central()`

class ParentMethods

Bases: object

antipode_on_basis(g)

Return the antipode of the element $g$ of the basis.

Each basis element $g$ is group-like, and so has antipode $g^{-1}$. This method is used to compute the antipode of any element.

EXAMPLES:

```python
sage: # needs sage.groups sage.modules
sage: A = CyclicPermutationGroup(6).algebra(ZZ); A
Algebra of
Cyclic group of order 6 as a permutation group over Integer Ring
sage: g = CyclicPermutationGroup(6).an_element(); g
(1,2,3,4,5,6)
sage: A.antipode_on_basis(g)
```

(continues on next page)
center_basis()

Return a basis of the center of the group algebra.

The canonical basis of the center of the group algebra is the family \((f_\sigma)_{\sigma \in C}\), where \(C\) is any collection of representatives of the conjugacy classes of the group, and \(f_\sigma\) is the sum of the elements in the conjugacy class of \(\sigma\).

OUTPUT:

- tuple of elements of self

Warning:

- This method requires the underlying group to have a method conjugacy_classes (every permutation group has one, thanks GAP!).

EXAMPLES:

```sage
sage: SymmetricGroup(3).algebra(QQ).center_basis()
((), (2,3) + (1,2) + (1,3), (1,2,3) + (1,3,2))
```

See also:

- Monoids.Algebras.ElementMethods.is_central()

coproduct_on_basis(g)

Return the coproduct of the element \(g\) of the basis.

Each basis element \(g\) is group-like. This method is used to compute the coproduct of any element.

EXAMPLES:

```sage
sage: A = CyclicPermutationGroup(6).algebra(ZZ); A
Algebra of
Cyclic group of order 6 as a permutation group over Integer Ring
sage: g = CyclicPermutationGroup(6).an_element(); g
(1,2,3,4,5,6)
sage: A.coproduct_on_basis(g)
(1,2,3,4,5,6) # (1,2,3,4,5,6)
sage: a = A.an_element(); a
() + 3*(1,2,3,4,5,6) + 3*(1,3,5)(2,4,6)
sage: a.coproduct()
() # () + 3*(1,2,3,4,5,6) # (1,2,3,4,5,6) + 3*(1,3,5)(2,4,6) # (1,3,5)(2,4,6)
```

counit(x)

Return the counit of the element \(x\) of the group algebra.

This is the sum of all coefficients of \(x\) with respect to the standard basis of the group algebra.
EXAMPLES:

```python
sage: A = CyclicPermutationGroup(6).algebra(ZZ); A  # needs sage.groups sage.modules
Algebra of
  Cyclic group of order 6 as a permutation group over Integer Ring
sage: a = A.an_element(); a  # needs sage.groups sage.modules
() + 3*(1,2,3,4,5,6) + 3*(1,3,5)(2,4,6)
sage: a.counit()  # needs sage.groups sage.modules
7
counit_on_basis(g)
Return the counit of the element g of the basis.
Each basis element g is group-like, and so has counit 1. This method is used to compute the counit of
any element.

EXAMPLES:

```python
sage: A = CyclicPermutationGroup(6).algebra(ZZ); A  # needs sage.groups sage.modules
Algebra of
  Cyclic group of order 6 as a permutation group over Integer Ring
sage: g = CyclicPermutationGroup(6).an_element(); g  # needs sage.groups sage.modules
(1,2,3,4,5,6)
sage: A.counit_on_basis(g)  # needs sage.groups sage.modules
1
group()
Return the underlying group of the group algebra.

EXAMPLES:

```python
sage: GroupAlgebras(QQ).example(GL(3, GF(11))).group()  # needs sage.groups sage.modules
General Linear Group of degree 3 over Finite Field of size 11
sage: SymmetricGroup(10).algebra(QQ).group()  # needs sage.groups sage.modules
Symmetric group of order 10! as a permutation group

is_integral_domain(proof=True)
Return True if self is an integral domain.
This is false unless self.base_ring() is an integral domain, and even then it is false unless self.
group() has no nontrivial elements of finite order. I don’t know if this condition suffices, but it obvi-
ously does if the group is abelian and finitely generated.

EXAMPLES:

```python
sage: # needs sage.groups sage.modules
sage: S2 = SymmetricGroup(2)
sage: GroupAlgebra(S2).is_integral_domain()  # needs sage.groups sage.modules
False
sage: S1 = SymmetricGroup(1)
```

(continues on next page)
example \( (G=None) \)

Return an example of group algebra.

EXAMPLES:

```sage
sage: GroupAlgebras(QQ['x']).example() # needs sage.groups sage.modules
Algebra of Dihedral group of order 8 as a permutation group
over Univariate Polynomial Ring in x over Rational Field
```

An other group can be specified as optional argument:

```sage
sage: GroupAlgebras(QQ).example(AlternatingGroup(4)) # needs sage.groups sage.modules
Algebra of
Alternating group of order 4!/2 as a permutation group over Rational Field
```

extra_super_categories()

Implement the fact that the algebra of a group is a Hopf algebra.

EXAMPLES:

```sage
sage: C = Groups().Algebras(QQ)
sage: C.extra_super_categories()
[Category of Hopf algebras over Rational Field]
sage: sorted(C.super_categories(), key=str)
[Category of Hopf algebras with basis over Rational Field,
Category of monoid algebras over Rational Field]
```

4.89 Groupoid

class \( \text{sage.categories.groupoid.Groupoid} \)(\(G=None\))

Bases: \( \text{CategoryWithParameters} \)

The category of groupoids, for a set (usually a group) \( G \).

FIXME:

- Groupoid or Groupoids ?
- definition and link with Wikipedia article Groupoid
- Should Groupoid inherit from Category\_over\_base?

EXAMPLES:
classmethod an_instance()

Returns an instance of this class.

EXAMPLES:

```python
sage: Groupoid.an_instance()  # indirect doctest
Groupoid with underlying set Symmetric group of order 8! as a permutation...
```

super_categories()

EXAMPLES:

```python
sage: Groupoid(DihedralGroup(3)).super_categories()
[Category of sets]
```

4.90 Groups

```python
sage: sage.categories.groups.Groups(base_category)
Bases: CategoryWithAxiom_singleton
The category of (multiplicative) groups, i.e. monoids with inverses.

EXAMPLES:

```python
sage: Groups()
Category of groups
sage: Groups().super_categories()
[Category of monoids, Category of inverse unital magmas]
```

Algebras

alias of GroupAlgebras
class CartesianProducts(category, *args)

Bases: CartesianProductsCategory
The category of groups constructed as Cartesian products of groups.
This construction gives the direct product of groups. See Wikipedia article Direct_product and Wikipedia article Direct_product_of_groups for more information.

class ParentMethods

Bases: object

group_generators()

Return the group generators of self.

EXAMPLES:

```python
sage: # needs sage.groups
sage: C5 = CyclicPermutationGroup(5)
sage: C4 = CyclicPermutationGroup(4)
sage: S4 = SymmetricGroup(3)
```

(continues on next page)
We check the other portion of `github issue #16718` is fixed:

```sage
sage: len(C.j_classes())
1
```

An example with an infinitely generated group (a better output is needed):

```sage
sage: # needs sage.groups
sage: G = Groups.free([1,2])
sage: H = Groups.free(ZZ)
sage: C = cartesian_product([G, H])
sage: C.monoid_generators()
Lazy family (gen(i))_{i in The Cartesian product of (...)}
```

```
order()
```

Return the cardinality of self.

**EXAMPLES:**

```sage
sage: C = cartesian_product([SymmetricGroup(10), SL(2, GF(3))])  # needs sage.groups sage.rings.finite_rings
sage: C.order()
# needs sage.groups sage.rings.finite_rings
87091200
```

**Todo:** this method is just here to prevent `FiniteGroups.ParentMethods` to call `_cardinality_from_iterator`.

**extra_super_categories()**

A Cartesian product of groups is endowed with a natural group structure.

**EXAMPLES:**

```sage
sage: C = Groups().CartesianProducts()
sage: C.extra_super_categories()
[Category of groups]
sage: sorted(C.super_categories(), key=str)
[Category of Cartesian products of inverse unital magmas,
 Category of Cartesian products of monoids,
 Category of groups]
```

**class Commutative** *(base_category)*

Bases: `CategoryWithAxiom`

Category of commutative (abelian) groups.

A group $G$ is *commutative* if $xy = yx$ for all $x, y \in G$. 

---

520 Chapter 4. Individual Categories
**static free**(*index_set=None, names=None, **kwds*)

Return the free commutative group.

**INPUT:**
- `index_set` – (optional) an index set for the generators; if an integer, then this represents \(\{0,1,\ldots,n-1\}\)
- `names` – a string or list/tuple/iterable of strings (default: `x`); the generator names or name prefix

**EXAMPLES:**

```python
sage: # needs sage.groups
sage: Groups.Commutative.free(index_set=ZZ)
Free abelian group indexed by Integer Ring
sage: Groups().Commutative().free(ZZ)
Free abelian group indexed by Integer Ring
sage: Groups().Commutative().free(5)
Multiplicative Abelian group isomorphic to \(\mathbb{Z} \times \mathbb{Z} \times \mathbb{Z} \times \mathbb{Z} \times \mathbb{Z}\)
```

```python
sage: F.<x,y,z> = Groups().Commutative().free(); F
Multiplicative Abelian group isomorphic to \(\mathbb{Z} \times \mathbb{Z} \times \mathbb{Z}\)
```

### class ElementMethods

Bases: object

**conjugacy_class()**

Return the conjugacy class of self.

**EXAMPLES:**

```python
sage: D = DihedralGroup(5)  # needs sage.groups
sage: g = D((1,3,5,2,4))  # needs sage.groups
sage: g.conjugacy_class()  # needs sage.groups
Conjugacy class of (1,3,5,2,4) in Dihedral group of order 10 as a permutation group
```

```python
sage: H = MatrixGroup([matrix(GF(5), 2, [1,2, -1,1]), matrix(GF(5), 2, [1,1, 0,1])])  # needs sage.modules....
```

```python
sage: h = H(matrix(GF(5), 2, [1,2, -1,1]))  # needs sage.modules
sage: h.conjugacy_class()  # needs sage.modules
Conjugacy class of 
\[
\begin{bmatrix}
1 & 2 \\
4 & 1
\end{bmatrix}
\]
in Matrix group over Finite Field of size 5 with 2 generators ( 
\[
\begin{bmatrix}
1 & 2 \\
0 & 1
\end{bmatrix}
\]
)
```

```python
sage: G = SL(2, GF(2))  # needs sage.modules
sage: g = G.gens()[0]  # needs sage.modules
sage: g.conjugacy_class()  # needs sage.modules
Conjugacy class of 
\[
\begin{bmatrix}
0 & 1 \\
1 & 0
\end{bmatrix}
\]
in Special Linear Group of degree 2 over Finite Field of size 2
```

(continues on next page)
sage: G = SL(2, QQ)  # needs sage.modules
sage: g = G([[1,1], [0,1]])  # needs sage.modules
sage: g.conjugacy_class()  # needs sage.groups sage.modules
Conjugacy class of [1 1]
[0 1] in Special Linear Group of degree 2 over Rational Field

Finite
alias of FiniteGroups

Lie
alias of LieGroups

class ParentMethods
Bases: object
cayley_table(names='letters', elements=None)

Return the “multiplication” table of this multiplicative group, which is also known as the “Cayley table”.

Note: The order of the elements in the row and column headings is equal to the order given by the table’s column_keys() method. The association between the actual elements and the names/symbols used in the table can also be retrieved as a dictionary with the translation() method.

For groups, this routine should behave identically to the multiplication_table() method for magmas, which applies in greater generality.

INPUT:
• names - the type of names used, values are:
  - 'letters' - lowercase ASCII letters are used for a base 26 representation of the elements’ positions in the list given by list(), padded to a common width with leading ‘a’s.
  - 'digits' - base 10 representation of the elements’ positions in the list given by column_keys(), padded to a common width with leading zeros.
  - 'elements' - the string representations of the elements themselves.
  - a list - a list of strings, where the length of the list equals the number of elements.
• elements - default = None. A list of elements of the group, in forms that can be coerced into the structure, eg. their string representations. This may be used to impose an alternate ordering on the elements, perhaps when this is used in the context of a particular structure. The default is to use whatever ordering is provided by the the group, which is reported by the column_keys() method. Or the elements can be a subset which is closed under the operation. In particular, this can be used when the base set is infinite.

OUTPUT:
An object representing the multiplication table. This is an OperationTable object and even more documentation can be found there.

EXAMPLES:
Permutation groups, matrix groups and abelian groups can all compute their multiplication tables.
### 4.90. Groups

Lowercase ASCII letters are the default symbols used for the table, but you can also specify the use of decimal digit strings, or provide your own strings (in the proper order if they have meaning). Also, if the elements themselves are not too complex, you can choose to just use the string representations of the elements themselves.
 sage: G = QuaternionGroup()
 sages: names = ['1', 'I', '-I', 'J', '-J', 'K', 'K']
 sage: G.cayley_table(names=names)

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>I</th>
<th>-1</th>
<th>-I</th>
<th>J</th>
<th>-K</th>
<th>-J</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>I</td>
<td>-1</td>
<td>-I</td>
<td>J</td>
<td>-K</td>
<td>-J</td>
<td>K</td>
</tr>
<tr>
<td>I</td>
<td>I</td>
<td>-1</td>
<td>1</td>
<td>K</td>
<td>J</td>
<td>-K</td>
<td>-J</td>
<td>K</td>
</tr>
<tr>
<td>-1</td>
<td>-1</td>
<td>-I</td>
<td>1</td>
<td>J</td>
<td>K</td>
<td>-I</td>
<td>1</td>
<td>I</td>
</tr>
<tr>
<td>-I</td>
<td>-I</td>
<td>1</td>
<td>-1</td>
<td>-K</td>
<td>-J</td>
<td>K</td>
<td>J</td>
<td>-K</td>
</tr>
<tr>
<td>J</td>
<td>J</td>
<td>-K</td>
<td>-J</td>
<td>K</td>
<td>-I</td>
<td>1</td>
<td>I</td>
<td>-1</td>
</tr>
<tr>
<td>-K</td>
<td>-K</td>
<td>-J</td>
<td>K</td>
<td>-K</td>
<td>1</td>
<td>-I</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td>-J</td>
<td>-J</td>
<td>K</td>
<td>J</td>
<td>-K</td>
<td>1</td>
<td>-I</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td>K</td>
<td>K</td>
<td>J</td>
<td>-K</td>
<td>-J</td>
<td>-I</td>
<td>1</td>
<td>I</td>
<td>-1</td>
</tr>
</tbody>
</table>

The `change_names()` routine behaves similarly, but changes an existing table “in-place.”

 sage: A = AbelianGroup([2, 2])
 sages: A.cayley_table(names='elements')

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>f1</th>
<th>f0</th>
<th>f0*f1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>f1</td>
<td>f0</td>
<td>f0*f1</td>
</tr>
<tr>
<td>f1</td>
<td>f1</td>
<td>f0</td>
<td>f0*f1</td>
<td>f0</td>
</tr>
<tr>
<td>f0</td>
<td>f0</td>
<td>f0*f1</td>
<td>f1</td>
<td></td>
</tr>
<tr>
<td>f0*f1</td>
<td>f0*f1</td>
<td>f0</td>
<td>f1</td>
<td></td>
</tr>
</tbody>
</table>

For an infinite group, you can still work with finite sets of elements, provided the set is closed under multiplication. Elements will be coerced into the group as part of setting up the table.
The `OperationTable` class provides even greater flexibility, including changing the operation. Here is one such example, illustrating the computation of commutators. `commutator` is defined as a function of two variables, before being used to build the table. From this, the commutator subgroup seems obvious, and creating a Cayley table with just these three elements confirms that they form a closed subset in the group.

```python
sage: # needs sage.groups sage.modules
sage: from sage.matrix.operation_table import OperationTable
sage: G = DiCyclicGroup(3)
sage: commutator = lambda x, y: x*y*x^-1*y^-1
sage: T = OperationTable(G, commutator); T
   a b c d e f g h i j k l
+------------------------
a| a a a a a a a a a a a a
b| a a a a a c c c c c c
c| a a a a a b b b b b b
d| a a a a a a a a a a a a
e| a a a a a c c c c c c
f| a a a a a a b b b b b b
g| a b c a b c a b c a b
h| a b c a b c b a c b a
d| a b c a b c c b a c b
j| a b c a b c a c b a c
k| a b c a b c c b a c b
l| a b c a b c b a c b a
sage: trans = T.translation()
sage: comm = [trans['a'], trans['b'], trans['c']]
sage: comm
[(), (5,6,7), (5,7,6)]
sage: P = G.cayley_table(elements=comm)
sage: P
   a b c
+------
a| a b c
b| b c a
c| c a b
```

**Todo:** Arrange an ordering of elements into cosets of a normal subgroup close to size $\sqrt{n}$. Then the quotient group structure is often apparent in the table. See comments on `github` issue #7555.

**AUTHOR:**
- Rob Beezer (2010-03-15)

`conjugacy_class(g)`

Return the conjugacy class of the element $g$.

This is a fall-back method for groups not defined over GAP.
EXAMPLES:

```python
sage: A = AbelianGroup([2, 2])                      #...
      # needs sage.groups
sage: c = A.conjugacy_class(A.an_element())         #...
      # needs sage.groups
sage: type(c)                                        #...
      # needs sage.groups
<class 'sage.groups.conjugacy_classes.ConjugacyClass_with_category'>
```

group_generators ()

Return group generators for self.

This default implementation calls `gens()`, for backward compatibility.

EXAMPLES:

```python
sage: A = AlternatingGroup(4)                       #...
      # needs sage.groups
sage: A.group_generators()                          #...
      # needs sage.groups
Family ((2,3,4), (1,2,3))
```

holomorph ()

The holomorph of a group

The holomorph of a group $G$ is the semidirect product $G \rtimes \text{id }\text{Aut}(G)$, where $\text{id }$ is the identity function on $\text{Aut}(G)$, the automorphism group of $G$.

See Wikipedia article Holomorph (mathematics)

EXAMPLES:

```python
sage: G = Groups().example()                        #...
      # needs sage.modules
sage: G.holomorph()                                 #...
      # needs sage.modules
Traceback (most recent call last):
...
NotImplementedError: holomorph of General Linear Group of degree 4
over Rational Field not yet implemented
```

monoid_generators ()

Return the generators of self as a monoid.

Let $G$ be a group with generating set $X$. In general, the generating set of $G$ as a monoid is given by $X \cup X^{-1}$, where $X^{-1}$ is the set of inverses of $X$. If $G$ is a finite group, then the generating set as a monoid is $X$.

EXAMPLES:

```python
sage: A = AlternatingGroup(4)
sage: A.monoid_generators()                        #...
Family ((2,3,4), (1,2,3))
```
**semidirect_product** \((N, \text{mapping}, \text{check}=\text{True})\)

The semi-direct product of two groups

**EXAMPLES:**

```python
sage: G = Groups().example()
# needs sage.modules
```

```python
sage: G.semidirect_product(G, Morphism(G, G))
# needs sage.modules
```

Traceback (most recent call last):
...
NotImplementedError: semidirect product of General Linear Group of degree 4 over Rational Field and General Linear Group of degree 4 over Rational Field not yet implemented

**class Topological**(category, *args)

Bases: **TopologicalSpacesCategory**

Category of topological groups.

A topological group \(G\) is a group which has a topology such that multiplication and taking inverses are continuous functions.

**REFERENCES:**

• Wikipedia article Topological_group

**example()**

**EXAMPLES:**

```python
sage: Groups().example()
# needs sage.modules
```

```python
General Linear Group of degree 4 over Rational Field
```

**static free**(index_set=None, names=None, **kwds)

Return the free group.

**INPUT:**

• **index_set** (optional) an index set for the generators; if an integer, then this represents \(\{0, 1, \ldots, n-1\}\)

• **names** - a string or list/tuple/iterable of strings (default: 'x'); the generator names or name prefix

When the index set is an integer or only variable names are given, this returns FreeGroup_class, which currently has more features due to the interface with GAP than IndexedFreeGroup.

**EXAMPLES:**

```python
sage: # needs sage.groups
sage: Groups().free(index_set=ZZ)
Free group indexed by Integer Ring
```

```python
sage: Groups().free(ZZ)
Free group indexed by Integer Ring
```

```python
sage: Groups().free(5)
Free Group on generators {x0, x1, x2, x3, x4}
```

```python
sage: F.<x,y,z> = Groups().free(); F
Free Group on generators {x, y, z}
```
4.91 Hecke modules

class sage.categories.hecke_modules.HeckeModules(R)

    Bases: Category_module

    The category of Hecke modules.

    A Hecke module is a module $M$ over the emph{anemic} Hecke algebra, i.e., the Hecke algebra generated by Hecke operators $T_n$ with $n$ coprime to the level of $M$. (Every Hecke module defines a level function, which is a positive integer.) The reason we require that $M$ only be a module over the anemic Hecke algebra is that many natural maps, e.g., degeneracy maps, Atkin-Lehner operators, etc., are $T$-module homomorphisms; but they are homomorphisms over the anemic Hecke algebra.

EXEMPLES:

We create the category of Hecke modules over $\mathbb{Q}$:

```
sage: C = HeckeModules(RationalField()); C
Category of Hecke modules over Rational Field
```

TODO: check that this is what we want:

```
sage: C.super_categories()

[Category of vector spaces with basis over Rational Field]
```

# [Category of vector spaces over Rational Field]

Note that the base ring can be an arbitrary commutative ring:

```
sage: HeckeModules(IntegerRing())
Category of Hecke modules over Integer Ring
sage: HeckeModules(FiniteField(5))
Category of Hecke modules over Finite Field of size 5
```

The base ring doesn’t have to be a principal ideal domain:

```
sage: HeckeModules(PolynomialRing(IntegerRing(), 'x'))
Category of Hecke modules over Univariate Polynomial Ring in x over Integer Ring
```

class Homsets (category, *args)

    Bases: HomsetsCategory

class ParentMethods

    Bases: object

    extra_super_categories()

class ParentMethods

    Bases: object

    super_categories()

EXAMPLES:

```
sage: HeckeModules(QQ).super_categories()

[Category of vector spaces with basis over Rational Field]
``"
### 4.92 Highest Weight Crystals

**class** `sage.categories.highest_weight_crystals.HighestWeightCrystalHomset(X, Y, category=\text{None})`

Bases: `CrystalHomset`

The set of crystal morphisms from a highest weight crystal to another crystal.

**See also:**

See `sage.categories.crystals.CrystalHomset` for more information.

**Element**

alias of `HighestWeightCrystalMorphism`

**class** `sage.categories.highest_weight_crystals.HighestWeightCrystalMorphism(parent, on_gens, cartan_type=\text{None}, virtualization=\text{None}, scaling_factors=\text{None}, gens=\text{None}, check=\text{True})`

Bases: `CrystalMorphismByGenerators`

A virtual crystal morphism whose domain is a highest weight crystal.

**INPUT:**

- `parent` – a homset
- `on_gens` – a function or list that determines the image of the generators (if given a list, then this uses the order of the generators of the domain) of the domain under `self`
- `cartan_type` – (optional) a Cartan type; the default is the Cartan type of the domain
- `virtualization` – (optional) a dictionary whose keys are in the index set of the domain and whose values are lists of entries in the index set of the codomain
- `scaling_factors` – (optional) a dictionary whose keys are in the index set of the domain and whose values are scaling factors for the weight, $\varepsilon$ and $\varphi$
- `gens` – (optional) a list of generators to define the morphism; the default is to use the highest weight vectors of the crystal
- `check` – (default: `True`) check if the crystal morphism is valid

**class** `sage.categories.highest_weight_crystals.HighestWeightCrystals`

Bases: `Category_singleton`

The category of highest weight crystals.

A crystal is highest weight if it is acyclic; in particular, every connected component has a unique highest weight element, and that element generate the component.
EXAMPLES:

```python
c sage: C = HighestWeightCrystals()
c sage: C
Category of highest weight crystals
c sage: C.super_categories()
[Category of crystals]
c sage: C.example()
Highest weight crystal of type A_3 of highest weight omega_1
```

```python
class ElementMethods
Bases: object

c def string_parameters(self, word=None):
    """Return the string parameters of self corresponding to the reduced word word."
    
    Given a reduced expression $w = s_{i_1} \cdots s_{i_k}$, the string parameters of $b \in B$ corresponding to $w$ are $(a_1, \ldots, a_k)$ such that
    $e_{i_m}^{a_m} \cdots e_{i_1}^{a_1} b \neq 0$
    $e_{i_m}^{a_m+1} \cdots e_{i_1}^{a_1} b = 0$
    
    for all $1 \leq m \leq k$.
    
    For connected components isomorphic to $B(\lambda)$ or $B(\infty)$, if $w = w_0$ is the longest element of the Weyl group, then the path determined by the string parametrization terminates at the highest weight vector.
    
    INPUT:
    • word – a word in the alphabet of the index set; if not specified and we are in finite type, then this will be some reduced expression for the long element determined by the Weyl group
    
    EXAMPLES:
```
sage: b = B(rows=[[1,1,1,1,1,3,3,0,-3,-3,-2,-2,-1,-1,-1,-1], [2,3,3,3]])
sage: b.string_parameters([2,1,2,1,2])
[5, 13, 11, 15, 4, 4]

sage: b.string_parameters([1,2,1,2,1,2])
[7, 12, 15, 8, 10, 0]

sage: C = crystals.Tableaux(['C',2], shape=[2,1])
sage: mg = C.highest_weight_vector()
sage: lw = C.lowest_weight_vectors()[0]
sage: lw.string_parameters([1,2,1,2])
[1, 2, 3, 1]
sage: lw.string_parameters([2,1,2,1])
[1, 3, 2, 1]

sage: lw.e_string([2,1,1,1,2,2,1]) == mg
True

sage: lw.e_string([1,2,2,1,1,1,2]) == mg
True

class ParentMethods
Bases: object

connected_components_generators()

Returns the highest weight vectors of self

This default implementation selects among the module generators those that are highest weight, and
 caches the result. A crystal element \( b \) is highest weight if \( e_i(b) = 0 \) for all \( i \) in the
 index set.

EXAMPLES:

sage: C = crystals.Letters(['A',5])
sage: C.highest_weight_vectors()
(1,)

sage: C = crystals.Letters(['A',2])
sage: T = crystals.TensorProduct(C, C, generators=[[C(2),C(1),C(1)], [C(1),C(2),C(1)]])

sage: T.highest_weight_vectors()

digraph (subset=\texttt{None}, index\_set=\texttt{None}, depth=\texttt{None})

Return the DiGraph associated to self.

INPUT:

- subset – (optional) a subset of vertices for which the digraph should be constructed
- index\_set – (optional) the index set to draw arrows
- depth – the depth to draw; optional only for finite crystals

EXAMPLES:

sage: T = crystals.Tableaux(['A',2], shape=[2,1])
sage: T.digraph()
Digraph on 8 vertices
highest_weight_vector()

Returns the highest weight vector if there is a single one; otherwise, raises an error.

Caveat: this assumes that `highest_weight_vectors()` returns a list or tuple.

**EXAMPLES:**

```
sage: C = crystals.Letters(['A', 5])
sage: C.highest_weight_vector()
1
```

highest_weight_vectors()

Returns the highest weight vectors of `self`.

This default implementation selects among the module generators those that are highest weight, and
 caches the result. A crystal element $b$ is highest weight if $e_i(b) = 0$ for all $i$ in the index set.

**EXAMPLES:**

```
sage: C = crystals.Letters(['A', 5])
sage: C.highest_weight_vectors()
(1,)
```

```
sage: C = crystals.Letters(['A', 2])
sage: T = crystals.TensorProduct(C, C, generators=[[C(2), C(1), C(1)], ....: [C(1), C(2), C(1)]])
sage: T.highest_weight_vectors()
([2, 1, 1], [1, 2, 1])
```

lowest_weight_vectors()

Return the lowest weight vectors of `self`.

This default implementation selects among all elements of the crystal those that are lowest weight, and cache the result. A crystal element $b$ is lowest weight if $f_i(b) = 0$ for all $i$ in the index set.

**EXAMPLES:**

```
sage: C = crystals.Letters(['A', 5])
sage: C.lowest_weight_vectors()
(6,)
```

```
sage: C = crystals.Letters(['A', 2])
sage: T = crystals.TensorProduct(C, C, generators=[[C(2), C(1), C(1)], ....: [C(1), C(2), C(1)]])
sage: T.lowest_weight_vectors()
([3, 2, 3], [3, 3, 2])
```

q_dimension($q=None$, $prec=None$, $use_product=False$)

Return the $q$-dimension of `self`. 

Let $B(\lambda)$ denote a highest weight crystal. Recall that the degree of the $\mu$-weight space of $B(\lambda)$ (under the principal gradation) is equal to $\langle \rho^\vee, \lambda - \mu \rangle$ where $\langle \rho^\vee, \alpha_i \rangle = 1$ for all $i \in I$ (in particular, take $\rho^\vee = \sum_{i \in I} h_i$).

The $q$-dimension of a highest weight crystal $B(\lambda)$ is defined as

$$
\dim_q B(\lambda) := \sum_{j \geq 0} \dim(B_j) q^j,
$$

where $B_j$ denotes the degree $j$ portion of $B(\lambda)$. This can be expressed as the product

$$
\dim_q B(\lambda) = \prod_{\alpha^\vee \in \Delta_+^\vee} \left( \frac{1 - q^{\langle \lambda + \rho, \alpha^\vee \rangle}}{1 - q^{\langle \rho, \alpha^\vee \rangle}} \right)^{\text{mult } \alpha},
$$

where $\Delta_+^\vee$ denotes the set of positive coroots. Taking the limit as $q \to 1$ gives the dimension of $B(\lambda)$. For more information, see [Ka1990] Section 10.10.

**INPUT:**

- **q** – (the generic parameter $q$
- **prec** – (default: None) The precision of the power series ring to use if the crystal is not known to be finite (i.e. the number of terms returned). If None, then the result is returned as a lazy power series.
- **use_product** – (default: False) if we have a finite crystal and True, use the product formula

**EXAMPLES:**

```python
sage: C = crystals.Tableaux(['A', 2], shape=[2, 1])
sage: qdim = C.q_dimension(); qdim
q^4 + 2*q^3 + 2*q^2 + 2*q + 1
sage: qdim(1)
8
sage: len(C) == qdim(1)
True
sage: C.q_dimension( use_product=True) == qdim
True
sage: C.q_dimension( prec=20)
q^4 + 2*q^3 + 2*q^2 + 2*q + 1
sage: C.q_dimension( prec=2)
2*q + 1
sage: R.<t> = QQ[]
sage: C.q_dimension( q=t^2)
t^8 + 2*t^6 + 2*t^4 + 2*t^2 + 1
sage: C = crystals.Tableaux(['A', 2], shape=[5, 2])
sage: C.q_dimension()
qu^{10} + 2*q^9 + 4*q^8 + 5*q^7 + 6*q^6 + 6*q^5 + 6*q^4 + 5*q^3 + 4*q^2 + 2*q + 1
sage: C = crystals.Tableaux(['B', 2], shape=[2, 1])
sage: qdim = C.q_dimension(); qdim
q^{10} + 2*q^9 + 3*q^8 + 4*q^7 + 5*q^6 + 5*q^5 + 5*q^4 + 4*q^3 + 3*q^2 + 2*q + 1
sage: qdim == C.q_dimension( use_product=True)
True
sage: C = crystals.Tableaux(['D', 4], shape=[2, 1])
sage: C.q_dimension()
(continues on next page)
```
We check with a finite tensor product:

```
sage: TP = crystals.TensorProduct(C, C)
sage: TP.cardinality()
25600
sage: qdim = TP.q_dimension(use_product=True); qdim # long time
q^32 + 2*q^31 + 8*q^30 + 15*q^29 + 34*q^28 + 63*q^27 + 110*q^26 + 175*q^25 + 276*q^24 + 389*q^23 + 550*q^22 + 725*q^21 + 930*q^20 + 1131*q^19 + 1362*q^18 + 1548*q^17 + 1736*q^16 + 1858*q^15 + 1947*q^14 + 1944*q^13 + 1918*q^12 + 1777*q^11 + 1628*q^10 + 1407*q^9 + 1186*q^8 + 928*q^7 + 720*q^6 + 498*q^5 + 342*q^4 + 201*q^3 + 117*q^2 + 48*q + 26
sage: qdim(1) # long time
25600
sage: TP.q_dimension() == qdim # long time
True
```

The \(q\)-dimensions of infinite crystals are returned as formal power series:

```
sage: C = crystals.LSPaths(['A',2,1], [1,0,0])
sage: C.q_dimension(prec=5)
1 + q + 2*q^2 + 2*q^3 + 4*q^4 + O(q^5)
sage: C.q_dimension(prec=10)
1 + q + 2*q^2 + 2*q^3 + 4*q^4 + 5*q^5 + 7*q^6 + 9*q^7 + 13*q^8 + 16*q^9 + O(q^10)
sage: qdim = C.q_dimension(); qdim
1 + q + 2*q^2 + 2*q^3 + 4*q^4 + 5*q^5 + 7*q^6 + 9*q^7 + 13*q^8 + 16*q^9 + O(q^10)
sage: qdim[:16]
[1, 1, 2, 2, 4, 5, 7, 9, 13, 16, 22, 27, 36, 44, 57, 70]
```

```
class TensorProducts

Bases: TensorProductsCategory

The category of highest weight crystals constructed by tensor product of highest weight crystals.

class ParentMethods

Bases: object

Implements operations on tensor products of crystals.

highest_weight_vectors()

Return the highest weight vectors of self.

This works by using a backtracing algorithm since if \(b_2 \otimes b_1\) is highest weight then \(b_1\) is highest weight.

EXAMPLES:

sage: C = crystals.Tableaux(['D',4], shape=[2,2])
sage: D = crystals.Tableaux(['D',4], shape=[1])
sage: T = crystals.TensorProduct(D, C)
sage: T.highest_weight_vectors()
([[1]], [[1], [2, 2]], [[3]], [[1], [2, 2]])
```

highest_weight_vectors_iterator()

Iterate over the highest weight vectors of self.

This works by using a backtracing algorithm since if $b_2 \otimes b_1$ is highest weight then $b_1$ is highest weight.

EXAMPLES:

```python
sage: C = crystals.Tableaux(['D',4], shape=[2,2])
sage: D = crystals.Tableaux(['D',4], shape=[1])
sage: T = crystals.TensorProduct(D, C)
sage: tuple(T.highest_weight_vectors_iterator())

([[], [[1], [1], [2], [2]]],
 [[[-2]], [[1], [1], [2], [2]]])
```

```python
sage: L = filter(lambda x: x.is_highest_weight(), T)
sage: tuple(L) == tuple(T.highest_weight_vectors_iterator())
True
```

extra_super_categories()

EXAMPLES:

```python
sage: HighestWeightCrystals().TensorProducts().extra_super_categories()

[Category of highest weight crystals]
```

additional_structure()

Return None.

Indeed, the category of highest weight crystals defines no additional structure: it only guarantees the existence of a unique highest weight element in each component.

See also:

Category.additional_structure()

Todo: Should this category be a CategoryWithAxiom?

EXAMPLES:

```python
sage: HighestWeightCrystals().additional_structure()
```

example()

Returns an example of highest weight crystals, as per Category.example().

EXAMPLES:

```python
sage: B = HighestWeightCrystals().example(); B
Highest weight crystal of type A_3 of highest weight omega_1
```

super_categories()

EXAMPLES:
4.93 Hopf algebras

class sage.categories.hopf_algebras.HopfAlgebras(base, name=None)
Bases: Category_over_base_ring

The category of Hopf algebras.

EXAMPLES:

sage: HopfAlgebras(QQ)
Category of Hopf algebras over Rational Field
sage: HopfAlgebras(QQ).super_categories()
[Category of bialgebras over Rational Field]

class DualCategory(base, name=None)
Bases: Category_over_base_ring

The category of Hopf algebras constructed as dual of a Hopf algebra

class ParentMethods
Bases: object

class ElementMethods
Bases: object

antipode()

Return the antipode of self

EXAMPLES:

sage: # needs sage.groups
sage: A = HopfAlgebrasWithBasis(QQ).example(); A
An example of Hopf algebra with basis: the group algebra of the
dihedral group of order 6 as a permutation group over Rational Field
sage: [a,b] = A.algebra_generators()
sage: a, a.antipode()
(B[(1,2,3)], B[(1,3,2)])
sage: b, b.antipode()
(B[(1,3)], B[(1,3)])

class Morphism
Bases: Category

The category of Hopf algebra morphisms.

class ParentMethods
Bases: object

class Realizations(category, *args)
Bases: RealizationsCategory

class ParentMethods
Bases: object
**antipode_by_coercion**($x$)

Returns the image of $x$ by the antipode

This default implementation coerces to the default realization, computes the antipode there, and coerces the result back.

**EXAMPLES:**

```python
sage: # needs sage.combinat sage.modules
sage: N = NonCommutativeSymmetricFunctions(QQ)
sage: R = N.ribbon()
sage: R.antipode_by_coercion.__module__
'sage.categories.hopf_algebras'
sage: R.antipode_by_coercion(R[1,3,1])
-R[2, 1, 2]
```

class **Super**(*base_category*)

Bases: **SuperModulesCategory**

The category of super Hopf algebras.

**Note:** A super Hopf algebra is **not** simply a Hopf algebra with a $\mathbb{Z}/2\mathbb{Z}$ grading due to the signed bialgebra compatibility conditions.

class **ElementMethods**

Bases: **object**

**antipode**()

Return the antipode of self.

**EXAMPLES:**

```python
sage: A = SteenrodAlgebra(3)
    # needs sage.combinat sage.modules
sage: a = A.an_element()
    # needs sage.combinat sage.modules
sage: a, a.antipode()  
(2 Q_1 Q_3 P(2,1), Q_1 Q_3 P(2,1))
```

dual()  

Return the dual category.

**EXAMPLES:**

The category of super Hopf algebras over any field is self dual:

```python
sage: C = HopfAlgebras(QQ).Super()
sage: C.dual()
Category of super Hopf algebras over Rational Field
```

class **TensorProducts**(*category*, **args)

Bases: **TensorProductsCategory**

The category of Hopf algebras constructed by tensor product of Hopf algebras

class **ElementMethods**

Bases: **object**
class ParentMethods
    Bases: object

extra_super_categories()

    EXAMPLES:

    sage: C = HopfAlgebras(QQ).TensorProducts()
    sage: C.extra_super_categories()
    [Category of Hopf algebras over Rational Field]
    sage: sorted(C.super_categories(), key=str)
    [Category of Hopf algebras over Rational Field,
     Category of tensor products of algebras over Rational Field,
     Category of tensor products of coalgebras over Rational Field]

WithBasis
    alias of HopfAlgebrasWithBasis
dual()

    Return the dual category

    EXAMPLES:

    The category of Hopf algebras over any field is self dual:

    sage: C = HopfAlgebras(QQ)
    sage: C.dual()
    Category of Hopf algebras over Rational Field

super_categories()

    EXAMPLES:

    sage: HopfAlgebras(QQ).super_categories()
    [Category of bialgebras over Rational Field]

4.94 Hopf algebras with basis

class sage.categories.hopf_algebras_with_basis.HopfAlgebrasWithBasis(base_category)

    Bases: CategoryWithAxiom_over_base_ring

    The category of Hopf algebras with a distinguished basis

    EXAMPLES:

    sage: C = HopfAlgebrasWithBasis(QQ)
    sage: C
    Category of Hopf algebras with basis over Rational Field
    sage: C.super_categories()
    [Category of Hopf algebras over Rational Field,
     Category of bialgebras with basis over Rational Field]

    We now show how to use a simple Hopf algebra, namely the group algebra of the dihedral group (see also AlgebrasWithBasis):
An example of Hopf algebra with basis: the group algebra of the Dihedral group of order 6 as a permutation group over Rational Field

```python
sage: A = C.example(); A
# needs sage.groups
```

Category of finite dimensional Hopf algebras with basis over Rational Field

```python
sage: A.rename("A")
# needs sage.groups
```

```python
sage: A.category()
# needs sage.groups
```

```python
sage: A.one_basis()
# needs sage.groups
```

```python
sage: A.one()
# needs sage.groups
```

```python
B[()]
```

```python
sage: A.base_ring()
# needs sage.groups
```

Rational Field

```python
sage: A.basis().keys()
# needs sage.groups
```

Dihedral group of order 6 as a permutation group

```python
sage: # needs sage.groups
```

```python
[a,b] = A.algebra_generators()
sage: a, b
(B[(1,2,3)], B[(1,3)])
sage: a^3, b^2
(B[()], B[()])
sage: a*b
B[(1,2)]
```

```python
sage: A.product # todo: not quite ...
# needs sage.groups
```

```python
<bound method MagmaticAlgebras.WithBasis.ParentMethods._product_from_product_on_ basis_multiply of A>
sage: A.product(b, b)
# needs sage.groups
```

```python
B[()]
```

```python
sage: A.zero().coproduct()
# needs sage.groups
```

```python
0
```

```python
sage: A.zero().coproduct().parent()
# needs sage.groups
```

```python
A # A
```

```python
sage: a.coproduct()
# needs sage.groups
```

```python
B[(1,2,3)] # B[(1,2,3)]
```

```python
sage: TestSuite(A).run( verbose=True)
# needs sage.groups
```

running ._test_additive_associativity() ... pass
running ._test_an_element() ... pass
running ._test_antipode() ... pass
running ._test_associativity() ... pass
```

(continues on next page)
Let us look at the code for implementing $A$:

```
sage: A.__class__
# not implemented
```

```python
class ElementMethods
    Bases: object
    Filtered
        alias of FilteredHopfAlgebrasWithBasis

FiniteDimensional
    alias of FiniteDimensionalHopfAlgebrasWithBasis

Graded
    alias of GradedHopfAlgebrasWithBasis

class ParentMethods
    Bases: object
    antipode()
        The antipode of this Hopf algebra.
```

The antipode of this Hopf algebra.
If `antipode_basis()` is available, this constructs the antipode morphism from `self` to `self` by extending it by linearity. Otherwise, `self.antipode_by_coercion()` is used, if available.

**EXAMPLES:**

```python
sage: # needs sage.groups
sage: A = HopfAlgebrasWithBasis(ZZ).example(); A
An example of Hopf algebra with basis: the group algebra of the
   Dihedral group of order 6 as a permutation group over Integer Ring
sage: A = HopfAlgebrasWithBasis(QQ).example()
sage: [a,b] = A.algebra_generators()
sage: a, A.antipode(a)
(B[(1,2,3)], B[(1,3,2)])
sage: b, A.antipode(b)
(B[(1,3)], B[(1,3)])
```

**antipode_on_basis**

The antipode of the Hopf algebra on the basis (optional)

**INPUT:**

- `x` – an index of an element of the basis of `self`

Returns the antipode of the basis element indexed by `x`.

If this method is implemented, then `antipode()` is defined from this by linearity.

**EXAMPLES:**

```python
sage: # needs sage.groups
sage: A = HopfAlgebrasWithBasis(QQ).example()
sage: W = A.basis().keys(); W
Dihedral group of order 6 as a permutation group
sage: w = W.gen(0); w
(1,2,3)
sage: A.antipode_on_basis(w)
B[(1,3,2)]
```

**Super**

alias of `SuperHopfAlgebrasWithBasis`

---

**class TensorProducts**(category, *args)**

Bases: `TensorProductsCategory`

The category of Hopf algebras with basis constructed by tensor product of Hopf algebras with basis

**class ElementMethods**

Bases: `object`

**class ParentMethods**

Bases: `object`

**extra_super_categories()**

**EXAMPLES:**

```python
sage: C = HopfAlgebrasWithBasis(QQ).TensorProducts()
sage: C.extra_super_categories()
[Category of Hopf algebras with basis over Rational Field]
sage: sorted(C.super_categories(), key=str)
[Category of Hopf algebras with basis over Rational Field,
   Category of tensor products of Hopf algebras over Rational Field,
   Category of tensor products of algebras with basis over Rational Field]
```
example \((G=None)\)

Returns an example of algebra with basis:

```python
sage: HopfAlgebrasWithBasis(QQ['x']).example()  #...
˓→needs sage.groups
An example of Hopf algebra with basis: the group algebra of the
Dihedral group of order 6 as a permutation group
over Univariate Polynomial Ring in x over Rational Field
```

An other group can be specified as optional argument:

```python
sage: HopfAlgebrasWithBasis(QQ).example(SymmetricGroup(4))  #...
˓→needs sage.groups
An example of Hopf algebra with basis: the group algebra of the
Symmetric group of order 4! as a permutation group over Rational Field
```

### 4.95 H-trivial semigroups

```python
class sage.categories.h_trivial_semigroups.HTrivialSemigroups(base_category)
    Bases: CategoryWithAxiom

Finite_extra_super_categories()
    Implement the fact that a finite \(H\)-trivial is aperiodic

EXAMPLES:

```python
sage: Semigroups().HTrivial().Finite_extra_super_categories()
[Category of aperiodic semigroups]
sage: Semigroups().HTrivial().Finite() is Semigroups().Aperiodic().Finite()
True
```

```python
Inverse_extra_super_categories()
    Implement the fact that an \(H\)-trivial inverse semigroup is \(J\)-trivial.

Todo: Generalization for inverse semigroups.

Recall that there are two invertibility axioms for a semigroup \(S\):

- One stating the existence, for all \(x\), of a local inverse \(y\) satisfying
  \(x = xyx\) and \(y = yxy\);  
- One stating the existence, for all \(x\), of a global inverse \(y\) satisfying
  \(xy = yx = 1\), where 1 is the unit of \(S\) (which must of course exist).

It is sufficient to have local inverses for \(H\)-triviality to imply \(J\)-triviality. However, at this stage, only the second axiom is implemented in Sage (see `Magmas.Unital.SubcategoryMethods.Inverse()`). Therefore this fact is only implemented for semigroups with global inverses, that is groups. However the trivial group is the unique \(H\)-trivial group, so this is rather boring.

EXAMPLES:

```python
sage: Semigroups().HTrivial().Inverse_extra_super_categories()
[Category of j trivial semigroups]
sage: Monoids().HTrivial().Inverse()
Category of h trivial groups
```

542 Chapter 4. Individual Categories
4.96 Infinite Enumerated Sets

AUTHORS:


```python
class sage.categories.infiniteEnumeratedSets.InfiniteEnumeratedSets(base_category):
    Bases: CategoryWithAxiom_singleton

    The category of infinite enumerated sets

    An infinite enumerated set is a countable set together with a canonical enumeration of its elements.

    EXAMPLES:

    sage: InfiniteEnumeratedSets()
    Category of infinite enumerated sets
    sage: InfiniteEnumeratedSets().super_categories()
    [Category of enumerated sets, Category of infinite sets]
    sage: InfiniteEnumeratedSets().all_super_categories()
    [Category of infinite enumerated sets,
        Category of enumerated sets,
        Category of infinite sets,
        Category of sets,
        Category of sets with partial maps,
        Category of objects]

class ParentMethods
    Bases: object

    list()
        Raise an error because self is an infinite enumerated set.

        EXAMPLES:

        sage: NN = InfiniteEnumeratedSets().example()
        sage: NN.list()
        Traceback (most recent call last):
        ...:
        NotImplementedError: cannot list an infinite set

    random_element()
        Raise an error because self is an infinite enumerated set.

        EXAMPLES:

        sage: NN = InfiniteEnumeratedSets().example()
        sage: NN.random_element()
        Traceback (most recent call last):
        ...:
        NotImplementedError: infinite set

    TODO: should this be an optional abstract_method instead?

tuple()
        Raise an error because self is an infinite enumerated set.

        EXAMPLES:
4.97 Integral domains

class sage.categories.integral_domains.IntegralDomains(base_category)
    Bases: CategoryWithAxiom_singleton

The category of integral domains

An integral domain is commutative ring with no zero divisors, or equivalently a commutative domain.

EXAMPLES:

```python
sage: C = IntegralDomains(); C
Category of integral domains
sage: sorted(C.super_categories(), key=str)
[Category of commutative rings, Category of domains]
sage: C is Domains().Commutative()
True
sage: C is Rings().Commutative().NoZeroDivisors()
True
```

class ElementMethods
    Bases: object

class ParentMethods
    Bases: object

    is_integral_domain(proof=True)

    Return True, since this in an object of the category of integral domains.

    EXAMPLES:

```python
sage: QQ.is_integral_domain()
True
sage: Parent(QQ, category=IntegralDomains()).is_integral_domain()
True

sage: L.<z> = LazyLaurentSeriesRing(QQ)  # needs sage.combinat
sage: L.is_integral_domain()  # needs sage.combinat
True
sage: L.is_integral_domain(proof=True)  # needs sage.combinat
True
```
4.98 J-trivial semigroups

class sage.categories.j_trivial_semigroups.JTrivialSemigroups(base_category):
    Bases: CategoryWithAxiom
    extra_super_categories()
    Implement the fact that a $J$-trivial semigroup is $L$ and $R$-trivial.

    EXAMPLES:
    sage: Semigroups().JTrivial().extra_super_categories()
    [Category of l trivial semigroups, Category of r trivial semigroups]

4.99 Kac-Moody Algebras

AUTHORS:

• Travis Scrimshaw (07-15-2017): Initial implementation

class sage.categories.kac_moody_algebras.KacMoodyAlgebras(base, name=None):
    Bases: Category_over_base_ring
    Category of Kac-Moody algebras.

class ParentMethods:
    Bases: object
    cartan_type()
    Return the Cartan type of self.

    EXAMPLES:
    sage: L = LieAlgebra(QQ, cartan_type=["A", 2])
    # needs sage.combinat sage.modules
    sage: L.cartan_type()
    ['A', 2]

    weyl_group()
    Return the Weyl group of self.

    EXAMPLES:
    sage: L = LieAlgebra(QQ, cartan_type=["A", 2])
    # needs sage.combinat sage.modules
    sage: L.weyl_group()
    Weyl Group of type ["A", 2] (as a matrix group acting on the ambient space)

    example (n=2)
    Return an example of a Kac-Moody algebra as per Category.example.

    EXAMPLES:
sage: from sage.categories.kac_moody_algebras import KacMoodyAlgebras
sage: KacMoodyAlgebras(QQ).example()  # needs sage.combinat sage.modules
Lie algebra of ['A', 2] in the Chevalley basis

We can specify the rank of the example:

sage: KacMoodyAlgebras(QQ).example(4)  # needs sage.combinat sage.modules
Lie algebra of ['A', 4] in the Chevalley basis

\texttt{super_categories()}

\textbf{EXAMPLES:}

sage: from sage.categories.kac_moody_algebras import KacMoodyAlgebras
sage: KacMoodyAlgebras(QQ).super_categories()
[Category of Lie algebras over Rational Field]

\section{4.100 Lambda Bracket Algebras}

\textbf{AUTHORS:}

\begin{itemize}
\item Reimundo Heluani (2019-10-05): Initial implementation.
\end{itemize}

class \texttt{sage.categories.lambda_bracket_algebras.LambdaBracketAlgebras (base, name=None)}

Bases: \texttt{Category\_over\_base\_ring}

The category of Lambda bracket algebras.

This is an abstract base category for Lie conformal algebras and super Lie conformal algebras.

class \texttt{ElementMethods}

Bases: \texttt{object}

\texttt{T(n=1)}

The $n$-th derivative of \texttt{self}.

\textbf{INPUT:}

\begin{itemize}
\item $n$ – integer (default:1); how many times to apply $T$ to this element
\end{itemize}

\textbf{OUTPUT:}

$T^n a$ where $a$ is this element. Notice that we use the \texttt{divided powers} notation $T^{(i)} = \frac{T^i}{i!}$.

\textbf{EXAMPLES:}

sage: # needs sage.combinat sage.modules
sage: Vir = lie_conformal_algebras.Virasoro(QQ)
sage: Vir.inject_variables()
Defining L, C
sage: L.T()
TL
sage: L.T(3)
6*T^3 L
sage: C.T()
0
**bracket** *(rhs)*

The $\lambda$-bracket of these two elements.

**EXAMPLES:**

The brackets of the Virasoro Lie conformal algebra:

```python
sage: Vir = lie_conformal_algebras.Virasoro(QQ); L = Vir.0
sage: L.bracket(L)
{0: TL, 1: 2*L, 3: 1/2*C}
sage: L.bracket(L.T())
{0: 2*T^(2)L, 1: 3*TL, 2: 4*L, 4: 2*C}
```

Now with a current algebra:

```python
sage: V = lie_conformal_algebras.Affine(QQ, 'A1')
sage: V.gens()
(B[alpha[1]], B[alphacheck[1]], B[-alpha[1]], B['K'])
sage: E = V.0; H = V.1; F = V.2
sage: H.bracket(H)
{1: 2*B['K']}
sage: E.bracket(F)
{0: B[alphacheck[1]], 1: B['K']}
```

**nproduct** *(rhs, n)*

The $n$-th product of these two elements.

**EXAMPLES:**

```python
sage: Vir = lie_conformal_algebras.Virasoro(QQ); L = Vir.0
sage: L.nproduct(L, 3)
1/2*C
sage: L.nproduct(L.T(), 0)
2*T^(2)L
sage: E = V.0; H = V.1; F = V.2
sage: E.nproduct(H, 0) == -2*E
True
sage: E.nproduct(F, 1)
B['K']
```

**FinitelyGeneratedAsLambdaBracketAlgebra**

alias of **FinitelyGeneratedLambdaBracketAlgebras**

**class ParentMethods**

**ideal** *(*gens, **kwds)*

The ideal of this Lambda bracket algebra generated by *gens*.

**Todo:** Ideals of Lie Conformal Algebras are not implemented yet.

**EXAMPLES:**
class SubcategoryMethods

    Bases: object

    FinitelyGenerated()

    The category of finitely generated Lambda bracket algebras.

    EXAMPLES:

        sage: LieConformalAlgebras(QQ).FinitelyGenerated()
        Category of finitely generated Lie conformal algebras over Rational Field

FinitelyGeneratedAsLambdaBracketAlgebra()

    The category of finitely generated Lambda bracket algebras.

    EXAMPLES:

        sage: LieConformalAlgebras(QQ).FinitelyGenerated()
        Category of finitely generated Lie conformal algebras over Rational Field

WithBasis

    alias of LambdaBracketAlgebrasWithBasis

super_categories()

    The list of super categories of this category.

    EXAMPLES:

        sage: from sage.categories.lambda_bracket_algebras import...
        sage: LambdaBracketAlgebras(QQ).super_categories()
        [Category of vector spaces over Rational Field]

4.101 Lambda Bracket Algebras With Basis

AUTHORS:

    • Reimundo Heluani (2020-08-21): Initial implementation.

class sage.categories.lambda_bracket_algebras_with_basis.LambdaBracketAlgebrasWithBasis(base_category)

    Bases: CategoryWithAxiom_over_base_ring

    The category of Lambda bracket algebras with basis.

    EXAMPLES:
class ElementMethods
   Bases: object

   index()

   The index of this basis element.

   EXAMPLES:

   sage: # needs sage.combinat sage.modules
   sage: V = lie_conformal_algebras.NeveuSchwarz(QQ)
   sage: V.inject_variables()
   Defining L, G, C
   sage: G.T(3).index()
   ('G', 3)
   sage: v = V.an_element(); v
   L + G + C
   sage: v.index()
   Traceback (most recent call last):
   ...
   ValueError: index can only be computed for monomials, got L + G + C

class FinitelyGeneratedAsLambdaBracketAlgebra(base_category)
   Bases: CategoryWithAxiom_over_base_ring

   The category of finitely generated lambda bracket algebras with basis.

   EXAMPLES:

   sage: # needs sage.rings.number_field
   sage: C = LieConformalAlgebras(QQbar)
   #
   sage: C1 = C.WithBasis().FinitelyGenerated(); C1
   Category of finitely generated Lie conformal algebras with basis over Algebraic Field
   sage: C2 = C.FinitelyGenerated().WithBasis(); C2
   Category of finitely generated Lie conformal algebras with basis over Algebraic Field
   sage: C1 is C2
   True

class Graded(base_category)
   Bases: GradedModulesCategory

   The category of H-graded finitely generated lambda bracket algebras with basis.

   EXAMPLES:

   sage: C = LieConformalAlgebras(QQbar) # needs sage.rings.number_field
   sage: C1 = C.WithBasis().FinitelyGenerated().Graded(); C1
   Category of H-graded finitely generated Lie conformal algebras with basis over Algebraic Field

class ParentMethods
   Bases: object

4.101. Lambda Bracket Algebras With Basis 549
**degree_on_basis** \( (m) \)

Return the degree of the basis element indexed by \( m \) in \( \text{self} \).

**EXAMPLES:**

```
sage: V = lie_conformal_algebras.Virasoro(QQ)  # needs sage.combinat sage.modules
sage: V.degree_on_basis(('L', 2))  # needs sage.combinat sage.modules
4
```

## 4.102 Lattice posets

```python
class sage.categories.lattice_posets.LatticePosets
    Bases: Category

    The category of lattices, i.e. partially ordered sets in which any two elements have a unique supremum (the elements’ least upper bound; called their **join**) and a unique infimum (greatest lower bound; called their **meet**).

    **EXAMPLES:**

    ```python
    sage: L = LatticePosets()
    Category of lattice posets
    sage: L.super_categories()
    [Category of posets]
    sage: L.example()
    NotImplemented
    ```

See also:

* Posets, FiniteLatticePosets, LatticePoset()*
```

### Finite

**alias of** FiniteLatticePosets

```python
class ParentMethods
    Bases: object

    **join** \( (x, y) \)

    Returns the join of \( x \) and \( y \) in this lattice

    **INPUT:**
    
    \( x, y \) – elements of \( \text{self} \)

    **EXAMPLES:**

    ```python
    sage: D = LatticePoset((divisors(60), attrcall("divides")))  # needs sage.graphs sage.modules
    sage: D.join( D(6), D(10) )  # needs sage.graphs sage.modules
    30
    ```
```

### meet \( (x, y) \)

Returns the meet of \( x \) and \( y \) in this lattice

**INPUT:**

\( x, y \) – elements of \( \text{self} \)

**EXAMPLES:**

```python
```
super_categories()

Returns a list of the (immediate) super categories of self, as per `Category.super_categories()`.

EXAMPLES:

```
sage: LatticePosets().super_categories()
[Category of posets]
```
We construct a typical parent in this category, and do some computations with it:

```
sage: A = C.example(); A
An example of a Lie algebra: the Lie algebra from the associative
algebra Symmetric group algebra of order 3 over Rational Field
generated by ([2, 1, 3], [2, 3, 1])
sage: A.category()
Category of Lie algebras over Rational Field
sage: A.base_ring()
Rational Field
sage: a, b = A.lie_algebra_generators()
sage: a.bracket(b)
-[-1, 3, 2] + [3, 2, 1]
sage: b.bracket(2*a + b)
2*[1, 3, 2] - 2*[3, 2, 1]
sage: A.bracket(a, b)
-[-1, 3, 2] + [3, 2, 1]
```

Please see the source code of \( A \) (with \( A? \)) for how to implement other Lie algebras.

**Todo:** Many of these tests should use Lie algebras that are not the minimal example and need to be added after [github issue #16820](https://github.com/sagemath/sage/issues/16820) (and [github issue #16823](https://github.com/sagemath/sage/issues/16823)).
Return the exponential of `self` in `lie_group`.

**INPUT:**

- `lie_group` (optional) the Lie group to map into; If `lie_group` is not given, the Lie group associated to the parent Lie algebra of `self` is used.

**EXAMPLES:**

```
sage: # needs sage.combinat sage.modules
sage: L.<X,Y,Z> = LieAlgebra(QQ, 2, symbol='X,Y,Z')
sage: g = (X + Y + Z).exp(); g
    #-- needs sage.symbolic
exp(X + Y + Z)
sage: h = X.exp(); h
    #-- needs sage.symbolic
exp(X)
sage: g.parent()
    #-- needs sage.symbolic
Lie group G of Free Nilpotent Lie algebra on 3 generators (X, Y, Z) over Rational Field
sage: g.parent() is h.parent()
    #-- needs sage.symbolic
True
```

The Lie group can be specified explicitly:

```
sage: # needs sage.combinat sage.modules sage.symbolic
sage: H = L.lie_group('H')
sage: k = Z.exp(lie_group=H); k
exp(Z)
sage: k.parent()
    #-- needs sage.symbolic
Lie group H of Free Nilpotent Lie algebra on 3 generators (X, Y, Z) over Rational Field
sage: g.parent() == k.parent()
False
```

**killing_form** (`x`)

Return the Killing form of `self` and `x`.

**EXAMPLES:**

```
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()  #-- needs sage.modules
sage: a, b, c = L.lie_algebra_generators()
    #-- needs sage.modules
sage: a.killing_form(b)
    #-- needs sage.modules
0
```

**lift()**

Return the image of `self` under the canonical lift from the Lie algebra to its universal enveloping algebra.

**EXAMPLES:**

```
sage: # needs sage.combinat sage.modules
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()
sage: a, b, c = L.lie_algebra_generators()
    (continues on next page)```
sage: elt = 3*a + b - c
sage: elt
3*a + b - c
sage: elt.lift()
3*b0 + b1 - b2
sage: L.<x,y> = LieAlgebra(QQ, abelian=True)  # needs sage.combinat sage.modules
sage: x
needs sage.combinat sage.modules
x

to_vector(order=None)

Return the vector in g.module() corresponding to the element self of g (where g is the parent of
self).

Implement this if you implement g.module(). See LieAlgebras.module() for how this is to
be done.

EXAMPLES:

sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()  # needs sage.modules
sage: u = L((1, 0, 0)).to_vector(); u
(1, 0, 0)
sage: parent(u)
Vector space of dimension 3 over Rational Field

class FiniteDimensional(base_category)

Bases: CategoryWithAxiom_over_base_ring

WithBasis

alias of FiniteDimensionalLieAlgebrasWithBasis

e extra_super_categories()

Implements the fact that a finite dimensional Lie algebra over a finite ring is finite.

EXAMPLES:

sage: LieAlgebras(IntegerModRing(4)).FiniteDimensional().extra_super_categories()
[Category of finite sets]
sage: LieAlgebras(ZZ).FiniteDimensional().extra_super_categories()
[]
sage: C = LieAlgebras(GF(5)).FiniteDimensional()
sage: C.is_subcategory(Sets().Finite())
True
sage: C = LieAlgebras(ZZ).FiniteDimensional()
sage: C.is_subcategory(Sets().Finite())
False
sage: C = LieAlgebras(GF(5)).WithBasis().FiniteDimensional()
sage: C.is_subcategory(Sets().Finite())
True

Graded

alias of GradedLieAlgebras
class Nilpotent (base_category)
Bases: CategoryWithAxiom_over_base_ring

Category of nilpotent Lie algebras.

class ParentMethods
Bases: object

is_nilpotent ()
Return True since self is nilpotent.

EXAMPLES:

sage: h = lie_algebras.Heisenberg(ZZ, oo)  # needs sage.combinat sage.modules
sage: h.is_nilpotent()  # needs sage.combinat sage.modules
True

step ()
Return the nilpotency step of self.

EXAMPLES:

sage: h = lie_algebras.Heisenberg(ZZ, oo)  # needs sage.combinat sage.modules
sage: h.step()  # needs sage.combinat sage.modules
2

class ParentMethods
Bases: object

baker_campbell_hausdorff (X, Y, prec=None)

Return the element log(exp(X) exp(Y)).

The BCH formula is an expression for log(exp(X) exp(Y)) as a sum of Lie brackets of X and Y with rational coefficients. It is only defined if the base ring of self has a coercion from the rationals.

INPUT:
• X – an element of self
• Y – an element of self
• prec – an integer; the maximum length of Lie brackets to be considered in the formula

EXAMPLES:
The BCH formula for the generators of a free nilpotent Lie algebra of step 4:

sage: L = LieAlgebra(QQ, 2, step=4)  # needs sage.combinat sage.modules
sage: L.inject_variables()  # needs sage.combinat sage.modules
Defining X_1, X_2, X_12, X_112, X_122, X_1112, X_1122, X_1222
sage: L.bch(X_1, X_2)  # needs sage.combinat sage.modules
X_1 + X_2 + 1/2*X_12 + 1/12*X_112 + 1/12*X_122 + 1/24*X_1122

An example of the BCH formula in a quotient:
The BCH formula for a non-nilpotent Lie algebra requires the precision to be explicitly stated:

```python
sage: L.<X,Y> = LieAlgebra(QQ)

sage: L.bch(X, Y)
ValueError: the Lie algebra is not known to be nilpotent, so you must specify the precision

sage: L.bch(X, Y, 4)
```

The BCH formula requires a coercion from the rationals:

```python
sage: L.<X,Y,Z> = LieAlgebra(ZZ, 2, step=2)

sage: L.bch(X, Y)
```

```
Traceback (most recent call last):
...
TypeError: the BCH formula is not well defined since Integer Ring has no coercion from Rational Field
```

\[ \text{bch} \left( X, Y, \text{prec} = \text{None} \right) \]

Return the element log(exp(\(X\)) exp(\(Y\))).

The BCH formula is an expression for log(exp(\(X\)) exp(\(Y\))) as a sum of Lie brackets of \(X\) and \(Y\) with rational coefficients. It is only defined if the base ring of \(self\) has a coercion from the rationals.

**INPUT:**
- \(X\) – an element of \(self\)
- \(Y\) – an element of \(self\)
- \(\text{prec}\) – an integer; the maximum length of Lie brackets to be considered in the formula

**EXAMPLES:**

The BCH formula for the generators of a free nilpotent Lie algebra of step 4:

```python
sage: L = LieAlgebra(QQ, 2, step=4)

sage: L.bch(X_1, X_2)
```

```
X_1 + X_2 + 1/2*X_12 + 1/12*X_112 + 1/12*X_122 + 1/24*X_1122
```

An example of the BCH formula in a quotient:
The BCH formula for a non-nilpotent Lie algebra requires the precision to be explicitly stated:

```
sage: L.<X,Y> = LieAlgebra(QQ)
#-- needs sage.combinat sage.modules
sage: L.bch(X, Y)
#-- needs sage.combinat sage.modules
Traceback (most recent call last):
...
ValueError: the Lie algebra is not known to be nilpotent, so you must specify the precision
sage: L.bch(X, Y, 4)
#-- needs sage.combinat sage.modules
X + 1/12*[X, [X, Y]] + 1/24*[X, [[X, Y], Y]] + 1/2*[X, Y] + 1/12*[[X, Y], Y] + Y
```

The BCH formula requires a coercion from the rationals:

```
sage: L.<X,Y,Z> = LieAlgebra(ZZ, 2, step=2)
#-- needs sage.combinat sage.modules
sage: L.bch(X, Y)
#-- needs sage.combinat sage.modules
Traceback (most recent call last):
...
TypeError: the BCH formula is not well defined since Integer Ring has no coercion from Rational Field
```

**bracket** *(lhs, rhs)*

Return the Lie bracket `[lhs, rhs]` after coercing `lhs` and `rhs` into elements of `self`.

If `lhs` and `rhs` are Lie algebras, then this constructs the product space, and if only one of them is a Lie algebra, then it constructs the corresponding ideal.

**EXAMPLES:**

```
sage: L = LieAlgebras(QQ).example()
sage: x, y = L.lie_algebra_generators()
sage: L.bracket(x, x + y)
-[1, 3, 2] + [3, 2, 1]
sage: L.bracket(x, 0)
0
sage: L.bracket(0, x)
0
```

Constructing the product space:

```
sage: L = lie_algebras.Heisenberg(QQ, 1)
#-- needs sage.combinat sage.modules
sage: Z = L.bracket(L, L); Z
#-- needs sage.combinat sage.modules
```

(continues on next page)
Ideal (z) of Heisenberg algebra of rank 1 over Rational Field

\[ \text{sage: } L\.bracket(L, Z) \quad \#\\text{needs sage.combinat sage.modules} \]
\[ \text{Ideal () of Heisenberg algebra of rank 1 over Rational Field} \]

Constructing ideals:

\[ \text{sage: } p, q, z = L\.basis(); p, q, z \quad \#\\text{needs sage.combinat sage.modules} \]
\[ (p1, q1, z) \]
\[ \text{sage: } L\.bracket(3*p, L) \quad \#\\text{needs sage.combinat sage.modules} \]
\[ \text{Ideal (3*p1) of Heisenberg algebra of rank 1 over Rational Field} \]
\[ \text{sage: } L\.bracket(L, q + p) \quad \#\\text{needs sage.combinat sage.modules} \]
\[ \text{Ideal (p1 + q1) of Heisenberg algebra of rank 1 over Rational Field} \]

\[ \text{from_vector}(v, order=None, coerce=False) \]

Return the element of \texttt{self} corresponding to the vector \texttt{v} in \texttt{self.module()}. Implement this if you implement \texttt{module()}; see the documentation of the latter for how this is to be done.

\[ \text{EXAMPLES:} \]

\[ \text{sage: } L = \text{LieAlgebras(QQ).FiniteDimensional().WithBasis().example()} \quad \#\text{needs sage.modules} \]
\[ \text{sage: } u = L\.from_vector(vector(QQ, (1, 0, 0))); u \quad \#\text{needs sage.modules} \]
\[ (1, 0, 0) \]
\[ \text{sage: } \text{parent}(u) \text{ is } L \quad \#\text{needs sage.modules} \]
\[ \text{True} \]

\[ \text{ideal}(*\text{gens}, **\text{kwds}) \]

Return the ideal of \texttt{self} generated by \texttt{gens}.

\[ \text{EXAMPLES:} \]

\[ \text{sage: } L = \text{LieAlgebras(QQ).FiniteDimensional().WithBasis().example()} \quad \#\text{needs sage.modules} \]
\[ \text{sage: } a, b, c = L\.lie_algebra_generators() \quad \#\text{needs sage.modules} \]
\[ \text{sage: } L\.ideal([2*a - c, b + c]) \quad \#\text{needs sage.modules} \]

An example of a finite dimensional Lie algebra with basis:
the 2-dimensional abelian Lie algebra over Rational Field
with basis matrix:
\[
\begin{bmatrix}
1 & 0 & -1/2 \\
0 & 1 & 1
\end{bmatrix}
\]

\[ \text{sage: } L = \text{LieAlgebras(QQ).example()} \quad \#\text{needs sage.combinat sage.modules} \]
\[ \text{sage: } x, y = L\.lie_algebra_generators() \quad \#\text{needs sage.combinat sage.modules} \]
\[ \text{sage: } L\.ideal([x + y]) \quad \#\text{needs sage.combinat sage.modules} \]
is_abelian()

Return True if this Lie algebra is abelian.

A Lie algebra \( \mathfrak{g} \) is abelian if \([x, y] = 0\) for all \( x, y \in \mathfrak{g} \).

EXAMPLES:

```python
sage: # needs sage.combinat sage.modules
sage: L = LieAlgebras(QQ).example()
sage: L.is_abelian()
False
sage: R = QQ['x, y']
sage: L = LieAlgebras(QQ).example(R.gens())
sage: L.is_abelian()
True
sage: # not implemented, needs sage.combinat sage.modules
sage: L.<x> = LieAlgebra(QQ, 1)
# not implemented
sage: L.is_abelian()
# not implemented
sage: L.<x,y> = LieAlgebra(QQ, 2)
# not implemented
sage: L.is_abelian()
False
```

is_commutative()

Return if self is commutative. This is equivalent to self being abelian.

EXAMPLES:

```python
sage: L = LieAlgebras(QQ).example() # not implemented
# needs sage.combinat sage.modules
sage: L.is_commutative() # not implemented
False
sage: L.<x> = LieAlgebra(QQ, 1) # not implemented
# needs sage.combinat sage.modules
sage: L.is_commutative() # not implemented
# needs sage.combinat sage.modules
sage: L.<x,y> = LieAlgebra(QQ, 2) # not implemented
# needs sage.combinat sage.modules
sage: L.is_commutative() # not implemented
True
```

is_ideal(A)

Return if self is an ideal of A.

EXAMPLES:

```python
sage: L = LieAlgebras(QQ).example() # not implemented
# needs sage.combinat sage.modules
sage: L.is_ideal(L) # not implemented
# needs sage.combinat sage.modules
sage: L.is_ideal(L)
True
```

4.104. Lie Algebras
\textbf{is\_nilpotent}()

Return if \texttt{self} is a nilpotent Lie algebra.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()  # needs sage.modules
sage: L.is_nilpotent()  # needs sage.modules
True
\end{verbatim}

\textbf{is\_solvable}()

Return if \texttt{self} is a solvable Lie algebra.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()  # needs sage.modules
sage: L.is_solvable()  # needs sage.modules
True
\end{verbatim}

\textbf{killing\_form}(x, y)

Return the Killing form of \texttt{x} and \texttt{y}.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()  # needs sage.modules
sage: a, b, c = L.lie_algebra_generators()  # needs sage.modules
sage: L.killing_form(a, b + c)  # needs sage.modules
0
\end{verbatim}

\textbf{lie\_group}(name='G', **kwds)

Return the simply connected Lie group related to \texttt{self}.

\textbf{INPUT:}

- name – string (default: 'G'); the name (symbol) given to the Lie group

\textbf{EXAMPLES:}

\begin{verbatim}
sage: L = lie_algebras.Heisenberg(QQ, 1)  # needs sage.combinat sage.modules
sage: G = L.lie_group('G'); G  # needs sage.combinat sage.modules sage.symbolic
Lie group G of Heisenberg algebra of rank 1 over Rational Field
\end{verbatim}

\textbf{lift}()

Construct the lift morphism from \texttt{self} to the universal enveloping algebra of \texttt{self} (the latter is implemented as \texttt{universal_enveloping_algebra()}).

This is a Lie algebra homomorphism. It is injective if \texttt{self} is a free module over its base ring, or if the base ring is a \texttt{Q}-algebra.

\textbf{EXAMPLES:}
module()

Return an $R$-module which is isomorphic to the underlying $R$-module of self.

The rationale behind this method is to enable linear algebraic functionality on self (such as computing the span of a list of vectors in self) via an isomorphism from self to an $R$-module (typically, although not always, an $R$-module of the form $R^n$ for an $n \in \mathbb{N}$) on which such functionality already exists. For this method to be of any use, it should return an $R$-module which has linear algebraic functionality that self does not have.

For instance, if self has ordered basis $(e, f, h)$, then self.module() will be the $R$-module $R^3$, and the elements $e$, $f$ and $h$ of self will correspond to the basis vectors $(1, 0, 0)$, $(0, 1, 0)$ and $(0, 0, 1)$ of self.module().

This method module() needs to be set whenever a finite-dimensional Lie algebra with basis is intended to support linear algebra (which is, e.g., used in the computation of centralizers and lower central series). One then needs to also implement the $R$-module isomorphism from self to self.module() in both directions; that is, implement:

- a to_vector ElementMethod which sends every element of self to the corresponding element of self.module();
- a from_vector ParentMethod which sends every element of self.module() to an element of self.

The from_vector method will automatically serve as an element constructor of self (that is, self(v) for any v in self.module() will return self.from_vector(v)).

Todo: Ensure that this is actually so.

EXAMPLES:

```sage
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()  # needs sage.modules
sage: L.module()  # needs sage.modules
Vector space of dimension 3 over Rational Field
```

representation (f=None, index_set=None, on_basis=False, **kwargs)

Return a representation of self.

If no arguments are given, then this returns the trivial representation.

Currently the only implemented method of constructing a representation is by explicitly specifying the action of

- the elements of self by matrices;
- the basis elements of self using a dict or a Family();
- a function on basis elements (either passed as on_basis or setting on_basis=True).

INPUT:

- f – the function that defines the action
- index_set – the index set of the representation
- on_basis – (optional) see above
See also: 

RepresentationByMorphism

**EXAMPLES:**

```
sage: L.<x,y> = LieAlgebra(QQ, {('x','y'): {'y':1}})
sage: f = {x: Matrix([[1,0],[0,0]]), y: Matrix([[0,1],[0,0]])}
sage: L.representation(f)
Representation of Lie algebra on 2 generators (x, y) over Rational Field
˓→ defined by:
  [1 0]
x |--> [0 0]
  [0 1]
y |--> [0 0]
sage: L.representation()
Trivial representation of Lie algebra on 2 generators (x, y) over...
˓→ Rational Field
```

**subalgebra** (**gens**, **names**=*None*, **index_set**=*None*, **category**=*None*)

Return the subalgebra of **self** generated by **gens**.

**EXAMPLES:**

```
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()  #...
˓→ needs sage.modules
sage: a, b, c = L.lie_algebra_generators()  #...
˓→ needs sage.modules
sage: L.subalgebra([2*a - c, b + c])  #...
˓→ needs sage.modules
An example of a finite dimensional Lie algebra with basis: the 2-dimensional abelian Lie algebra over Rational Field with basis matrix:
[ 1 0 -1/2]
[ 0 1 1]
sage: L = LieAlgebras(QQ).example()  #...
˓→ needs sage.combinat sage.modules
sage: x,y = L.lie_algebra_generators()  #...
˓→ needs sage.combinat sage.modules
sage: L.subalgebra([x + y])  #...
˓→ needs sage.combinat sage.modules
Traceback (most recent call last):
...
NotImplementedError: subalgebras not yet implemented: see #17416
```

**trivial_representation** (**self**)

Return the trivial representation of **self**.

**EXAMPLES:**

```
sage: L = lie_algebras.strictly_upper_triangular_matrices(QQ, 4)
sage: L.trivial_representation()
Trivial representation of Lie algebra of 4-dimensional strictly upper triangular matrices over Rational Field
```

**universal_enveloping_algebra** (**self**)

Return the universal enveloping algebra of **self**.
EXAMPLES:

```
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()  #...
   # needs sage.modules
sage: L.universal_enveloping_algebra()  #...
   # needs sage.combinat sage.modules
Noncommutative Multivariate Polynomial Ring in b0, b1, b2
   over Rational Field, nc-relations: {}  
```

```
sage: L = LieAlgebra(QQ, 3, 'x', abelian=True)  #...
   # needs sage.combinat sage.modules
sage: L.universal_enveloping_algebra()  #...
   # needs sage.combinat sage.modules
Multivariate Polynomial Ring in x0, x1, x2 over Rational Field
```

See also:

`lift()`

class SubcategoryMethods
class Methods
    Bases: object

Nilpotent()

Return the full subcategory of nilpotent objects of `self`.

A Lie algebra \( L \) is nilpotent if there exist an integer \( s \) such that all iterated brackets of \( L \) of length more than \( s \) vanish. The integer \( s \) is called the nilpotency step. For instance any abelian Lie algebra is nilpotent of step 1.

EXAMPLES:

```
sage: LieAlgebras(QQ).Nilpotent()
Category of nilpotent Lie algebras over Rational Field
sage: LieAlgebras(QQ).WithBasis().Nilpotent()
Category of nilpotent Lie algebras with basis over Rational Field
```

WithBasis

alias of `LieAlgebrasWithBasis`

eexample (gens=None)

Return an example of a Lie algebra as per `Category.example`.

EXAMPLES:

```
sage: LieAlgebras(QQ).example()  #...
   # needs sage.groups sage.modules
An example of a lie algebra: the Lie algebra from the associative algebra
   Symmetric group algebra of order 3 over Rational Field
   generated by ([2, 1, 3], [2, 3, 1])
```

Another set of generators can be specified as an optional argument:

```
sage: F.<x,y,z> = FreeAlgebra(QQ)  #...
   # needs sage.combinat sage.modules
sage: LieAlgebras(QQ).example(F.gens())  #...
   # needs sage.combinat sage.modules
An example of a lie algebra: the Lie algebra from the associative algebra
   Free Algebra on 3 generators (x, y, z) over Rational Field
   generated by (x, y, z)
```

4.104. Lie Algebras
super_categories()

EXAMPLES:

```
sage: LieAlgebras(QQ).super_categories()
[Category of vector spaces over Rational Field]
```

class sage.categories.lie_algebras.LiftMorphism(domain, codomain)

Bases: Morphism

The natural lifting morphism from a Lie algebra to its enveloping algebra.

### 4.105 Lie Algebras With Basis

AUTHORS:

- Travis Scrimshaw (07-15-2013): Initial implementation

```
class sage.categories.lie_algebras_with_basis.LieAlgebrasWithBasis(base_category)

Bases: CategoryWithAxiom_over_base_ring

Category of Lie algebras with a basis.

class ElementMethods

Bases: object

    lift()

    Lift self to the universal enveloping algebra.
```

EXAMPLES:

```
sage: # needs sage.groups
sage: S = SymmetricGroup(3).algebra(QQ)
sage: L = LieAlgebra(associative=S)
sage: x = L.gen(3)
sage: y = L.gen(1)
sage: x.lift()
b3
sage: y.lift()
b1
sage: x * y
b1*b3 + b4 - b5
```

to_vector(order=None)

Return the vector in g.module() corresponding to the element self of g (where g is the parent of self).

Implement this if you implement g.module(). See sage.categories.lie_algebras.LieAlgebras.module() for how this is to be done.

EXAMPLES:

```
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()  
˓→# needs sage.modules
sage: L.an_element().to_vector()  
˓→# needs sage.modules
(0, 0, 0)
```
Todo: Doctest this implementation on an example not overshadowed.

Graded

alias of GradedLieAlgebrasWithBasis

class ParentMethods

Bases: object

bracket_on_basis(x, y)

Return the bracket of basis elements indexed by x and y where x < y. If this is not implemented, then the method _bracket_() for the elements must be overwritten.

EXAMPLES:

```
sage: L = LieAlgebras(QQ).WithBasis().example()  # needs sage.combinat sage.modules
sage: L.bracket_on_basis(Partition([3,1]), Partition([2,2,1,1]))  # needs sage.combinat sage.modules
0
```

dimension()

Return the dimension of self.

EXAMPLES:

```
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()  # needs sage.modules
sage: L.dimension()  # needs sage.modules
3
```

from_vector(v, order=None, coerce=False)

Return the element of self corresponding to the vector v in self.module().

Implement this if you implement module(); see the documentation of sage.categories.lie_algebras.LieAlgebras.module() for how this is to be done.

EXAMPLES:

```
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()  # needs sage.modules
sage: u = L.from_vector(vector(QQ, (1, 0, 0))); u  # needs sage.combinat sage.modules
(1, 0, 0)
sage: parent(u) is L  # needs sage.modules
True
```

module()

Return an R-module which is isomorphic to the underlying R-module of self.
See `sage.categories.lie_algebras.LieAlgebras.module()` for an explanation.

**EXAMPLES:**

```python
sage: L = LieAlgebras(QQ).WithBasis().example()  #-- needs sage.combinat sage.modules
sage: L.module()  #-- needs sage.combinat sage.modules
Free module generated by Partitions over Rational Field```

**pbw_basis** *(basis_key=None, **kwds)*

Return the Poincare-Birkhoff-Witt basis of the universal enveloping algebra corresponding to `self`.

**EXAMPLES:**

```python
sage: L = lie_algebras.sl(QQ, 2)  #-- needs sage.combinat sage.modules
sage: PBW = L.pbw_basis()  #-- needs sage.combinat sage.modules
```

**poincare_birkhoff_witt_basis** *(basis_key=None, **kwds)*

Return the Poincare-Birkhoff-Witt basis of the universal enveloping algebra corresponding to `self`.

**EXAMPLES:**

```python
sage: L = lie_algebras.sl(QQ, 2)  #-- needs sage.combinat sage.modules
sage: PBW = L.pbw_basis()  #-- needs sage.combinat sage.modules
```

**example** *(gens=None)*

Return an example of a Lie algebra as per `Category.example`.

**EXAMPLES:**

```python
sage: LieAlgebras(QQ).WithBasis().example()  #-- needs sage.combinat sage.modules
An example of a Lie algebra: the abelian Lie algebra on the generators indexed by Partitions over Rational Field
```

Another set of generators can be specified as an optional argument:

```python
sage: LieAlgebras(QQ).WithBasis().example(Compositions())  #-- needs sage.combinat sage.modules
An example of a Lie algebra: the abelian Lie algebra on the generators indexed by Compositions of non-negative integers over Rational Field
```
4.106 Lie Conformal Algebras

Let $R$ be a commutative ring, a super Lie conformal algebra [Kac1997] over $R$ (also known as a vertex Lie algebra) is an $R[T]$ super module $L$ together with a $\mathbb{Z}/2\mathbb{Z}$-graded $R$-bilinear operation (called the $\lambda$-bracket) $L \otimes L \to L[\lambda]$ (polynomials in $\lambda$ with coefficients in $L$), $a \otimes b \mapsto [a_\lambda b]$ satisfying

1. Sesquilinearity:
   $$[Ta_\lambda b] = -\lambda[a_\lambda b], \quad [a_\lambda Tb] = (\lambda + T)[a_\lambda b].$$

2. Skew-Symmetry:
   $$[a_\lambda b] = -(-1)^{p(a)p(b)}[b_{\lambda - T}a],$$
   where $p(a)$ is 0 if $a$ is even and 1 if $a$ is odd. The bracket in the RHS is computed as follows. First we evaluate $[b_\mu a]$ with the formal parameter $\mu$ to the left, then replace each appearance of the formal variable $\mu$ by $-\lambda - T$. Finally apply $T$ to the coefficients in $L$.

3. Jacobi identity:
   $$[a_\lambda [b_\mu c]] = [[a_\lambda + \mu b_\mu c] + (-1)^{p(a)p(b)}[b_\mu [a_\lambda c]],$$
   which is understood as an equality in $L[\lambda, \mu]$.

$T$ is usually called the translation operation or the derivative. For an element $a \in L$ we will say that $Ta$ is the derivative of $a$. We define the $n$-th products $a_{(n)}b$ for $a, b \in L$ by

$$[a_\lambda b] = \sum_{n \geq 0} \frac{\lambda^n}{n!} a_{(n)}b.$$  

A Lie conformal algebra is called $H$-Graded [DSK2006] if there exists a decomposition $L = \oplus L_n$ such that the $\lambda$-bracket becomes graded of degree $-1$, that is:

$$a_{(n)}b \in L_{p+q-n-1} \quad a \in L_p, b \in L_q, n \geq 0.$$  

In particular this implies that the action of $T$ increases degree by 1.

**Note:** In the literature arbitrary gradings are allowed. In this implementation we only support non-negative rational gradings.

**EXAMPLES:**

1. The Virasoro Lie conformal algebra $Vir$ over a ring $R$ where 12 is invertible has two generators $L, C$ as an $R[T]$-module. It is the direct sum of a free module of rank 1 generated by $L$, and a free rank one $R$ module generated by $C$ satisfying $TC = 0$. $C$ is central (the $\lambda$-bracket of $C$ with any other vector vanishes). The remaining $\lambda$-bracket is given by

$$[L_\lambda L] = TL + 2\lambda L + \frac{\lambda^3}{12} C.$$  

2. The affine or current Lie conformal algebra $L(g)$ associated to a finite dimensional Lie algebra $g$ with non-degenerate, invariant $R$-bilinear form $(,)$ is given as a central extension of the free $R[T]$ module generated by $g$ by a central element $K$. The $\lambda$-bracket of generators is given by

$$[a_\lambda b] = [a, b] + \lambda(a, b)K, \quad a, b \in g.$$  

4.106. Lie Conformal Algebras 567
3. The Weyl Lie conformal algebra, or $\beta - \gamma$ system is given as the central extension of a free $R[T]$ module with two generators $\beta$ and $\gamma$, by a central element $K$. The only non-trivial brackets among generators are

$$[\beta \gamma] = -[\gamma \beta] = K$$

4. The Neveu-Schwarz super Lie conformal algebra is a super Lie conformal algebra which is an extension of the Virasoro Lie conformal algebra. It consists of a Virasoro generator $L$ as in example 1 above and an odd generator $G$. The remaining brackets are given by:

$$[L_\lambda G] = \left(T + \frac{3}{2} \lambda\right) G \quad [G_\lambda G] = 2L + \frac{\lambda^2}{3} C$$

See also:

- sage.algebras.lie_conformal_algebras.lie_conformal_algebra
- sage.algebras.lie_conformal_algebras.examples

AUTHORS:


```python
class sage.categories.lie_conformal_algebras.LieConformalAlgebras(base, name=None):
    Bases: Category_over_base_ring

    The category of Lie conformal algebras.

    This is the base category for all Lie conformal algebras. Subcategories with axioms are FinitelyGenerated and WithBasis. A finitely generated Lie conformal algebra is a Lie conformal algebra over $R$ which is finitely generated as an $R[T]$-module. A Lie conformal algebra with basis is one with a preferred basis as an $R$-module.

    EXAMPLES:

    The base category:

    ```
    sage: C = LieConformalAlgebras(QQ); C
    Category of Lie conformal algebras over Rational Field
    sage: C.is_subcategory(VectorSpaces(QQ))
    True
    ```

    Some subcategories:

    ```
    sage: LieConformalAlgebras(QQbar).FinitelyGenerated().WithBasis() #...
    Category of finitely generated Lie conformal algebras with basis over Algebraic Field
    ```

    In addition we support functorial constructions Graded and Super. These functors commute:

    ```
    sage: CGS = LieConformalAlgebras(AA).Graded().Super(); CGS #...
    Category of H-graded super Lie conformal algebras over Algebraic Real Field
    sage: CGS is LieConformalAlgebras(AA).Super().Graded() #...
    True
    ```

    That is, we only consider gradings on super Lie conformal algebras that are compatible with the $\mathbb{Z}/2\mathbb{Z}$ grading.

    The base ring needs to be a commutative ring:

    ```
```
class ElementMethods
    Bases: object

    _is_even_odd()
    Return 0 if this element is even and 1 if it is odd.

Note: This method returns 0 by default since every Lie conformal algebra can be thought as a purely even Lie conformal algebra. In order to implement a super Lie conformal algebra, the user needs to implement this method.

EXAMPLES:

    sage: R = lie_conformal_algebras.NeveuSchwarz(QQ)
    sage: R.inject_variables()
    Defining L, G, C
    sage: G.is_even_odd()
    1

FinitelyGeneratedAsLambdaBracketAlgebra
    alias of FinitelyGeneratedLieConformalAlgebras

Graded
    alias of GradedLieConformalAlgebras

class ParentMethods
    Bases: object

Super
    alias of SuperLieConformalAlgebras

WithBasis
    alias of LieConformalAlgebrasWithBasis

def example():
    An example of parent in this category.

    EXAMPLES:

    sage: LieConformalAlgebras(QQ).example()
    The Virasoro Lie conformal algebra over Rational Field

super_categories()
    The list of super categories of this category.

    EXAMPLES:
4.107 Lie Conformal Algebras With Basis

AUTHORS:


class sage.categories.lie_conformal_algebras_with_basis.LieConformalAlgebrasWithBasis(base_category)

Bases: CategoryWithAxiom_over_base_ring

The category of Lie conformal algebras with basis.

EXAMPLES:

sage: LieConformalAlgebras(QQbar).WithBasis() #...
Category of lie conformal algebras with basis over Algebraic Field

class FinitelyGeneratedAsLambdaBracketAlgebra(base_category)

Bases: CategoryWithAxiom_over_base_ring

The category of finitely generated Lie conformal algebras with basis.
EXAMPLES:

```python
sage: C = LieConformalAlgebras(QQbar)
# needs sage.rings.number_field
sage: CWF = C.WithBasis().FinitelyGenerated(); CWF
# needs sage.rings.number_field
Category of finitely generated Lie conformal algebras with basis over Algebraic Field
sage: CWF is C.FinitelyGenerated().WithBasis()
# needs sage.rings.number_field
True
```

class Graded(base_category)

Bases: GradedLieConformalAlgebrasCategory

The category of H-graded finitely generated Lie conformal algebras with basis.

EXAMPLES:

```python
sage: LieConformalAlgebras(QQbar).WithBasis().FinitelyGenerated().Graded()
# needs sage.rings.number_field
Category of H-graded finitely generated Lie conformal algebras with basis over Algebraic Field
```

class Super(base_category)

Bases: SuperModulesCategory

The category of super finitely generated Lie conformal algebras with basis.

EXAMPLES:

```python
sage: LieConformalAlgebras(AA).WithBasis().FinitelyGenerated().Super()  # needs sage.rings.number_field
Category of super finitely generated Lie conformal algebras with basis over Algebraic Real Field
```

class Graded(base_category)

Bases: GradedModulesCategory

The category of H-graded super finitely generated Lie conformal algebras with basis.

EXAMPLES:

```python
sage: C = LieConformalAlgebras(QQbar).WithBasis().FinitelyGenerated()  # needs sage.rings.number_field
sage: C.Graded().Super()  # needs sage.rings.number_field
Category of H-graded super finitely generated Lie conformal algebras with basis over Algebraic Field
sage: C.Graded().Super() is C.Super().Graded()  # needs sage.rings.number_field
True
```

class Graded(base_category)

Bases: GradedLieConformalAlgebrasCategory

The category of H-graded Lie conformal algebras with basis.

EXAMPLES:
class Super(base_category)

Bases: SuperModulesCategory

The category of super Lie conformal algebras with basis.

EXAMPLES:

sage: LieConformalAlgebras(AA).WithBasis().Super()  # needs sage.rings.number_field
Category of super Lie conformal algebras with basis over Algebraic Real Field

class Graded(base_category)

Bases: GradedLieConformalAlgebrasCategory

The category of H-graded super Lie conformal algebras with basis.

EXAMPLES:

sage: LieConformalAlgebras(QQbar).WithBasis().Super().Graded()  # needs sage.rings.number_field
Category of H-graded super Lie conformal algebras with basis over Algebraic Field

class ParentMethods

Bases: object

4.108 Lie Groups

class sage.categories.lie_groups.LieGroups(base, name=None)

Bases: Category_over_base_ring

The category of Lie groups.

A Lie group is a topological group with a smooth manifold structure.

EXAMPLES:

sage: from sage.categories.lie_groups import LieGroups
sage: C = LieGroups(QQ); C
Category of lie groups over Rational Field

additional_structure()

Return None.

Indeed, the category of Lie groups defines no new structure: a morphism of topological spaces and of smooth manifolds is a morphism as Lie groups.

See also:

Category.additional_structure()

EXAMPLES:
```python
sage: from sage.categories.lie_groups import LieGroups
sage: LieGroups(QQ).additional_structure()
```

```
super_categories()

EXAMPLES:
```
```
sage: from sage.categories.lie_groups import LieGroups
sage: LieGroups(QQ).super_categories()
[Category of topological groups,
 Category of smooth manifolds over Rational Field]
```

4.109 Loop Crystals

```python
class sage.categories.loop_crystals.KirillovReshetikhinCrystals
Bases: Category_singleton

Category of Kirillov-Reshetikhin crystals.

class ElementMethods
Bases: object

energy_function()

Return the energy function of self.

Let $B$ be a KR crystal. Let $b^\ast$ denote the unique element such that $\varphi(b^\ast) = \ell \Lambda_0$ with $\ell = \min\{\langle c, \varphi(b) \rangle | b \in B\}$. Let $u_B$ denote the maximal element of $B$. The energy of $b \in B$ is given by

$$D(b) = H(b \otimes b^\ast) - H(u_B \otimes b^\ast),$$

where $H$ is the local energy function.

EXAMPLES:
```
sage: K = crystals.KirillovReshetikhin(['D', 4, 1], 2, 1)
sage: for x in K.classically_highest_weight_vectors():
    ....:     x, x.energy_function()
([[], 1)
([[1], [2]], 0)
```
```
sage: K = crystals.KirillovReshetikhin(['D', 4, 3], 1, 2)
sage: for x in K.classically_highest_weight_vectors():
    ....:     x, x.energy_function()
([[], 2)
([[1]], 1)
([[1, 1]], 0)
```
```
lusztig_involution()

Return the result of the classical Lusztig involution on self.

EXAMPLES:
```
sage: KRT = crystals.KirillovReshetikhin(['D', 4, 1], 2, 3, model='KR')
sage: mg = KRT.module_generators[1]
sage: mg.lusztig_involution()
[-2, -2, 1], [-1, -1, 2]
```
```
(continues on next page)```
class ParentMethods

Bases: object

\texttt{R\_matrix}(K)

Return the combinatorial $R$-matrix of self to $K$.

The \textit{combinatorial $R$-matrix} is the affine crystal isomorphism $R : L \otimes K \rightarrow K \otimes L$ which maps $u_L \otimes u_K$ to $u_K \otimes u_L$, where $u_K$ is the unique element in $K = B_{r,s}$ of weight $s\Lambda_r - sc\Lambda_0$ (see \texttt{maximal\_vector()}).

\textbf{INPUT:}

- \texttt{self} -- a crystal $L$
- \texttt{K} -- a Kirillov-Reshetikhin crystal of the same type as $L$

\textbf{EXAMPLES:}

\begin{verbatim}
sage: K = crystals.KirillovReshetikhin(['A',2,1],1,1)
sage: L = crystals.KirillovReshetikhin(['A',2,1],1,2)
sage: f = K.R_matrix(L)
sage: [[b,f(b)] for b in crystals.TensorProduct(K,L)]
[[[[1], [1, 1]], [[1, 1], [1]]],
 [[[1], [1, 2]], [[1, 1], [2]]],
 [[[1], [2, 1]], [[1, 2], [1]]],
 [[[1], [2, 2]], [[1, 2], [2]]],
 [[[1], [1, 3]], [[1, 1], [1]]],
 [[[1], [2, 3]], [[1, 2], [1]]],
 [[[1], [3, 3]], [[1, 3], [1]]],
 [[[2], [1, 1]], [[2, 1], [1]]],
 [[[2], [1, 2]], [[2, 1], [2]]],
 [[[2], [2, 2]], [[2, 1], [2]]],
 [[[2], [1, 3]], [[2, 1], [1]]],
 [[[2], [2, 3]], [[2, 2], [1]]],
 [[[2], [3, 3]], [[2, 2], [2]]],
 [[[3], [1, 1]], [[3, 1], [1]]],
 [[[3], [1, 2]], [[3, 1], [2]]],
 [[[3], [2, 2]], [[3, 2], [2]]],
 [[[3], [1, 3]], [[3, 2], [1]]],
 [[[3], [2, 3]], [[3, 3], [1]]],
 [[[3], [3, 3]], [[3, 3], [2]]],
 [[[3], [3, 3]], [[3, 3], [3]]]]

sage: K = crystals.KirillovReshetikhin(['D',4,1],1,1)
sage: L = crystals.KirillovReshetikhin(['D',4,1],2,1)
sage: f = K.R_matrix(L)
sage: T = crystals.TensorProduct(K,L)
sage: b = T( K(rows=[[1]]), L(rows=[]) )
sage: f(b)
[[[2], [-2]], [[1]]]
\end{verbatim}

Alternatively, one can compute the combinatorial $R$-matrix using the isomorphism method of digraphs:

\begin{verbatim}
sage: K1 = crystals.KirillovReshetikhin(['A',2,1],1,1)
sage: K2 = crystals.KirillovReshetikhin(['A',2,1],2,1)
sage: T1 = crystals.TensorProduct(K1,K2)
sage: T2 = crystals.TensorProduct(K2,K1)
\end{verbatim}
affinization()

Return the corresponding affinization crystal of self.

EXAMPLES:

```
sage: K = crystals.KirillovReshetikhin(['A',2,1], 1, 1)
sage: K.affinization()
Affinization of Kirillov-Reshetikhin crystal of type ['A', 2, 1] with (r, s)=(1,1)
```

```
sage: K = crystals.KirillovReshetikhin(['A',2,1], 1, 1, model='KR')
sage: K.affinization()
Affinization of Kirillov-Reshetikhin tableaux of type ['A', 2, 1] and shape (1, 1)
```

b_sharp()

Return the element $b^{\dagger}$ of self.

Let $B$ be a KR crystal. The element $b^{\dagger}$ is the unique element such that
\[
\varphi(b^{\dagger}) = \ell \Lambda_0 \text{ with } \ell = \min \{ \langle c, \varphi(b) \rangle \mid b \in B \}.
\]

EXAMPLES:

```
sage: K = crystals.KirillovReshetikhin(['A',6,2], 2,1)
sage: K.b_sharp()
[]
sage: K.b_sharp().Phi()
Lambda[0]
```

```
sage: K = crystals.KirillovReshetikhin(['C',3,1], 1,3)
sage: K.b_sharp()
[-1]
sage: K.b_sharp().Phi()
2*Lambda[0]
```

```
sage: K = crystals.KirillovReshetikhin(['D',6,2], 2,2)
sage: K.b_sharp() # long time
[]
sage: K.b_sharp().Phi() # long time
2*Lambda[0]
```

cardinality()

Return the cardinality of self.

EXAMPLES:
```python
sage: K = crystals.KirillovReshetikhin(['E',6,1], 1,1)
sage: K.cardinality()
27
sage: K = crystals.KirillovReshetikhin(['C',6,1], 4,3)
sage: K.cardinality()
4736732
```

**classical_decomposition()**

Return the classical decomposition of self.

**EXAMPLES:**

```python
sage: K = crystals.KirillovReshetikhin(['A',3,1], 2,2)
sage: K.classical_decomposition()
The crystal of tableaux of type ['A', 3] and shape(s) [[2, 2]]
```

**classically_highest_weight_vectors()**

Return the classically highest weight elements of self.

**EXAMPLES:**

```python
sage: K = crystals.KirillovReshetikhin(['E',6,1],1,1)
sage: K.classically_highest_weight_vectors()
(((1,),))
```

**is_perfect(ell=None)**

Check if self is a perfect crystal of level ell.

A crystal $\mathcal{B}$ is perfect of level $\ell$ if:
1. $\mathcal{B}$ is isomorphic to the crystal graph of a finite-dimensional $U'_q(\mathfrak{g})$-module.
2. $\mathcal{B} \otimes \mathcal{B}$ is connected.
3. There exists a $\lambda \in X$, such that $\text{wt}(\mathcal{B}) \subseteq \lambda + \sum_{i \in \mathcal{I}} Z_{\leq 0} \alpha_i$ and there is a unique element in $\mathcal{B}$ of classical weight $\lambda$.
4. For all $b \in \mathcal{B}$, $\text{level}(\varepsilon(b)) \geq \ell$.
5. For all $\Lambda$ dominant weights of level $\ell$, there exist unique elements $b_\Lambda, b^\Lambda \in \mathcal{B}$, such that $\varepsilon(b_\Lambda) = \Lambda = \varphi(b^\Lambda)$.

Points (1)-(3) are known to hold. This method checks points (4) and (5).

If self is the Kirillov-Reshetikhin crystal $B^{r,s}$, then it was proven for non-exceptional types in [FOS2010] that it is perfect if and only if $s/c_r$ is an integer (where $c_r$ is a constant related to the type of the crystal).

It is conjectured this is true for all affine types.

**INPUT:**
- `ell` - (default: $s/c_r$) integer; the level

**REFERENCES:**

[FOS2010]

**EXAMPLES:**

```python
sage: K = crystals.KirillovReshetikhin(['A',2,1], 1, 1)
sage: K.is_perfect()
True
sage: K = crystals.KirillovReshetikhin(['C',2,1], 1, 1)
sage: K.is_perfect()
```

(continues on next page)
False

```python
sage: K = crystals.KirillovReshetikhin(['C',2,1], 1, 2)
sage: K.is_perfect()
True

sage: K = crystals.KirillovReshetikhin(['E',6,1], 1, 3)
sage: K.is_perfect()
True
```

**Todo:** Implement a version for tensor products of KR crystals.

### level()

Return the level of `self` when `self` is a perfect crystal.

**See also:**

`is_perfect()`

**EXAMPLES:**

```python
sage: K = crystals.KirillovReshetikhin(['A',2,1], 1, 1)
sage: K.level()
1
sage: K = crystals.KirillovReshetikhin(['C',2,1], 1, 2)
sage: K.level()
1
sage: K = crystals.KirillovReshetikhin(['D',4,1], 1, 3)
sage: K.level()
3

sage: K = crystals.KirillovReshetikhin(['C',2,1], 1, 1)
sage: K.level()
Traceback (most recent call last):
... ValueError: this crystal is not perfect
```

### local_energy_function(B)

Return the local energy function of `self` and `B`.

**See LocalEnergyFunction for a definition.**

**EXAMPLES:**

```python
sage: K = crystals.KirillovReshetikhin(['A',6,2], 2,1)
sage: Kp = crystals.KirillovReshetikhin(['A',6,2], 1,1)
sage: H = K.local_energy_function(Kp); H

Local energy function of Kirillov-Reshetikhin crystal of type [\textit{BC}, 3, 2] with (r,s)=(2,1) tensor
Kirillov-Reshetikhin crystal of type [\textit{BC}, 3, 2] with (r,s)=(1,1)
```

### maximal_vector()

Return the unique element of classical weight $s\Lambda_r$ in `self`.

**EXAMPLES:**

4.109. Loop Crystals 577
### module_generator()()

Return the unique module generator of classical weight $s\Lambda_r$ of the Kirillov-Reshetikhin crystal $B^{r,s}$.

**EXAMPLES:**

```python
sage: La = RootSystem(['G',2,1]).weight_space().fundamental_weights()
sage: K = crystals.ProjectedLevelZeroLSPaths(La[1])
sage: K.module_generator()
(-Lambda[0] + Lambda[1],)
```

### q_dimension(q=None, prec=None, use_product=False)

Return the $q$-dimension of self.

The $q$-dimension of a KR crystal is defined as the $q$-dimension of the underlying classical crystal.

**EXAMPLES:**

```python
sage: KRC = crystals.KirillovReshetikhin(['A',2,1], 2,2)
sage: KRC.q_dimension()
qu^4 + q^3 + 2*q^2 + q + 1
sage: KRC = crystals.KirillovReshetikhin(['D',4,1], 2,1)
sage: KRC.q_dimension()
q^10 + q^9 + 3*q^8 + 3*q^7 + 4*q^6 + 4*q^5 + 4*q^4 + 3*q^3 + 3*q^2 + q + 2
```

### r()()

Return the value $r$ in self written as $B^{r,s}$.

**EXAMPLES:**

```python
sage: K = crystals.KirillovReshetikhin(['A',3,1], 2,4)
sage: K.r()
2
```

### s()()

Return the value $s$ in self written as $B^{r,s}$.

**EXAMPLES:**

```python
sage: K = crystals.KirillovReshetikhin(['A',3,1], 2,4)
sage: K.s()
4
```

### class TensorProducts(category, *args)

Bases: TensorProductsCategory

The category of tensor products of Kirillov-Reshetikhin crystals.
class ElementMethods
Bases: object

affine_grading()

Return the affine grading of self.

The affine grading is calculated by finding a path from self to a ground state path (using the helper method e_string_to_ground_state()) and counting the number of affine Kashiwara operators $e_0$ applied on the way.

OUTPUT: an integer

EXAMPLES:

```
sage: K = crystals.KirillovReshetikhin(['A', 2, 1], 1, 1)
sage: T = crystals.TensorProduct(K,K)
sage: t = T.module_generators[0]
sage: t.affine_grading()
1
```

```
sage: K = crystals.KirillovReshetikhin(['A', 2, 1], 1, 1)
sage: T = crystals.TensorProduct(K,K,K)
sage: hw = T.classically_highest_weight_vectors()
sage: for b in hw:
    print("{} {}".format(b, b.affine_grading()))
[[], [], []] 3
[[[2]], [[1]], [[1]]] 2
[[[1]], [[1]], [[1]]] 1
[[[3]], [[2]], [[1]]] 0
```

```
e_string_to_ground_state()

Return a string of integers in the index set $(i_1, \ldots, i_k)$ such that $e_{i_k} \cdots e_{i_1}$ of self is the ground state.

This method calculates a path from self to a ground state path using Demazure arrows as defined in Lemma 7.3 in [ST2011].

OUTPUT: a tuple of integers $(i_1, \ldots, i_k)$

EXAMPLES:

```
sage: K = crystals.KirillovReshetikhin(['A', 2, 1], 1, 1)
sage: T = crystals.TensorProduct(K,K)
sage: t = T.module_generators[0]
sage: t.e_string_to_ground_state()
(0, 2)
```

(continues on next page)
energy_function(algorithm=None)

Return the energy function of self.

ALGORITHM:

definition

Let $T$ be a tensor product of Kirillov-Reshetikhin crystals. Let $R_i$ and $H_i$ be the combinatorial $R$-matrix and local energy functions, respectively, acting on the $i$ and $i+1$ factors. Let $D_B$ be the energy function of a single Kirillov-Reshetikhin crystal. The energy function is given by

$$D = \sum_{j>i} H_i R_{i+1} R_{i+2} \cdots R_{j-1} + \sum_j D_B R_1 R_2 \cdots R_{j-1},$$

where $D_B$ acts on the rightmost factor.

grading

If self is an element of $T$, a tensor product of perfect crystals of the same level, then use the affine grading to determine the energy. Specifically, let $g$ denote the affine grading of self and $d$ the affine grading of the maximal vector in $T$. Then the energy of self is given by $d - g$.

For more details, see Theorem 7.5 in [ST2011].

INPUT:
• algorithm – (default: None) use one of the following algorithms to determine the energy function:
  – 'definition' - use the definition of the energy function;
  – 'grading' - use the affine grading;
  if not specified, then this uses 'grading' if all factors are perfect of the same level and otherwise this uses 'definition'

OUTPUT: an integer

EXAMPLES:
class ParentMethods
    
    Bases: object

    cardinality()
    
    Return the cardinality of self.

    EXAMPLES:

    sage: RC = RiggedConfigurations(['A', 3, 1], [[3, 2], [1, 2]])
    sage: RC.cardinality()
    100
    sage: len(RC.list())
    100

    sage: RC = RiggedConfigurations(['E', 7, 1], [[1,1]])
    sage: RC.cardinality()
    134
    sage: len(RC.list())
    134

    sage: RC = RiggedConfigurations(['B', 3, 1], [[2,2],[1,2]])
    sage: RC.cardinality()
    5130

    classically_highest_weight_vectors()
    
    Return the classically highest weight elements of self.
    
    This works by using a backtracking algorithm since if \( b_2 \otimes b_1 \) is classically highest weight then \( b_1 \) is classically highest weight.
EXAMPLES:

```python
sage: K = crystals.KirillovReshetikhin(['A', 2, 1], 1, 1)
sage: T = crystals.TensorProduct(K, K)
sage: T.classically_highest_weight_vectors()
([[1]], [[1]], [[1]]),
([[2]], [[1]], [[1]]),
([[1]], [[2]], [[1]]),
([[3]], [[2]], [[1]])
```

**maximal_vector()**

Return the maximal vector of self.

EXAMPLES:

```python
sage: K = crystals.KirillovReshetikhin(['A', 2, 1], 1, 1)
sage: T = crystals.TensorProduct(K, K)
sage: T.maximal_vector()
([[1]], [[1]], [[1]])
```

**one_dimensional_configuration_sum**(q=None, group_components=True)

Compute the one-dimensional configuration sum of self.

INPUT:

- • q – (default: None) a variable or None; if None, a variable \( q \) is set in the code
- • group_components – (default: True) boolean; if True, then the terms are grouped by classical component

The one-dimensional configuration sum is the sum of the weights of all elements in the crystal weighted by the energy function.

EXAMPLES:

```python
sage: K = crystals.KirillovReshetikhin(['A', 2, 1], 1, 1)
sage: T = crystals.TensorProduct(K, K)
sage: T.one_dimensional_configuration_sum()
B[-2*Lambda[1] + 2*Lambda[2]] + (q+1)*B[-Lambda[1]]
+ (q+1)*B[2*Lambda[1]] + B[-2*Lambda[2]]
```

```python
sage: R.<t> = ZZ[]
sage: T.one_dimensional_configuration_sum(t, False)
B[-2*Lambda[1] + 2*Lambda[2]] + (t+1)*B[-Lambda[1]]
+ (t+1)*B[2*Lambda[1]] + B[-2*Lambda[2]]
```

```python
sage: R = RootSystem(['A', 2, 1])
sage: La = R.weight_space().basis()
sage: LS = crystals.ProjectedLevelZeroLSPaths(2*La[1])
sage: (LS.one_dimensional_configuration_sum() == T.one_dimensional_configuration_sum())
True
```

**extra_super_categories()**

EXAMPLES:

```python
sage: from sage.categories.loop_crystals import...
sage: KirillovReshetikhinCrystals
sage: KirillovReshetikhinCrystals().TensorProducts().extra_super_`
```

(continues on next page)
super_categories()

EXAMPLES:

```python
sage: from sage.categories.loop_crystals import KirillovReshetikhinCrystals
sage: KirillovReshetikhinCrystals().super_categories()
[Category of finite regular loop crystals]
```

class `sage.categories.loop_crystals.LocalEnergyFunction`

*Bases: `Map`*

The local energy function.

Let \( B \) and \( B' \) be Kirillov-Reshetikhin crystals with maximal vectors \( u_B \) and \( u_{B'} \) respectively. The *local energy function* \( H : B \otimes B' \rightarrow \mathbb{Z} \) is the function which satisfies

\[
H(e_0(b \otimes b')) = H(b \otimes b') + \begin{cases} 
1 & \text{if } i = 0 \text{ and LL}, \\
-1 & \text{if } i = 0 \text{ and RR}, \\
0 & \text{otherwise},
\end{cases}
\]

where LL (resp. RR) denote \( e_0 \) acts on the left (resp. right) on both \( b \otimes b' \) and \( R(b \otimes b') \), and normalized by \( H(u_B \otimes u_{B'}) = 0 \).

**INPUT:**

- \( B \) – a Kirillov-Reshetikhin crystal
- \( B' \) – a Kirillov-Reshetikhin crystal
- \( \text{normalization} \) – (default: 0) the normalization value

**EXAMPLES:**

```python
sage: K = crystals.KirillovReshetikhin(['C',2,1], 1,2)
sage: K2 = crystals.KirillovReshetikhin(['C',2,1], 2,1)
sage: H = K.local_energy_function(K2)
sage: T = tensor([K, K2])
sage: hw = T.classically_highest_weight_vectors()
sage: for b in hw:
....:     b, H(b)
([[[], [[1], [2]]], 1),
([[1, 1]], [[1], [2]]), 0),
([[2, -2]], [[1], [2]], 1),
([[1, -2]], [[1], [2]], 1))
```

**REFERENCES:**

[KKMMN1992]

**class `sage.categories.loop_crystals.LoopCrystals`**

*Bases: `Category_singleton`*

The category of \( U'_q(\mathfrak{g}) \)-crystals, where \( \mathfrak{g} \) is of affine type.

The category is called loop crystals as we can also consider them as crystals corresponding to the loop algebra \( g_0[t] \), where \( g_0 \) is the corresponding classical type.

**EXAMPLES:**

4.109. Loop Crystals
sage: from sage.categories.loop_crystals import LoopCrystals
sage: C = LoopCrystals()
sage: C
Category of loop crystals
sage: C.super_categories()
[Category of crystals]
sage: C.example()
Kirillov-Reshetikhin crystal of type ['A', 3, 1] with (r,s)=(1,1)

class ParentMethods

Bases: object

digraph (subset=None, index_set=None)

Return the DiGraph associated to self.

INPUT:
• subset – (optional) a subset of vertices for which the digraph should be constructed
• index_set – (optional) the index set to draw arrows

See also:
sage.categories.crystals.Crystals.ParentMethods.digraph()

EXAMPLES:

sage: C = crystals.KirillovReshetikhin(['D',4,1], 2, 1)
sage: G = C.digraph()
LaTeX options for Digraph on 29 vertices:
{...’edge_options’: <function ... at ...>...}
sage: view(G, tightpage=True)  # optional - dot2tex graphviz, not tested
(opens external window)

weight_lattice_realization()

Return the weight lattice realization used to express weights of elements in self.

The default is to use the non-extended affine weight lattice.

EXAMPLES:

sage: C = crystals.Letters(['A', 5])
sage: C.weight_lattice_realization()
Ambient space of the Root system of type ['A', 5]
sage: K = crystals.KirillovReshetikhin(['A',2,1], 1, 1)
sage: K.weight_lattice_realization()
Weight lattice of the Root system of type ['A', 2, 1]

element (n=3)

Return an example of Kirillov-Reshetikhin crystals, as per Category.example().

EXAMPLES:

sage: from sage.categories.loop_crystals import LoopCrystals
sage: B = LoopCrystals().example(); B
Kirillov-Reshetikhin crystal of type ['A', 3, 1] with (r,s)=(1,1)

super_categories()

EXAMPLES:
class sage.categories.loop_crystals.RegularLoopCrystals
    Bases: Category_singleton

    The category of regular $U'_q(\mathfrak{g})$-crystals, where $\mathfrak{g}$ is of affine type.

class ElementMethods
    Bases: object

    classical_weight()
        Return the classical weight of self.

        EXAMPLES:
        sage: R = RootSystem(['A',2,1])
        sage: La = R.weight_space().basis()
        sage: LS = crystals.ProjectedLevelZeroLSPaths(2*La[1])
        sage: hw = LS.classically_highest_weight_vectors()
        sage: [(v.weight(), v.classical_weight()) for v in hw]
        [(-2*Lambda[0] + 2*Lambda[1], (2, 0, 0)),
         (-Lambda[0] + Lambda[2], (1, 1, 0))]

    super_categories()
        EXAMPLES:
        sage: from sage.categories.loop_crystals import RegularLoopCrystals
        sage: RegularLoopCrystals().super_categories()
        [Category of regular crystals,
         Category of loop crystals]
extra_super_categories()

Implement the fact that a $L$-trivial semigroup is $H$-trivial.

EXAMPLES:

```python
sage: Semigroups().LTrivial().extra_super_categories()
[Category of h trivial semigroups]
```

### 4.111 Magmas

class sage.categories.magmas.Magmas

**Bases:** Category_singleton

The category of (multiplicative) magmas.

A magma is a set with a binary operation $\ast$.

**EXAMPLES:**

```python
sage: Magmas()
Category of magmas
sage: Magmas().super_categories()
[Category of sets]
sage: Magmas().all_super_categories()
[Category of magmas, Category of sets, Category of sets with partial maps, Category of objects]
```

The following axioms are defined by this category:

```python
sage: Magmas().Associative()
Category of semigroups
sage: Magmas().Unital()
Category of unital magmas
sage: Magmas().Commutative()
Category of commutative magmas
sage: Magmas().Unital().Inverse()
Category of inverse unital magmas
sage: Magmas().Associative()
Category of semigroups
sage: Magmas().Associative().Unital()
Category of monoids
sage: Magmas().Associative().Unital().Inverse()
Category of groups
```

class Algebras(category, *args)

**Bases:** AlgebrasCategory

**class ParentMethods**

**Bases:** object

is_field (proof=True)

Return True if self is a field.

For a magma algebra $RS$ this is always false unless $S$ is trivial and the base ring $R$ is a field.

**EXAMPLES:**
sage: SymmetricGroup(1).algebra(QQ).is_field()  # needs sage.groups
True
sage: SymmetricGroup(1).algebra(ZZ).is_field()  # needs sage.groups
False
sage: SymmetricGroup(2).algebra(QQ).is_field()  # needs sage.groups
False

extra_super_categories()

EXAMPLES:

sage: MCA = Magmas().Commutative().Algebras(QQ)
sage: MCA.extra_super_categories()
[Category of commutative magmas]

This implements the fact that the algebra of a commutative magma is commutative:

sage: MCA.super_categories()
[Category of magma algebras over Rational Field,
 Category of commutative magmas]

In particular, commutative monoidal algebras are commutative algebras:

sage: MoCA = Monoids().Commutative().Algebras(QQ)
sage: MoCA.is_subcategory(Algebras(QQ).Commutative())
True

Associative

alias of Semigroups

class CartesianProducts(category, *args)

Bases: CartesianProductsCategory
class ParentMethods

Bases: object

product (left, right)

EXAMPLES:

sage: C = Magmas().CartesianProducts().example(); C
The Cartesian product of (Rational Field, Integer Ring, Integer Ring)
sage: x = C.an_element(); x
(1/2, 1, 1)
sage: x * x
(1/4, 1, 1)
sage: # needs sage.groups sage.modules
sage: A = SymmetricGroupAlgebra(QQ, 3)
sage: x = cartesian_product([A([1,3,2]), A([2,3,1])])
sage: y = cartesian_product([A([1,3,2]), A([2,3,1])])
sage: cartesian_product([A,A]).product(x,y)
B[(0, [1, 2, 3])] + B[(1, [3, 1, 2])]
sage: x*y
B[(0, [1, 2, 3])] + B[(1, [3, 1, 2])]
example()

Return an example of Cartesian product of magmas.

EXAMPLES:

```sage
C = Magmas().CartesianProducts().example(); C
The Cartesian product of (Rational Field, Integer Ring, Integer Ring)
sage: C.category()
Join of Category of Cartesian products of commutative rings and
Category of Cartesian products of metric spaces
sage: sorted(C.category().axioms())
['AdditiveAssociative', 'AdditiveCommutative', 'AdditiveInverse',
 'AdditiveUnital', 'Associative', 'Commutative',
 'Distributive', 'Unital']
sage: TestSuite(C).run()
```

extra_super_categories()

This implements the fact that a subquotient (and therefore a quotient or subobject) of a finite set is finite.

EXAMPLES:

```sage
Semigroups().CartesianProducts().extra_super_categories()
[Category of semigroups]
sage: Semigroups().CartesianProducts().super_categories()
[Category of semigroups, Category of Cartesian products of magmas]
```

class Commutative(base_category)

Bases: CategoryWithAxiom_singleton

class Algebras(category, *args)

Bases: AlgebrasCategory

extra_super_categories()

EXAMPLES:

```sage
MCA = Magmas().Commutative().Algebras(QQ)
sage: MCA.extra_super_categories()
[Category of commutative magmas]
sage: MCA.super_categories()
[Category of magma algebras over Rational Field,
 Category of commutative magmas]
```

This implements the fact that the algebra of a commutative magma is commutative:

```sage
MCA = Magmas().Commutative().Algebras(QQ)
sage: MCA.is_subcategory(Algebras(QQ).Commutative())
True
```

In particular, commutative monoid algebras are commutative algebras:

```sage
MoCA = Monoids().Commutative().Algebras(QQ)
sage: MoCA.is_subcategory(Algebras(QQ).Commutative())
True
```

class CartesianProducts(category, *args)

Bases: CartesianProductsCategory

extra_super_categories()

Implement the fact that a Cartesian product of commutative additive magmas is still a commutative additive magmas.
EXAMPLES:

```python
sage: C = Magmas().Commutative().CartesianProducts()
sage: C.extra_super_categories()
[Category of commutative magmas]
sage: C.axioms()
frozenset({'Commutative'})
```

class ParentMethods
Bases: object

```python
is_commutative()
```
Return True, since commutative magmas are commutative.

EXAMPLES:

```python
sage: Parent(QQ, category=CommutativeRings()).is_commutative()
True
```

class ElementMethods
Bases: object

```python
is_idempotent()
```
Test whether self is idempotent.

EXAMPLES:

```python
sage: S = Semigroups().example("free"); S
An example of a semigroup:
the free semigroup generated by ('a', 'b', 'c', 'd')
sage: a = S('a')
sage: a^2
'aa'
sage: a.is_idempotent()
False
```

```python
sage: L = Semigroups().example("leftzero"); L
An example of a semigroup: the left zero semigroup
sage: x = L('x')
sage: x^2
'x'
sage: x.is_idempotent()
True
```

**FinitelyGeneratedAsMagma**

alias of **FinitelyGeneratedMagmas**

class JTrivial(base_category)
Bases: CategoryWithAxiom

class ParentMethods
Bases: object

```python
multiplication_table(names='letters', elements=None)
```
Returns a table describing the multiplication operation.
Note: The order of the elements in the row and column headings is equal to the order given by the table’s list() method. The association can also be retrieved with the dict() method.

INPUT:
- names - the type of names used
  - 'letters' - lowercase ASCII letters are used for a base 26 representation of the elements’ positions in the list given by column_keys(), padded to a common width with leading ‘a’s.
  - 'digits' - base 10 representation of the elements’ positions in the list given by column_keys(), padded to a common width with leading zeros.
  - 'elements' - the string representations of the elements themselves.
  - a list - a list of strings, where the length of the list equals the number of elements.
- elements - default = None. A list of elements of the magma, in forms that can be coerced into the structure, eg. their string representations. This may be used to impose an alternate ordering on the elements, perhaps when this is used in the context of a particular structure. The default is to use whatever ordering the S.list method returns. Or the elements can be a subset which is closed under the operation. In particular, this can be used when the base set is infinite.

OUTPUT:
The multiplication table as an object of the class OperationTable which defines several methods for manipulating and displaying the table. See the documentation there for full details to supplement the documentation here.

EXAMPLES:
The default is to represent elements as lowercase ASCII letters.

```
sage: G = CyclicPermutationGroup(5)  # needs sage.groups
sage: G.multiplication_table()  # needs sage.groups
+-------
| a b c d e |
| a c d e a |
| b d e a c |
| c e a b c |
| d a b c e |
```

All that is required is that an algebraic structure has a multiplication defined. A LeftRegularBand is an example of a finite semigroup. The names argument allows displaying the elements in different ways.

```
sage: from sage.categories.examples.finite_semigroups import LeftRegularBand
sage: L = LeftRegularBand(['a', 'b'])
sage: T = L.multiplication_table(names='digits')  # needs sage.modules
sage: T.column_keys()  # needs sage.modules
('a', 'ab', 'b', 'ba')
sage: T  # needs sage.modules
+--------
| 0 1 2 3 |
| 1 1 1 1 |
| 1 1 1 1 |
```
(continues on next page)
Specifying the elements in an alternative order can provide more insight into how the operation behaves.

```python
sage: L = LeftRegularBand(('a', 'b', 'c'))
sage: elts = sorted(L.list())
sage: L.multiplication_table(elements=elts)
```

```
<table>
<thead>
<tr>
<th></th>
<th>a</th>
<th>b</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>a</td>
<td>b</td>
<td>c</td>
</tr>
<tr>
<td>b</td>
<td>b</td>
<td>b</td>
<td>c</td>
</tr>
<tr>
<td>c</td>
<td>c</td>
<td>c</td>
<td>c</td>
</tr>
</tbody>
</table>
```

The `elements` argument can be used to provide a subset of the elements of the structure. The subset must be closed under the operation. Elements need only be in a form that can be coerced into the set. The `names` argument can also be used to request that the elements be represented with their usual string representation.

```python
sage: L = LeftRegularBand(('a', 'b', 'c'))
sage: elts = ['a', 'c', 'ac', 'ca']
sage: L.multiplication_table(names='elements', elements=elts)
```

The table returned can be manipulated in various ways. See the documentation for `OperationTable` for more comprehensive documentation.
product \((x, y)\)

The binary multiplication of the magma.

INPUT:

- \(x, y\) – elements of this magma

OUTPUT:

- an element of the magma (the product of \(x\) and \(y\))

EXAMPLES:

```python
sage: S = Semigroups().example("free")
sage: x = S('a'); y = S('b')
sage: S.product(x, y)
'ab'
```

A parent in \(\text{Magmas}()\) must either implement \(\text{product()}\) in the parent class or \_mul\_ in the element class. By default, the addition method on elements \(x\)_mul_(y) calls \(S\).product\((x, y)\), and reciprocally.

As a bonus, \(S\).product models the binary function from \(S\) to \(S\):

```python
sage: bin = S.product
sage: bin(x,y)
'ab'
```

Currently, \(S\).product is just a bound method:

```python
sage: bin
<bound method FreeSemigroup.product of An example of a semigroup: the free semigroup generated by ('a', 'b', 'c', 'd')>
```

When Sage will support multivariate morphisms, it will be possible, and in fact recommended, to enrich \(S\).product with extra mathematical structure. This will typically be implemented using lazy attributes:

```python
sage: bin # todo: not implemented
Generic binary morphism:
From: (S x S)
To: S
```

product\_from\_element\_class\_mul \((x, y)\)

The binary multiplication of the magma.

INPUT:

- \(x, y\) – elements of this magma

OUTPUT:

- an element of the magma (the product of \(x\) and \(y\))

EXAMPLES:
A parent in `Magmas()` must either implement `product()` in the parent class or `_mul_` in the element class. By default, the addition method on elements `x._mul_(y)` calls `S.product(x, y)`, and reciprocally.

As a bonus, `S.product` models the binary function from `S` to `S`:

```python
sage: bin = S.product
sage: bin(x,y)
'ab'
```

Currently, `S.product` is just a bound method:

```python
sage: bin
<bound method FreeSemigroup.product of An example of a semigroup: the free semigroup generated by ['a', 'b', 'c', 'd']>
```

When Sage will support multivariate morphisms, it will be possible, and in fact recommended, to enrich `S.product` with extra mathematical structure. This will typically be implemented using lazy attributes:

```python
sage: bin # todo: not implemented
Generic binary morphism:
From: (S x S)
To:   S
```

### Realizations

**class** Realizations *(category, *args)*

**Bases:** RealizationsCategory

**class** ParentMethods

**Bases:** object

**product_by_coercion**(left, right)

Default implementation of product for realizations.

This method coerces to the realization specified by `self.realization_of()`, `a_realization()`, computes the product in that realization, and then coerces back.

**EXAMPLES:**

```python
sage: # needs sage.combinat sage.modules
sage: Out = Sets().WithRealizations().example().Out(); Out
The subset algebra of {1, 2, 3} over Rational Field
in the Out basis
sage: Out.product<br>Out.product.__module__
'sage.categories.magmas'
sage: x = Out.an_element()
sage: y = Out.an_element()
sage: Out.product(x, y)
Out[{}] + 4*Out[{1}] + 9*Out[{2}] + Out[{1, 2}]```
class SubcategoryMethods
    Bases: object

    Associative()
    Return the full subcategory of the associative objects of self.
    A (multiplicative) magma $M$ is associative if, for all $x, y, z \in M$,
    $$x * (y * z) = (x * y) * z$$

    See also:
    Wikipedia article Associative_property

    EXAMPLES:
    sage: Magmas().Associative()
    Category of semigroups

    Commutative()
    Return the full subcategory of the commutative objects of self.
    A (multiplicative) magma $M$ is commutative if, for all $x, y \in M$,
    $$x * y = y * x$$

    See also:
    Wikipedia article Commutative_property

    EXAMPLES:
    sage: Magmas().Commutative()
    Category of commutative magmas
    sage: Monoids().Commutative()
    Category of commutative monoids

    Distributive()
    Return the full subcategory of the objects of self where $*$ is distributive on $+$.

    INPUT:
    • self — a subcategory of Magmas and AdditiveMagmas

    Given that Sage does not yet know that the category MagmasAndAdditiveMagmas
    is the intersection of the categories Magmas and AdditiveMagmas, the method
    MagmasAndAdditiveMagmas.SubcategoryMethods.Distributive() is not available,
    as would be desirable, for this intersection.

    This method is a workaround. It checks that self is a subcategory of both Magmas and AdditiveMagmas
    and upgrades it to a subcategory of MagmasAndAdditiveMagmas before applying
    the axiom. It complains otherwise, since the Distributive axiom does not make sense for a plain
    magma.

    EXAMPLES:
    sage: (Magmas() & AdditiveMagmas()).Distributive()
    Category of distributive magmas and additive magmas
    sage: (Monoids() & CommutativeAdditiveGroups()).Distributive()
    Category of rings

    (continues on next page)
FinitelyGenerated()

Return the subcategory of the objects of self that are endowed with a distinguished finite set of (multiplicative) magma generators.

EXAMPLES:

This is a shorthand for FinitelyGeneratedAsMagma(), which see:

```python
sage: Magmas().FinitelyGenerated()
Category of finitely generated magmas
sage: Semigroups().FinitelyGenerated()
Category of finitely generated semigroups
sage: Groups().FinitelyGenerated()
Category of finitely generated enumerated groups
```

An error is raised if this is ambiguous:

```python
sage: (Magmas() & AdditiveMagmas()).FinitelyGenerated()
Traceback (most recent call last):
  ... ValueError: FinitelyGenerated is ambiguous for
Join of Category of magmas and Category of additive magmas.
Please use explicitly one of the FinitelyGeneratedAsXXX methods
```

Note: Checking that there is no ambiguity currently assumes that all the other “finitely generated” axioms involve an additive structure. As of Sage 6.4, this is correct.

The use of this shorthand should be reserved for casual interactive use or when there is no risk of ambiguity.

FinitelyGeneratedAsMagma()

Return the subcategory of the objects of self that are endowed with a distinguished finite set of (multiplicative) magma generators.

A set $S$ of elements of a multiplicative magma form a set of generators if any element of the magma can be expressed recursively from elements of $S$ and products thereof.

It is not imposed that morphisms shall preserve the distinguished set of generators; hence this is a full subcategory.

See also:

Wikipedia article Unital_magma#unital

EXAMPLES:
Being finitely generated does depend on the structure: for a ring, being finitely generated as a magma, as an additive magma, or as a ring are different concepts. Hence the name of this axiom is explicit:

```
sage: Rings().FinitelyGeneratedAsMagma()
Category of finitely generated as magma enumerated rings
```

On the other hand, it does not depend on the multiplicative structure: for example a group is finitely generated if and only if it is finitely generated as a magma. A short hand is provided when there is no ambiguity, and the output tries to reflect that:

```
sage: Semigroups().FinitelyGenerated()
sage: Groups().FinitelyGenerated()
sage: Semigroups().FinitelyGenerated().axioms()
frozenset({'Associative', 'Enumerated', 'FinitelyGeneratedAsMagma'})
```

Note that the set of generators may depend on the actual category; for example, in a group, one can often use less generators since it is allowed to take inverses.

**JTrivial()**

Return the full subcategory of the $J$-trivial objects of `self`.

This axiom is in fact only meaningful for `semigroups`. This stub definition is here as a workaround for [github issue #20515](https://github.com/sagemath/sage/issues/20515), in order to define the $J$-trivial axiom as the intersection of the $L$ and $R$-trivial axioms.

**See also:**

`Semigroups.SubcategoryMethods.JTrivial()`

**Unital()**

Return the subcategory of the unital objects of `self`.

A (multiplicative) magma $\text{Magmas } M$ is unital if it admits an element $1$, called unit, such that for all $x \in M$,

$$1 \ast x = x \ast 1 = x$$

This element is necessarily unique, and should be provided as $M\text{.one()}$.

**See also:**

Wikipedia article Unital_magma#unital

**EXAMPLES:**

```
sage: Magmas().Unital()
Category of unital magmas
sage: Semigroups().Unital()
Category of monoids
sage: Monoids().Unital()
Category of monoids
sage: from sage.categories.associative_algebras import AssociativeAlgebras
sage: AssociativeAlgebras(QQ).Unital()
Category of algebras over Rational Field
```
class Subquotients(category, *args)
    Bases: SubquotientsCategory

The category of subquotient magmas.

See Sets.SubcategoryMethods.Subquotients() for the general setup for subquotients. In the case of a subquotient magma $S$ of a magma $G$, the condition that $r$ be a morphism in $AS$ can be rewritten as follows:

- for any two $a, b \in S$ the identity $a \times_S b = r(l(a) \times_G l(b))$ holds.

This is used by this category to implement the product $\times_S$ of $S$ from $l$ and $r$ and the product of $G$.

EXAMPLES:

```python
sage: Semigroups().Subquotients().all_super_categories()
[Category of subquotients of semigroups, Category of semigroups, Category of subquotients of magmas, Category of magmas, Category of subquotients of sets, Category of sets, Category of sets with partial maps, Category of objects]
```

class ParentMethods
    Bases: object

    product(x, y)

    Return the product of two elements of self.

    EXAMPLES:

```python
sage: S = Semigroups().Subquotients().example()
sage: S
An example of a (sub)quotient semigroup: a quotient of the left zero semigroup
sage: S.product(S(19), S(3))
19
```

Here is a more elaborate example involving a sub algebra:

```python
sage: Z = SymmetricGroup(5).algebra(QQ).center()  # needs sage.groups
sage: B = Z.basis()  # needs sage.groups
```

class Unital(base_category)
    Bases: CategoryWithAxiom_singleton

class Algebras(category, *args)
    Bases: AlgebrasCategory

    extra_super_categories()

    EXAMPLES:

```python
sage: MCA = Magmas().Commutative().Algebras(QQ)
sage: MCA.extra_super_categories()
[Category of commutative magmas]
```
This implements the fact that the algebra of a commutative magma is commutative:

```python
sage: MCA.super_categories()
[Category of magma algebras over Rational Field,
 Category of commutative magmas]
```

In particular, commutative monoidal algebras are commutative algebras:

```python
sage: MoCA = Monoids().Commutative().Algebras(QQ)
sage: MoCA.is_subcategory(Algebras(QQ).Commutative())
True
```

```python
class CartesianProducts(category, *args)
    Bases: CartesianProductsCategory

class ElementMethods
    Bases: object

class ParentMethods
    Bases: object

    one()
    Return the unit of this Cartesian product.
    It is built from the units for the Cartesian factors of self.

    EXAMPLES:

        sage: cartesian_product([QQ, ZZ, RR]).one()
        # needs sage.rings.real_mpfr
        (1, 1, 1.00000000000000)
```

```python
extra_super_categories()
    Implement the fact that a Cartesian product of unital magmas is a unital magma

    EXAMPLES:

        sage: C = Magmas().Unital().CartesianProducts()
sage: C.extra_super_categories()
[Category of unital magmas]
sage: C.axioms()
frozenset({'Unital'})
sage: Monoids().CartesianProducts().is_subcategory(Monoids())
True
```

```python
class ElementMethods
    Bases: object

class Inverse (base_category)
    Bases: CategoryWithAxiom_singleton

class CartesianProducts (category, *args)
    Bases: CartesianProductsCategory

    extra_super_categories()
    Implement the fact that a Cartesian product of magmas with inverses is a magma with inverse.

    EXAMPLES:
```
class ParentMethods
    Bases: object

    is_empty()
    Return whether self is empty.
    Since this set is a unital magma it is not empty and this method always return False.
    EXAMPLES:

    sage: S = SymmetricGroup(2)
    # needs sage.groups
    sage: S.is_empty()               # needs sage.groups
    False
    sage: M = Monoids().example()
    sage: M.is_empty()               # needs sage.groups
    False

    one()
    Return the unit of the monoid, that is the unique neutral element for *.

    Note: The default implementation is to coerce 1 into self. It is recommended to override this method because the coercion from the integers:
    * is not always meaningful (except for 1);
    * often uses self.one().
    EXAMPLES:

    sage: M = Monoids().example(); M
    An example of a monoid: the free monoid generated by ('a', 'b', 'c', 'd')
    sage: M.one()
    ..

class Realizations(category, *args)
    Bases: RealizationsCategory
class ParentMethods
    Bases: object

    one()
    Return the unit element of self.
    EXAMPLES:

    sage: # needs sage.combinat sage.groups
    sage: from sage.combinat.root_system.extended_affine_weyl_group import ExtendedAffineWeylGroup
    (continues on next page)
class SubcategoryMethods
    Bases: object
    
    Inverse()
    
    Return the full subcategory of the inverse objects of self.

    An inverse :class:`(multiplicative) magma <Magmas>` is a unital magma such that every element
    admits both an inverse on the left and on the right. Such a magma is also called a loop.

    See also:
    Wikipedia article Inverse_element, Wikipedia article Quasigroup

    EXAMPLES:

    sage: Magmas().Unital().Inverse()
    Category of inverse unital magmas
    sage: Monoids().Inverse()
    Category of groups

additional_structure()

    Return self.

    Indeed, the category of unital magmas defines an additional structure, namely the unit of the magma
    which shall be preserved by morphisms.

    See also:
    Category.additional_structure()

    EXAMPLES:

    sage: Magmas().Unital().additional_structure()
    Category of unital magmas

super_categories()

    EXAMPLES:

    sage: Magmas().super_categories()
    [Category of sets]

4.112 Magmas and Additive Magmas

class sage.categories.magmas_and_additive_magmas.MagmasAndAdditiveMagmas
    Bases: Category_singleton

    The category of sets $(S, +, *)$ with an additive operation `+` and a multiplicative operation `*`

    EXAMPLES:
This is the base category for the categories of rings and their variants:

```python
sage: C.Distributive()
Category of distributive magmas and additive magmas
```

This category is really meant to represent the intersection of the categories of `Magmas` and `AdditiveMagmas`; however, Sage’s infrastructure does not allow yet to model this:

```python
sage: Magmas() & AdditiveMagmas()
Join of Category of magmas and Category of additive magmas
```

```python
sage: Magmas() & AdditiveMagmas()  # todo: not implemented
Category of magmas and additive magmas
```

```python
class CartesianProducts(category, *args)
    Bases: CartesianProductsCategory
    extra_super_categories()
        Implement the fact that this structure is stable under Cartesian products.

Distributive
    alias of DistributiveMagmasAndAdditiveMagmas

class SubcategoryMethods
    Bases: object

    Distributive()
        Return the full subcategory of the objects of self where * is distributive on +.
        A magma and additive magma M is distributive if, for all x, y, z ∈ M,
        
x * (y + z) = x * y + x * z and (x + y) * z = x * z + y * z

    EXAMPLES:
        sage: from sage.categories.magmas_and_additive_magmas import...
        →MagmasAndAdditiveMagmas
        sage: C = MagmasAndAdditiveMagmas().Distributive(); C
        Category of distributive magmas and additive magmas
```

Note: Given that Sage does not know that `MagmasAndAdditiveMagmas` is the intersection of `Magmas` and `AdditiveMagmas`, this method is not available for:
Still, the natural syntax works:

```
sage: (Magmas() & AdditiveMagmas()).Distributive()
Category of distributive magmas and additive magmas
```

thanks to a workaround implemented in `Magmas.SubcategoryMethods.Distributive()`:

```
sage: (Magmas() & AdditiveMagmas()).Distributive.__module__
sage.categories.magmas
```

### additional_structure()

```
Return None.
```

Indeed, this category is meant to represent the join of `AdditiveMagmas` and `Magmas`. As such, it defines no additional structure.

**See also:**

`Category.additional_structure()`

**EXAMPLES:**

```
sage: from sage.categories.magmas_and_additive_magmas import MagmasAndAdditiveMagmas
sage: MagmasAndAdditiveMagmas().additional_structure()
```

### super_categories()

```
EXAMPLES:
```

```
sage: from sage.categories.magmas_and_additive_magmas import MagmasAndAdditiveMagmas
sage: MagmasAndAdditiveMagmas().super_categories()
[Category of magmas, Category of additive magmas]
```

## 4.113 Non-unital non-associative algebras

### class `sage.categories.magmatic_algebras.MagmaticAlgebras(base, name=None)`

**Bases:** `Category_over_base_ring`

The category of algebras over a given base ring.

An algebra over a ring $R$ is a module over $R$ endowed with a bilinear multiplication.

**Warning:** `MagmaticAlgebras` will eventually replace the current `Algebras` for consistency with e.g. Wikipedia article `Algebras` which assumes neither associativity nor the existence of a unit (see [github issue #15043](https://github.com/sagemath/sage/issues/15043)).

**EXAMPLES:**
sage: from sage.categories.magmatic_algebras import MagmaticAlgebras
sage: C = MagmaticAlgebras(ZZ); C
Category of magmatic algebras over Integer Ring
sage: C.super_categories()
[Category of additive commutative additive associative additive
 unital distributive magmas and additive magmas,
 Category of modules over Integer Ring]

Associative
alias of AssociativeAlgebras
class ParentMethods

Bases: object

algebra_generators()

Return a family of generators of this algebra.

EXAMPLES:

sage: F = AlgebrasWithBasis(QQ).example(); F
# needs sage.combinat sage.modules
An example of an algebra with basis:
the free algebra on the generators ('a', 'b', 'c') over Rational Field
sage: F.algebra_generators()
# needs sage.combinat sage.modules
Family (B[a], B[b], B[c])

Unital

alias of UnitalAlgebras
class WithBasis(base_category)

Bases: CategoryWithAxiom_over_base_ring
class FiniteDimensional(base_category)

Bases: CategoryWithAxiom_over_base_ring
class ParentMethods

Bases: object
derivations_basis()

Return a basis for the Lie algebra of derivations of self as matrices.

A derivation $D$ of an algebra is an endomorphism of $A$ such that

$$D(ab) = D(a)b + aD(b)$$

for all $a, b \in A$. The set of all derivations form a Lie algebra.

EXAMPLES:

We construct the Heisenberg Lie algebra as a multiplicative algebra:

sage: # needs sage.combinat sage.modules
sage: p_mult = matrix([[0,0,0], [0,0,-1], [0,0,0]])
sage: q_mult = matrix([[0,1], [0,0],[0,0,0]])
sage: A = algebras.FiniteDimensional(QQ,
....: [p_mult, q_mult, matrix(QQ, 3, 3)], 'p,q,z')
sage: A.inject_variables()

(continues on next page)
Defining $p$, $q$, $z$

```python
sage: p * q
z
sage: q * p
-z
sage: A.derivations_basis()
```

We construct another example using the exterior algebra and verify we obtain a derivation:

```python
sage: # needs sage.combinat sage.modules
sage: A = algebras.Exterior(QQ, 1)
sage: A.derivations_basis()

sage: D = A.module_morphism(matrix=A.derivations_basis()[0],
....: codomain=A)
sage: one, e = A.basis()
sage: all(D(a*b) == D(a) * b + a * D(b)
....: for a in A.basis() for b in A.basis())
True
```

REFERENCES:

Wikipedia article Derivation_(differential_algebra)

class ParentMethods

Bases: object

algebra_generators()

Return generators for this algebra.

This default implementation returns the basis of this algebra.

OUTPUT: a family

See also:

• basis()
• MagmaticAlgebras.ParentMethods.algebra_generators()

EXAMPLES:
.. needs sage.combinat sage.modules

Lazy family (Term map
from Partition diagrams of order 1
to Partition Algebra of rank 1 with parameter x
over Univariate Polynomial Ring in x
over Integer Ring(i)_{i in Partition diagrams of order 1}

.. needs sage.combinat sage.modules

**product()**

The product of the algebra, as per :meth:`Magmas.ParentMethods.product`

By default, this is implemented using one of the following methods, in the specified order:

- :meth:`product_on_basis`
- :meth:`product_by_coercion`

**EXAMPLES:**

```python
sage: A = AlgebrasWithBasis(QQ).example()  #...
    needs sage.combinat sage.modules
sage: a, b, c = A.algebra_generators()  #...
    needs sage.combinat sage.modules
sage: A.product(a + 2*b, 3*c)  #...
    needs sage.combinat sage.modules
3*B[word: ac] + 6*B[word: bc]
```

.. needs sage.combinat sage.modules

**product_on_basis** (*i, j*)

The product of the algebra on the basis (optional).

**INPUT:**

- *i, j* – the indices of two elements of the basis of *self*

Return the product of the two corresponding basis elements indexed by *i* and *j*.

If implemented, :meth:`product()` is defined from it by linearity.

**EXAMPLES:**

```python
sage: A = AlgebrasWithBasis(QQ).example()  #...
    needs sage.combinat sage.modules
sage: Word = A.basis().keys()  #...
    needs sage.combinat sage.modules
sage: A.product_on_basis(Word("abc"), Word("cba"))  #...
    needs sage.combinat sage.modules
B[word: abccba]
```

.. needs sage.combinat sage.modules

**additional_structure()**

Return None.

Indeed, the category of (magmatic) algebras defines no new structure: a morphism of modules and of magmas between two (magmatic) algebras is a (magmatic) algebra morphism.

See also:

.. autosummary::
   :toctree: generated/

   :ref:`Category.additional_structure`

**Todo:** This category should be a :class:`CategoryWithAxiom`, the axiom specifying the compatibility between the magma and module structure.

**EXAMPLES:**
4.114 Manifolds

class sage.categories.manifolds.ComplexManifolds (base, name=None)

Bases: Category_over_base_ring

The category of complex manifolds.

A $d$-dimensional complex manifold is a manifold whose underlying vector space is $\mathbb{C}^d$ and has a holomorphic atlas.

super_categories()

EXAMPLES:

sage: from sage.categories.manifolds import Manifolds
sage: Manifolds(RR).super_categories()
[Category of topological spaces]

class sage.categories.manifolds.Manifolds (base, name=None)

Bases: Category_over_base_ring

The category of manifolds over any topological field.

Let $k$ be a topological field. A $d$-dimensional $k$-manifold $M$ is a second countable Hausdorff space such that the neighborhood of any point $x \in M$ is homeomorphic to $k^d$.

EXAMPLES:

sage: # needs sage.rings.real_mpfr
sage: from sage.categories.manifolds import Manifolds
sage: C = Manifolds(RR); C
Category of manifolds over Real Field with 53 bits of precision
sage: C.super_categories()
[Category of topological spaces]

class AlmostComplex (base_category)

Bases: CategoryWithAxiom_over_base_ring

The category of almost complex manifolds.
An almost complex manifold \( M \) is a manifold with a smooth tensor field \( J \) of rank \((1, 1)\) such that \( J^2 = -1 \) when regarded as a vector bundle isomorphism \( J : TM \to TM \) on the tangent bundle. The tensor field \( J \) is called the almost complex structure of \( M \).

**extra_super_categories()**

Return the extra super categories of \( \text{self} \).

An almost complex manifold is smooth.

**EXAMPLES:**

```python
sage: from sage.categories.manifolds import Manifolds
sage: Manifolds(RR).AlmostComplex().super_categories()
\[
\text{[Category of smooth manifolds over Real Field with 53 bits of precision]}
\]
```

**class Analytic(base_category)**

Bases: `CategoryWithAxiom_over_base_ring`

The category of complex manifolds.

An analytic manifold is a manifold with an analytic atlas.

**extra_super_categories()**

Return the extra super categories of \( \text{self} \).

An analytic manifold is smooth.

**EXAMPLES:**

```python
sage: from sage.categories.manifolds import Manifolds
sage: Manifolds(RR).Analytic().super_categories()
\[
\text{[Category of smooth manifolds over Real Field with 53 bits of precision]}
\]
```

**class Connected(base_category)**

Bases: `CategoryWithAxiom_over_base_ring`

The category of connected manifolds.

**EXAMPLES:**

```python
sage: from sage.categories.manifolds import Manifolds
sage: C = Manifolds(RR).Connected()
sage: TestSuite(C).run(skip="_test_category_over_bases")
```

**class Differentiable(base_category)**

Bases: `CategoryWithAxiom_over_base_ring`

The category of differentiable manifolds.

A differentiable manifold is a manifold with a differentiable atlas.

**class FiniteDimensional(base_category)**

Bases: `CategoryWithAxiom_over_base_ring`

Category of finite dimensional manifolds.

**EXAMPLES:**
class ParentMethods
Bases: object
dimension()
    Return the dimension of self.

EXAMPLES:

class Smooth(base_category)
Bases: CategoryWithAxiom_over_base_ring
The category of smooth manifolds.
A smooth manifold is a manifold with a smooth atlas.
extra_super_categories()
    Return the extra super categories of self.
    A smooth manifold is differentiable.

EXAMPLES:

class SubcategoryMethods
Bases: object
AlmostComplex()
    Return the subcategory of the almost complex objects of self.

EXAMPLES:

Analytic()
    Return the subcategory of the analytic objects of self.

EXAMPLES:
sage: from sage.categories.manifolds import Manifolds
sage: Manifolds(RR).Analytic()          # needs sage.rings.real_mpfr
Category of analytic manifolds over Real Field with 53 bits of precision

Complex()

Return the subcategory of manifolds over \( \mathbb{C} \) of self.

EXAMPLES:

sage: from sage.categories.manifolds import Manifolds
sage: Manifolds(CC).Complex()          # needs sage.rings.real_mpfr
Category of complex manifolds over Complex Field with 53 bits of precision

Connected()

Return the full subcategory of the connected objects of self.

EXAMPLES:

sage: from sage.categories.manifolds import Manifolds
sage: Manifolds(RR).Connected()        # needs sage.rings.real_mpfr
Category of connected manifolds over Real Field with 53 bits of precision

Differentiable()

Return the subcategory of the differentiable objects of self.

EXAMPLES:

sage: from sage.categories.manifolds import Manifolds
sage: Manifolds(RR).Differentiable()   # needs sage.rings.real_mpfr
Category of differentiable manifolds over Real Field with 53 bits of precision

FiniteDimensional()

Return the full subcategory of the finite dimensional objects of self.

EXAMPLES:

sage: from sage.categories.manifolds import Manifolds
sage: C = Manifolds(RR).Connected().FiniteDimensional(); C # needs sage.rings.real_mpfr
Category of finite dimensional connected manifolds over Real Field with 53 bits of precision

Smooth()

Return the subcategory of the smooth objects of self.

EXAMPLES:

sage: from sage.categories.manifolds import Manifolds
sage: Manifolds(RR).Smooth()          # needs sage.rings.real_mpfr

(continues on next page)
**Category of smooth manifolds over Real Field with 53 bits of precision**

**additional_structure()**

Return None.

Indeed, the category of manifolds defines no new structure: a morphism of topological spaces between manifolds is a manifold morphism.

See also:

Category.additional_structure()

**EXAMPLES:**

```python
sage: from sage.categories.manifolds import Manifolds
sage: Manifolds(RR).additional_structure()
```

**super_categories()**

**EXAMPLES:**

```python
sage: from sage.categories.manifolds import Manifolds
sage: Manifolds(RR).super_categories()
[Category of topological spaces]
```

### 4.115 Matrix algebras

**class** `sage.categories.matrix_algebras.MatrixAlgebras(base, name=None)`

Bases: `Category_over_base_ring`

The category of matrix algebras over a field.

**EXAMPLES:**

```python
sage: MatrixAlgebras(RationalField())
Category of matrix algebras over Rational Field
```

**super_categories()**

**EXAMPLES:**

```python
sage: MatrixAlgebras(QQ).super_categories()
[Category of algebras over Rational Field]
```
4.116 Metric Spaces

```python
class sage.categories.metric_spaces.MetricSpaces(category, *args):
    Bases: MetricSpacesCategory

    The category of metric spaces.

    A metric on a set \( S \) is a function \( d : S \times S \to \mathbb{R} \) such that:
    - \( d(a, b) \geq 0 \),
    - \( d(a, b) = 0 \) if and only if \( a = b \).

    A metric space is a set \( S \) with a distinguished metric.

Implementation

Objects in this category must implement either a `dist` on the parent or the elements or `metric` on the parent; otherwise this will cause an infinite recursion.

Todo:

- Implement a general geodesics class.
- Implement a category for metric additive groups and move the generic distance \( d(a, b) = |a - b| \) there.
- Incorporate the length of a geodesic as part of the default distance cycle.

EXAMPLES:

```python
sage: from sage.categories.metric_spaces import MetricSpaces
sage: C = MetricSpaces()

sage: C
Category of metric spaces

sage: TestSuite(C).run()
```

```python
class CartesianProducts(category, *args):
    Bases: CartesianProductsCategory

class ParentMethods:
    Bases: object

    dist (a, b)

    Return the distance between \( a \) and \( b \) in `self`.

    It is defined as the maximum of the distances within the Cartesian factors.

EXAMPLES:

```python
sage: from sage.categories.metric_spaces import MetricSpaces
sage: Q2 = QQ.cartesian_product(QQ)

sage: Q2 in MetricSpaces()
True
```
```
extra_super_categories()

Implement the fact that a (finite) Cartesian product of metric spaces is a metric space.

EXAMPLES:

```python
sage: from sage.categories.metric_spaces import MetricSpaces
sage: C = MetricSpaces().CartesianProducts()
```

```python
sage: C.extra_super_categories()
[Category of metric spaces]
```

```python
sage: C.super_categories()
[Category of Cartesian products of topological spaces,
 Category of metric spaces]
```

```python
sage: C.axioms()
 frozenset()
```

**class** Complete**(base_category)**

**Bases:** CategoryWithAxiom

The category of complete metric spaces.

**class** CartesianProducts**(category, *args)**

**Bases:** CartesianProductsCategory

extra_super_categories()

Implement the fact that a (finite) Cartesian product of complete metric spaces is a complete metric space.

**EXAMPLES:**

```python
sage: from sage.categories.metric_spaces import MetricSpaces
sage: C = MetricSpaces().Complete().CartesianProducts()
```

```python
sage: C.extra_super_categories()
[Category of complete metric spaces]
```

```python
sage: C.super_categories()
[Category of Cartesian products of metric spaces,
 Category of complete metric spaces]
```

```python
sage: C.axioms()
 frozenset({"Complete"})
```

```python
sage: R2 = RR.cartesian_product(RR)
```

```python
sage: R2 in MetricSpaces()
True
```

```python
sage: R2 in MetricSpaces().Complete()
True
```

```python
sage: QR = QQ.cartesian_product(RR)
```

```python
sage: QR in MetricSpaces()
True
```

```python
sage: QR in MetricSpaces().Complete()
False
```

**class** ElementMethods

**Bases:** object
abs()  
Return the absolute value of self.

EXAMPLES:

```
sage: CC(I).abs() # unchanged needs sage.rings.real_mpfr sage.symbolic
1.00000000000000
```

dist(b)  
Return the distance between self and other.

EXAMPLES:

```
sage: # needs sage.symbolic
sage: UHP = HyperbolicPlane().UHP()
```

```
sage: p1 = UHP.get_point(5 + 7*I)
sage: p2 = UHP.get_point(1 + I)
sage: UHP.dist(p1, p2)
arccosh(33/7)
```

class Homsets(category, *args)

Bases: HomsetsCategory

The category of homsets of metric spaces

It consists of the metric maps, that is, the Lipschitz functions with Lipschitz constant 1.

class ElementMethods

Bases: object

class ParentMethods

Bases: object

dist(a, b)  
Return the distance between a and b in self.

EXAMPLES:

```
sage: # needs sage.symbolic
sage: UHP = HyperbolicPlane().UHP()
```

```
sage: p1 = UHP.get_point(5 + 7*I)
sage: p2 = UHP.get_point(1.0 + I)
sage: UHP.dist(p1, p2)
2.23230104635820
```

metric(*args, **kwds)

Deprecated: Use metric_function() instead. See github issue #30062 for details.

metric_function()  
Return the metric function of self.

EXAMPLES:
class SubcategoryMethods
Bases: object

Complete()

Return the full subcategory of the complete objects of self.

EXAMPLES:

```
sage: Sets().Metric().Complete()
Category of complete metric spaces
```

class WithRealizations (category, *args)
Bases: WithRealizationsCategory
class ParentMethods
Bases: object
dist (a, b)

Return the distance between a and b by converting them to a realization of self and doing the computation.

EXAMPLES:

```
sage: # needs sage.symbolic
sage: H = HyperbolicPlane()
sage: PD = H.PD()
sage: p1 = PD.get_point(0)
sage: p2 = PD.get_point(I/2)
sage: H.dist(p1, p2)
arccosh(5/3)
```

class sage.categories.metric_spaces.MetricSpacesCategory (category, *args)
Bases: RegressiveCovariantConstructionCategory
classmethod default_super_categories (category)

Return the default super categories of category.Metric().

Mathematical meaning: if A is a metric space in the category C, then A is also a topological space.

INPUT:

- cls – the class MetricSpaces
- category – a category Cat

OUTPUT:

A (join) category

In practice, this returns category.Metric(), joined together with the result of the method RegressiveCovariantConstructionCategory.default_super_categories() (that is the join of category and cat.Metric() for each cat in the super categories of category).
EXAMPLES:

Consider `category=Groups()`. Then, a group $G$ with a metric is simultaneously a topological group by itself, and a metric space:

```python
sage: Groups().Metric().super_categories()
[Category of topological groups, Category of metric spaces]
```

This resulted from the following call:

```python
sage: sage.categories.metric_spaces.MetricSpacesCategory.default_super_categories(Groups())
Join of Category of topological groups and Category of metric spaces
```

### 4.117 Modular abelian varieties

**class** `sage.categories.modular_abelian_varieties.ModularAbelianVarieties(Y)`

Bases: `Category_over_base`

The category of modular abelian varieties over a given field.

**EXAMPLES:**

```python
sage: ModularAbelianVarieties(QQ)
Category of modular abelian varieties over Rational Field
```

**class** `Homsets` (*category*, *args)

Bases: `HomsetsCategory`

**class** `Endset` (*base_category*)

Bases: `CategoryWithAxiom`

**extra_super_categories()**

Implement the fact that an endset of modular abelian variety is a ring.

**EXAMPLES:**

```python
sage: ModularAbelianVarieties(QQ).Endsets().extra_super_categories()
[Category of rings]
```

**base_field()**

**EXAMPLES:**

```python
sage: ModularAbelianVarieties(QQ).base_field()
Rational Field
```

**super_categories()**

**EXAMPLES:**

```python
sage: ModularAbelianVarieties(QQ).super_categories()
[Category of sets]
```
4.118 Modules

class sage.categories.modules.Modules(base, name=None)

Bases: Category_module

The category of all modules over a base ring $R$.

An $R$-module $M$ is a left and right $R$-module over a commutative ring $R$ such that:

$$r \cdot (x \cdot s) = (r \cdot x) \cdot s \quad \forall r, s \in R \text{ and } x \in M$$

INPUT:

- base_ring – a ring $R$ or subcategory of Rings()
- dispatch – a boolean (for internal use; default: True)

When the base ring is a field, the category of vector spaces is returned instead (unless dispatch == False).

Warning: Outside of the context of symmetric modules over a commutative ring, the specifications of this category are fuzzy and not yet set in stone (see below). The code in this category and its subcategories is therefore prone to bugs or arbitrary limitations in this case.

EXAMPLES:

```python
sage: Modules(ZZ)
Category of modules over Integer Ring
sage: Modules(QQ)
Category of vector spaces over Rational Field
sage: Modules(Rings())
Category of modules over rings
sage: Modules(FiniteFields())
Category of vector spaces over finite enumerated fields
sage: Modules(Integers(9))
Category of modules over Ring of integers modulo 9
sage: Modules(Integers(9)).super_categories()
[Category of bimodules over Ring of integers modulo 9 on the left
 and Ring of integers modulo 9 on the right]
```

Todo:
• Clarify the distinction, if any, with BiModules\((R, R)\). In particular, if \(R\) is a commutative ring (e.g. a field), some pieces of the code possibly assume that \(M\) is a symmetric \(R\)-\(R\)-bimodule:

\[
r \cdot x = x \cdot r \quad \forall r \in R \text{ and } x \in M
\]

• Make sure that non symmetric modules are properly supported by all the code, and advertise it.
• Make sure that non commutative rings are properly supported by all the code, and advertise it.
• Add support for base semirings.
• Implement a FreeModules\((R)\) category, when so prompted by a concrete use case: e.g. modeling a free module with several bases (using Sets.SubcategoryMethods.Realizations()) or with an atlas of local maps (see e.g. github issue #15916).

```python
class CartesianProducts(category, *args):
    Bases: CartesianProductsCategory

    The category of modules constructed as Cartesian products of modules

    This construction gives the direct product of modules. The implementation is based on the following resources:
    - http://groups.google.fr/group/sage-devel/browse_thread/thread/35a72b1d0a2fc77a/348f42ae77a66d16
    - Wikipedia article Direct_product

class ElementMethods
    Bases: object

class ParentMethods
    Bases: object

extra_super_categories()

A Cartesian product of modules is endowed with a natural module structure.

EXAMPLES:

```
sage: Modules(ZZ).CartesianProducts().extra_super_categories()
[Category of modules over Integer Ring]
sage: Modules(ZZ).CartesianProducts().super_categories()
[Category of Cartesian products of commutative additive groups, Category of modules over Integer Ring]
```

```python
class ElementMethods
    Bases: object

Filtered
    alias of FilteredModules

class FiniteDimensional(base_category)
    Bases: CategoryWithAxiom_over_base_ring

class TensorProducts(category, *args)
    Bases: TensorProductsCategory
```
extra_super_categories()

Implement the fact that a (finite) tensor product of finite dimensional modules is a finite dimensional module.

EXAMPLES:

```
sage: Modules(ZZ).FiniteDimensional().TensorProducts().extra_super_categories()
[Category of finite dimensional modules over Integer Ring]
sage: Modules(QQ).FiniteDimensional().TensorProducts().FiniteDimensional()
Category of tensor products of finite dimensional vector spaces over Rational Field
```

eextra_super_categories()

Implement the fact that a finite dimensional module over a finite ring is finite.

EXAMPLES:

```
sage: Modules(IntegerModRing(4)).FiniteDimensional().extra_super_categories()
[Category of finite sets]
sage: Modules(ZZ).FiniteDimensional().extra_super_categories()
[]
sage: Modules(GF(5)).FiniteDimensional().is_subcategory(Sets().Finite())
True
sage: Modules(ZZ).FiniteDimensional().is_subcategory(Sets().Finite())
False
sage: Modules(Rings().Finite()).FiniteDimensional().is_subcategory(Sets().Finite())
True
sage: Modules(Rings()).FiniteDimensional().is_subcategory(Sets().Finite())
False
```

class FinitelyPresented(base_category)

Bases: CategoryWithAxiom_over_base_ring

extra_super_categories()

Implement the fact that a finitely presented module over a finite ring is finite.

EXAMPLES:

```
sage: Modules(IntegerModRing(4)).FiniteDimensional().extra_super_categories()
[Category of finite sets]
sage: Modules(ZZ).FiniteDimensional().extra_super_categories()
[]
sage: Modules(GF(5)).FiniteDimensional().is_subcategory(Sets().Finite())
True
sage: Modules(ZZ).FiniteDimensional().is_subcategory(Sets().Finite())
False
sage: Modules(Rings().Finite()).FiniteDimensional().is_subcategory(Sets().Finite())
True
sage: Modules(Rings()).FiniteDimensional().is_subcategory(Sets().Finite())
False
```
Graded
alias of GradedModules

class Homsets (category, *args)
Bases: HomsetsCategory
The category of homomorphism sets \( \text{hom}(X, Y) \) for \( X, Y \) modules.

class Endset (base_category)
Bases: CategoryWithAxiom_over_base_ring
The category of endomorphism sets \( \text{End}(X) \) for \( X \) a module (this is not used yet)

extra_super_categories()
Implement the fact that the endomorphism set of a module is an algebra.

See also:
CategoryWithAxiom.extra_super_categories()

EXAMPLES:

```
sage: Modules(ZZ).Endsets().extra_super_categories()
[Category of magmatic algebras over Integer Ring]
sage: End(ZZ^3) in Algebras(ZZ)
˓→needs sage.modules
True
```

class ParentMethods
Bases: object

base_ring()
Return the base ring of self.

EXAMPLES:

```
sage: # needs sage.modules
sage: E = CombinatorialFreeModule(ZZ, [1,2,3])
sage: F = CombinatorialFreeModule(ZZ, [2,3,4])
sage: H = Hom(E, F)
sage: H.base_ring()
Integer Ring
```

This base_ring method is actually overridden by \texttt{sage.structure.category_object.CategoryObject.base_ring()}:

```
sage: H.base_ring.__module__ ˓→needs sage.modules
˓→needs sage.modules
```

Here we call it directly:

```
sage: method = H.category().parent_class.base_ring ˓→needs sage.modules
˓→needs sage.modules
sage: method._get_(__H)() ˓→needs sage.modules
Integer Ring
```
zero()

EXAMPLES:

```sage
# needs sage.modules
sage: E = CombinatorialFreeModule(ZZ, [1,2,3])
sage: F = CombinatorialFreeModule(ZZ, [2,3,4])
sage: H = Hom(E, F)
sage: f = H.zero()
sage: f
Generic morphism:
    From: Free module generated by {1, 2, 3} over Integer Ring
    To:   Free module generated by {2, 3, 4} over Integer Ring
sage: f(E.monomial(2))
0
sage: f(E.monomial(3)) == F.zero()
True
```

base_ring()

EXAMPLES:

```sage
sage: Modules(ZZ).Homsets().base_ring()
Integer Ring
```

Todo: Generalize this so that any homset category of a full subcategory of modules over a base ring is a category over this base ring.

extra_super_categories()

EXAMPLES:

```sage
sage: Modules(ZZ).Homsets().extra_super_categories()
[Category of modules over Integer Ring]
```

class ParentMethods

Bases: object

linear_combination(iter_of_elements_coeff, factor_on_left=True)

Return the linear combination $\lambda_1 v_1 + \cdots + \lambda_k v_k$ (resp. the linear combination $v_1 \lambda_1 + \cdots + v_k \lambda_k$) where `iter_of_elements_coeff` iterates through the sequence $((\lambda_1, v_1), \ldots, (\lambda_k, v_k))$.

INPUT:

- `iter_of_elements_coeff` – iterator of pairs (element, coeff) with element in self and coeff in self.base_ring()
- `factor_on_left` – (optional) if True, the coefficients are multiplied from the left; if False, the coefficients are multiplied from the right

EXAMPLES:

```sage
sage: m = matrix([[0,1], [1,1]])
# needs sage.modules
sage: J.<a,b,c> = JordanAlgebra(m)
# needs sage.combinat sage.modules
sage: J.linear_combination(((a+b, 1), (-2*b + c, -1)))
# needs sage.combinat sage.modules
1 + (3, -1)
```
module_morphism (function, category, codomain, **keywords)

Construct a module morphism from self to codomain.

Let self be a module $X$ over a ring $R$. This constructs a morphism $f : X \to Y$.

INPUT:
- self – a parent X in Modules(R).
- function – a function $f$ from $X$ to $Y$
- codomain – the codomain $Y$ of the morphism (default: $f$.codomain() if it’s defined; otherwise it must be specified)
- category – a category or None (default: None)

EXAMPLES:

```
sage: V = FiniteRankFreeModule(QQ, 2)
sage: e = V.basis('e'); e
Basis (e_0,e_1) on the 2-dimensional vector space over the Rational Field
sage: neg = V.module_morphism(function=operator.neg, codomain=V); neg
Generic endomorphism of 2-dimensional vector space over the Rational Field
sage: neg(e[0])
Element -e_0 of the 2-dimensional vector space over the Rational Field
```

quotient (submodule, check=True, **kwds)

Construct the quotient module self / submodule.

INPUT:
- submodule – a submodule with basis of self, or something that can be turned into one via self.submodule(submodule)
- check, other keyword arguments: passed on to quotient_module().

This method just delegates to quotient_module(). Classes implementing modules should override that method.

Parents in categories with additional structure may override quotient(). For example, in algebras, quotient() will be the same as quotient_ring().

EXAMPLES:

```
sage: C = CombinatorialFreeModule(QQ, ['a', 'b', 'c'])
# needs sage.combinat sage.modules
sage: TA = TensorAlgebra(C)
# needs sage.combinat sage.modules
sage: TA.quotient
<bound method Rings.ParentMethods.quotient of Tensor Algebra of Free module generated by {'a', 'b', 'c'} over Rational Field>
```

tensor_square()

Returns the tensor square of self

EXAMPLES:

```
sage: A = HopfAlgebrasWithBasis(QQ).example()
# needs sage.groups sage.modules
sage: A.tensor_square()
```

(continues on next page)
An example of Hopf algebra with basis:
the group algebra of the Dihedral group of order 6
as a permutation group over Rational Field

An example of Hopf algebra with basis: the group algebra of the Dihedral
group of order 6 as a permutation group over Rational Field

class SubcategoryMethods
Bases: object

DualObjects()
Return the category of spaces constructed as duals of spaces of self.

The dual of a vector space \( V \) is the space consisting of all linear functionals on \( V \) (see Wikipedia article Dual_space). Additional structure on \( V \) can endow its dual with additional structure; for example, if \( V \) is a finite dimensional algebra, then its dual is a coalgebra.

This returns the category of spaces constructed as dual of spaces in self, endowed with the appropriate additional structure.

Warning:
- This semantic of dual and DualObject is imposed on all subcategories, in particular to make dual a covariant functorial construction.
  - A subcategory that defines a different notion of dual needs to use a different name.
- Typically, the category of graded modules should define a separate graded_dual construction (see github issue #15647). For now the two constructions are not distinguished which is an oversimplified model.

See also:
- dual.DualObjectsCategory
- CovariantFunctorialConstruction.

EXAMPLES:

```
sage: VectorSpaces(QQ).DualObjects()
Category of duals of vector spaces over Rational Field
```

The dual of a vector space is a vector space:

```
sage: VectorSpaces(QQ).DualObjects().super_categories()
[Category of vector spaces over Rational Field]
```

The dual of an algebra is a coalgebra:

```
sage: sorted(Algebras(QQ).DualObjects().super_categories(), key=str)
[Category of coalgebras over Rational Field,
Category of duals of vector spaces over Rational Field]
```

The dual of a coalgebra is an algebra:

```
sage: sorted(Coalgebras(QQ).DualObjects().super_categories(), key=str)
[Category of algebras over Rational Field,
Category of duals of vector spaces over Rational Field]
```
As a shorthand, this category can be accessed with the \(\texttt{dual()}\) method:

\[
\begin{align*}
\texttt{sage: VectorSpaces(QQ).dual()} \\
\text{Category of duals of vector spaces over Rational Field}
\end{align*}
\]

**Filtered** \((\texttt{base\_ring=\textit{None}})\)

Return the subcategory of the filtered objects of \texttt{self}.

**INPUT:**

- \texttt{base\_ring} – this is ignored

**EXAMPLES:**

\[
\begin{align*}
\texttt{sage: Modules(ZZ).Filtered()} \\
\text{Category of filtered modules over Integer Ring} \\
\texttt{sage: Coalgebras(QQ).Filtered()} \\
\text{Category of filtered coalgebras over Rational Field} \\
\texttt{sage: AlgebrasWithBasis(QQ).Filtered()} \\
\text{Category of filtered algebras with basis over Rational Field}
\end{align*}
\]

**Todo:**

- Explain why this does not commute with \texttt{WithBasis()}
- Improve the support for covariant functorial constructions categories over a base ring so as to get rid of the \texttt{base\_ring} argument.

**FiniteDimensional()**

Return the full subcategory of the finite dimensional objects of \texttt{self}.

**EXAMPLES:**

\[
\begin{align*}
\texttt{sage: Modules(ZZ).FiniteDimensional()} \\
\text{Category of finite dimensional modules over Integer Ring} \\
\texttt{sage: Coalgebras(QQ).FiniteDimensional()} \\
\text{Category of finite dimensional coalgebras over Rational Field} \\
\texttt{sage: AlgebrasWithBasis(QQ).FiniteDimensional()} \\
\text{Category of finite dimensional algebras with basis over Rational Field}
\end{align*}
\]

**FinitelyPresented()**

Return the full subcategory of the finitely presented objects of \texttt{self}.

**EXAMPLES:**

\[
\begin{align*}
\texttt{sage: Modules(ZZ).FinitelyPresented()} \\
\text{Category of finitely presented modules over Integer Ring} \\
\texttt{sage: A = SteenrodAlgebra(2)} \\
\texttt{# Needs sage.combinat sage.modules} \\
\texttt{\texttt{\textit{\_needs sage.combinat sage.modules}}} \\
\texttt{sage: from sage.modules.fp_graded.module import FPModule} \\
\texttt{\texttt{\_needs sage.combinat sage.modules}} \\
\texttt{sage: FPModule(A, [0, 1], [[Sq(2), Sq(1)]]).category()} \\
\texttt{\texttt{\_needs sage.combinat sage.modules}} \\
\texttt{\texttt{\_needs sage.combinat sage.modules}} \\
\text{Category of finitely presented graded modules over mod 2 Steenrod algebra, milnor basis}
\end{align*}
\]

**Graded** \((\texttt{base\_ring=\textit{None}})\)

Return the subcategory of the graded objects of \texttt{self}.
INPUT:
- `base_ring` – this is ignored

EXAMPLES:

```
sage: Modules(ZZ).Graded()
Category of graded modules over Integer Ring
```

```
sage: Coalgebras(QQ).Graded()
Category of graded coalgebras over Rational Field
```

```
sage: AlgebrasWithBasis(QQ).Graded()
Category of graded algebras with basis over Rational Field
```

Todo:
- Explain why this does not commute with `WithBasis()`
- Improve the support for covariant functorial constructions categories over a base ring so as to get rid of the `base_ring` argument.

```
Super (base_ring=None)
```

Return the super-analogue category of `self`.

INPUT:
- `base_ring` – this is ignored

EXAMPLES:

```
sage: Modules(ZZ).Super()
Category of super modules over Integer Ring
```

```
sage: Coalgebras(QQ).Super()
Category of super coalgebras over Rational Field
```

```
sage: AlgebrasWithBasis(QQ).Super()
Category of super algebras with basis over Rational Field
```

Todo:
- Explain why this does not commute with `WithBasis()`
- Improve the support for covariant functorial constructions categories over a base ring so as to get rid of the `base_ring` argument.

```
TensorProducts ()
```

Return the full subcategory of objects of `self` constructed as tensor products.

See also:

- `tensor.TensorProductsCategory`
- `RegressiveCovariantFunctorialConstruction`

EXAMPLES:

```
sage: ModulesWithBasis(QQ).TensorProducts()
Category of tensor products of vector spaces with basis over Rational Field
```

```
WithBasis ()
```

Return the full subcategory of the objects of `self` with a distinguished basis.
EXAMPLES:

```
sage: Modules(ZZ).WithBasis()
Category of modules with basis over Integer Ring
sage: Coalgebras(QQ).WithBasis()
Category of coalgebras with basis over Rational Field
sage: AlgebrasWithBasis(QQ).WithBasis()
Category of algebras with basis over Rational Field
```

**base_ring()**

Return the base ring (category) for self.

This implements a `base_ring` method for all subcategories of `Modules(K)`.

**EXAMPLES:**

```
sage: C = Modules(QQ) & Semigroups(); C
Join of Category of semigroups and Category of vector spaces over Rational Field
sage: C.base_ring()
Rational Field
sage: C.base_ring.__module__
sage.categories.modules
sage: C2 = Modules(Rings()) & Semigroups(); C2
Join of Category of semigroups and Category of modules over rings
sage: C2.base_ring()
Category of rings
sage: C2.base_ring.__module__
sage.categories.modules
sage: # needs sage.combinat sage.modules
sage: C3 = DescentAlgebra(QQ,3).B().category()
sage: C3.base_ring.__module__
sage.categories.modules
sage: C3.base_ring()
Rational Field
sage: # needs sage.combinat sage.modules
sage: C4 = QuasiSymmetricFunctions(QQ).F().category()
sage: C4.base_ring.__module__
sage.categories.modules
sage: C4.base_ring()
Rational Field
```

**dual()**

Return the category of spaces constructed as duals of spaces of self.

The dual of a vector space $V$ is the space consisting of all linear functionals on $V$ (see Wikipedia article Dual_space). Additional structure on $V$ can endow its dual with additional structure; for example, if $V$ is a finite dimensional algebra, then its dual is a coalgebra.

This returns the category of spaces constructed as dual of spaces in self, endowed with the appropriate additional structure.

**Warning:**
• This semantic of dual and DualObject is imposed on all subcategories, in particular to make dual a covariant functorial construction.
  
  A subcategory that defines a different notion of dual needs to use a different name.
• Typically, the category of graded modules should define a separate graded_dual construction (see github issue #15647). For now the two constructions are not distinguished which is an oversimplified model.

See also:
• dual.DualObjectsCategory
• CovariantFunctorialConstruction.

EXAMPLES:
sage: VectorSpaces(QQ).DualObjects()  
Category of duals of vector spaces over Rational Field

The dual of a vector space is a vector space:
sage: VectorSpaces(QQ).DualObjects().super_categories()  
[Category of vector spaces over Rational Field]

The dual of an algebra is a coalgebra:
sage: sorted(Algebras(QQ).DualObjects().super_categories(), key=str)  
[Category of coalgebras over Rational Field,  
Category of duals of vector spaces over Rational Field]

The dual of a coalgebra is an algebra:
sage: sorted(Coalgebras(QQ).DualObjects().super_categories(), key=str)  
[Category of algebras over Rational Field,  
Category of duals of vector spaces over Rational Field]

As a shorthand, this category can be accessed with the dual() method:
sage: VectorSpaces(QQ).dual()  
Category of duals of vector spaces over Rational Field

Super
  alias of SuperModules

class TensorProducts (category, *args)
  Bases: TensorProductsCategory
  The category of modules constructed by tensor product of modules.

class ParentMethods
  Bases: object
  Implement operations on tensor products of modules.
  
  construction()
    Return the construction of self.

  EXAMPLES:
sage: A = algebras.Free(QQ, 2)  # needs sage.combinat sage.modules
sage: T = A.tensor(A)  # needs sage.combinat sage.modules
sage: T.construction()  # needs sage.combinat sage.modules
(The tensor functorial construction,
  (Free Algebra on 2 generators (None0, None1) over Rational Field,
   Free Algebra on 2 generators (None0, None1) over Rational Field))

**tensor_factors()**

Return the tensor factors of this tensor product.

**EXAMPLES:**

```sage
sage: # needs sage.modules
sage: F = CombinatorialFreeModule(ZZ, [1,2])
sage: F.rename("F")
sage: G = CombinatorialFreeModule(ZZ, [3,4])
sage: G.rename("G")
sage: T = tensor([F, G]); T
F # G
sage: T.tensor_factors()
(F, G)
```

**extra_super_categories()**

**EXAMPLES:**

```sage
sage: Modules(ZZ).TensorProducts().extra_super_categories()
[Category of modules over Integer Ring]
sage: Modules(ZZ).TensorProducts().super_categories()
[Category of modules over Integer Ring]
```

**WithBasis**

alias of **ModulesWithBasis**

**additional_structure()**

Return None.

Indeed, the category of modules defines no additional structure: a bimodule morphism between two modules is a module morphism.

See also:

Category.additionaI_structure()
4.119 Modules With Basis

AUTHORS:

- Jason Bandlow and Florent Hivert (2010): Triangular Morphisms
- Christian Stump (2010): github issue #9648 module_morphism’s to a wider class of codomains

class sage.categories.modules_with基礎.ModulesWithBasis(base_category):

Bases: CategoryWithAxiom_over_base_ring

The category of modules with a distinguished basis.

The elements are represented by expanding them in the distinguished basis. The morphisms are not required to respect the distinguished basis.

EXAMPLES:

sage: ModulesWithBasis(ZZ)
Category of modules with basis over Integer Ring
sage: ModulesWithBasis(ZZ).super_categories()
[Category of modules over Integer Ring]

If the base ring is actually a field, this constructs instead the category of vector spaces with basis:

sage: ModulesWithBasis(QQ)
Category of vector spaces with basis over Rational Field
sage: ModulesWithBasis(QQ).super_categories()
[Category of modules with basis over Rational Field, Category of vector spaces over Rational Field]

Let $X$ and $Y$ be two modules with basis. We can build $\text{Hom}(X,Y)$:

sage: X = CombinatorialFreeModule(QQ, [1,2]); X.rename("X")
#...

sage: Y = CombinatorialFreeModule(QQ, [3,4]); Y.rename("Y")
#...

sage: H = Hom(X, Y); H
#...

Set of Morphisms from $X$ to $Y$
in Category of finite dimensional vector spaces with basis over Rational Field

The simplest morphism is the zero map:
which we can apply to elements of $X$:

```python
sage: x = X.monomial(1) + 3 * X.monomial(2)  #...
   → needs sage.modules
sage: H.zero()(x)  #...
   → needs sage.modules
0
```

**EXAMPLES:**

We now construct a more interesting morphism by extending a function by linearity:

```python
sage: phi = H(on_basis=lambda i: Y.monomial(i + 2)); phi  #...
   → needs sage.modules
Generic morphism:
   From: X
   To:   Y
sage: phi(x)  #...
   → needs sage.modules
```

We can retrieve the function acting on indices of the basis:

```python
sage: f = phi.on_basis()  #...
   → needs sage.modules
sage: f(1), f(2)  #...
   → needs sage.modules
(B[3], B[4])
```

$\text{Hom}(X, Y)$ has a natural module structure (except for the zero, the operations are not yet implemented though). However since the dimension is not necessarily finite, it is not a module with basis; but see `FiniteDimensionalModulesWithBasis` and `GradedModulesWithBasis`:

```python
sage: H in ModulesWithBasis(QQ), H in Modules(QQ)  #...
   → needs sage.modules
(False, True)
```

Some more playing around with categories and higher order homsets:

```python
sage: H.category()  #...
   → needs sage.modules
Category of homsets of modules with basis over Rational Field
sage: Hom(H, H).category()  #...
   → needs sage.modules
Category of endsets of homsets of modules with basis over Rational Field
```

**Todo:** End$(X)$ is an algebra.

**Note:** This category currently requires an implementation of an element method `support`. Once [github issue](https://github.com/sagemath/sage/issues/4119)
#18066 is merged, an implementation of an `items` method will be required.

```python
class CartesianProducts(category, *args):
    Bases: CartesianProductsCategory

    The category of modules with basis constructed by Cartesian products of modules with basis.

class ParentMethods:
    Bases: object

    extra_super_categories()

    EXAMPLES:
    
    sage: ModulesWithBasis(QQ).CartesianProducts().extra_super_categories()
    [Category of vector spaces with basis over Rational Field]
    sage: ModulesWithBasis(QQ).CartesianProducts().super_categories()
    [Category of Cartesian products of modules with basis over Rational Field, 
     Category of vector spaces with basis over Rational Field, 
     Category of Cartesian products of vector spaces over Rational Field]

class DualObjects(category, *args):
    Bases: DualObjectsCategory

    extra_super_categories()

    EXAMPLES:
    
    sage: ModulesWithBasis(ZZ).DualObjects().extra_super_categories()
    [Category of modules over Integer Ring]
    sage: ModulesWithBasis(QQ).DualObjects().super_categories()
    [Category of duals of vector spaces over Rational Field, 
     Category of duals of modules with basis over Rational Field]

class ElementMethods:
    Bases: object

    coefficient(m)

    Return the coefficient of \( m \) in \( self \) and raise an error if \( m \) is not in the basis indexing set.

    INPUT:
    
    \* \( m \) – a basis index of the parent of \( self \)

    OUTPUT:

    The \( B[m] \)-coordinate of \( self \) with respect to the basis \( B \). Here, \( B \) denotes the given basis of the parent of \( self \).

    EXAMPLES:
    
    sage: # needs sage.combinat sage.modules
    sage: s = CombinatorialFreeModule(QQ, Partitions())
    sage: z = s([4]) - 2*s([2,1]) + s([1,1,1]) + s([1])
    sage: z.coefficient([4])
    1
    sage: z.coefficient([2,1])
    -2
    sage: z.coefficient(Partition([2,1]))
    -2
    sage: z.coefficient([1,2])
    
    (continues on next page)
```

(continues on next page)
Test that coefficient also works for those parents that do not have an element_class:

```python
sage: # needs sage.modules sage.rings.padics
sage: H = pAdicWeightSpace(3)
sage: F = CombinatorialFreeModule(QQ, H)
sage: hasattr(H, "element_class")
False
sage: h = H.an_element()
sage: (2*F.monomial(h)).coefficient(h)
2
```

coefficients (sort=True)
Return a list of the (non-zero) coefficients appearing on the basis elements in self (in an arbitrary order).

INPUT:
- sort – (default: True) to sort the coefficients based upon the default ordering of the indexing set

See also:
- dense_coefficient_list()

EXAMPLES:

```python
sage: # needs sage.modules
sage: F = CombinatorialFreeModule(QQ, ['a','b','c'])
sage: B = F.basis()
sage: f = B['a'] - 3*B['c']
sage: f.coefficients()
[1, -3]
```

```python
sage: # needs sage.combinat sage.modules
sage: z = s([4]) + s([2,1]) + s([1,1,1]) + s([1])
```

```python
sage: s = SymmetricFunctions(QQ).schur()
```

```python
sage: is_zero()
Return True if and only if self == 0.

EXAMPLES:
```
```
leading_coefficient (*args, **kwds)

Return the leading coefficient of self.

This is the coefficient of the term whose corresponding basis element is maximal. Note that this may not be the term which actually appears first when self is printed.

If the default term ordering is not what is desired, a comparison key, key(x, y), can be provided.

EXAMPLES:

```
sage: # needs sage.modules
sage: X = CombinatorialFreeModule(QQ, [1, 2, 3]); X.rename("X")
sage: x = 3*X.monomial(1) + 2*X.monomial(2) + X.monomial(3)
sage: x.leading_coefficient()
1
sage: def key(x): return -x
sage: x.leading_coefficient(key=key)
3
```

leading_item (*args, **kwds)

Return the pair \((k, c)\) where

\[ c \cdot (\text{the basis element indexed by } k) \]

is the leading term of self.

Here ‘leading term’ means that the corresponding basis element is maximal. Note that this may not be the term which actually appears first when self is printed.

If the default term ordering is not what is desired, a comparison function, key(x), can be provided.

EXAMPLES:

```
sage: s = SymmetricFunctions(QQ).schur()  # needs sage.combinat sage.modules
sage: f.leading_coefficient()  # needs sage.combinat sage.modules
-5
```
sage: # needs sage.modules
sage: X = CombinatorialFreeModule(QQ, [1, 2, 3]); X.rename("X")
sage: x = 3*X.monomial(1) + 2*X.monomial(2) + 4*X.monomial(3)
sage: x.leading_item()
(3, 4)
sage: def key(x): return -x
sage: x.leading_item(key=key)
(1, 3)

sage: s = SymmetricFunctions(QQ).schur()


sage: f.leading_monomial()

sage: s[3]

leading_monomial(*args, **kwds)

Return the leading monomial of self.

This is the monomial whose corresponding basis element is maximal. Note that this may not be the term which actually appears first when self is printed.

If the default term ordering is not what is desired, a comparison key, key(x), can be provided.

EXAMPLES:

sage: # needs sage.modules
sage: X = CombinatorialFreeModule(QQ, [1, 2, 3]); X.rename("X")
sage: x = 3*X.monomial(1) + 2*X.monomial(2) + 4*X.monomial(3)
sage: x.leading_support()

leading_support(*args, **kwds)

Return the maximal element of the support of self.

Note that this may not be the term which actually appears first when self is printed.

If the default ordering of the basis elements is not what is desired, a comparison key, key(x), can be provided.

EXAMPLES:

sage: # needs sage.modules
sage: X = CombinatorialFreeModule(QQ, [1, 2, 3])
sage: X.rename("X"); x = X.basis()
sage: x = 3*X.monomial(1) + 2*X.monomial(2) + 4*X.monomial(3)
sage: x.leading_support()
leading_term(*args, **kwds)

Return the leading term of self.

This is the term whose corresponding basis element is maximal. Note that this may not be the term which actually appears first when self is printed.

If the default term ordering is not what is desired, a comparison key, key(x), can be provided.

EXAMPLES:

```python
sage: # needs sage.modules
sage: X = CombinatorialFreeModule(QQ, [1, 2, 3]); X.rename("X")
sage: x = 3*X.monomial(1) + 2*X.monomial(2) + X.monomial(3)
sage: x.leading_term()
B[3]
sage: def key(x): return -x
sage: x.leading_term(key=key)
3*B[1]
```

length()

Return the number of basis elements whose coefficients in self are nonzero.

EXAMPLES:

```python
sage: # needs sage.modules
sage: F = CombinatorialFreeModule(QQ, ['a', 'b', 'c'])
sage: B = F.basis()
sage: f = B['a'] - 3*B['c']
sage: f.length()
2
```

```python
sage: s = SymmetricFunctions(QQ).schur()
sage: z = s([4]) + s([2,1]) + s([1,1,1]) + s([1])
sage: z.length()
```
map_coefficients \( f \)

Mapping a function on coefficients.

INPUT:

* \( f \) – an endofunction on the coefficient ring of the free module

Return a new element of \( \text{self.parent()} \) obtained by applying the function \( f \) to all of the coefficients of \( \text{self} \).

EXAMPLES:

\[
\begin{align*}
\text{sage: } & \text{# needs sage.modules} \\
\text{sage: } & F = \text{CombinatorialFreeModule}(\mathbb{Q}, \{\text{a}, \text{b}, \text{c}\}) \\
\text{sage: } & B = F.basis() \\
\text{sage: } & f = B[\text{a}] - 3*B[\text{c}] \\
\text{sage: } & f.map_coefficients(\lambda x: x + 5) \\
& 6*B[\text{a}] + 2*B[\text{c}] \\
\text{sage: } & f.map_coefficients(\lambda x: 0) \\
& 0 \\
\text{sage: } & \text{list}(f.map_coefficients(\lambda x: 0)) \\
& []
\end{align*}
\]

Killed coefficients are handled properly:

\[
\begin{align*}
\text{sage: } & s = \text{SymmetricFunctions}(\mathbb{Q}).schur() \\
\text{sage: } & a = s([2,1]) + 2*s([3,2]) \\
\text{sage: } & a.map_coefficients(\lambda x: x * 2) \\
& 2*s[2, 1] + 4*s[3, 2]
\end{align*}
\]

map_item \( f \)

Mapping a function on items.

INPUT:

* \( f \) – a function mapping pairs \((\text{index}, \text{coeff})\) to other such pairs

Return a new element of \( \text{self.parent()} \) obtained by applying the function \( f \) to all items \((\text{index}, \text{coeff})\) of \( \text{self} \).

EXAMPLES:

\[
\begin{align*}
\text{sage: } & B = \text{CombinatorialFreeModule}(\mathbb{Z}, \{-1, 0, 1\}) \\
\text{sage: } & x = B.an_element(); x \\
\text{sage: } & x.map_item(\lambda i, c: (-i, 2*c)) \\
\end{align*}
\]

\( f \) needs not be injective:
map_support(f)
Mapping a function on the support.

INPUT:

• f – an endofunction on the indices of the free module

Return a new element of self.parent() obtained by applying the function f to all of the objects indexing the basis elements.

EXAMPLES:

sage: B = CombinatorialFreeModule(ZZ, [-1, 0, 1])
˓→ needs sage.modules
sage: x = B.an_element(); x
˓→ needs sage.modules
2*B[-1] + 2*B[0] + 3*B[1]
sage: x.map_support(lambda i: -i)
˓→ needs sage.modules
3*B[-1] + 2*B[0] + 2*B[1]

f needs not be injective:

sage: x.map_support(lambda i: 1)
˓→ needs sage.modules
7*B[1]

map_support_skip_none(f)
Mapping a function on the support.

INPUT:

• f – an endofunction on the indices of the free module

Returns a new element of self.parent() obtained by applying the function f to all of the objects indexing the basis elements.

EXAMPLES:

sage: B = CombinatorialFreeModule(ZZ, [-1, 0, 1])
˓→ needs sage.modules
\[ sage: x = B.an_element(); x \]  
\[ \text{# needs sage.modules} \]  
\[ 2*B[-1] + 2*B[0] + 3*B[1] \]  
\[ sage: x.map_support_skip_none(\text{\texttt{lambda i: -i if i else None}}) \]  
\[ \text{# needs sage.modules} \]  
\[ 3*B[-1] + 2*B[1] \]  

\[ f \text{ needs not be injective:} \]  
\[ sage: x.map_support_skip_none(\text{\texttt{lambda i: 1 if i else None}}) \]  
\[ \text{# needs sage.modules} \]  
\[ 5*B[1] \]  

\textbf{\texttt{monomial\_coefficients}} (\textit{copy=True})

Return a dictionary whose keys are indices of basis elements in the support of \texttt{self} and whose values are the corresponding coefficients.

\textit{INPUT:}

- \texttt{copy} – (default: \texttt{True}) if \texttt{self} is internally represented by a dictionary \texttt{d}, then make a copy of \texttt{d}; if \texttt{False}, then this can cause undesired behavior by mutating \texttt{d}

\textit{EXAMPLES:}

\texttt{sage: \text{"# needs sage.modules}\}}\texttt{sage: F = CombinatorialFreeModule(QQ, ['a','b','c'])}
\texttt{sage: B = F.basis()}
\texttt{sage: f = B['a'] + 3*B['c']}
\texttt{sage: d = f.monomial\_coefficients()}
\texttt{sage: d['a']}
\texttt{1}
\texttt{sage: d['c']}
\texttt{3}

\textbf{\texttt{monomials}}()

Return a list of the monomials of \texttt{self} (in an arbitrary order).

The monomials of an element \( a \) are defined to be the basis elements whose corresponding coefficients of \( a \) are non-zero.

\textit{EXAMPLES:}

\texttt{sage: \text{"# needs sage.modules}\}}\texttt{sage: F = CombinatorialFreeModule(QQ, ['a','b','c'])}
\texttt{sage: B = F.basis()}
\texttt{sage: f = B['a'] + 2*B['c']}
\texttt{sage: f.monomials()}
\texttt{[B['a'], B['c']]}\texttt{\text{"# needs sage.modules\}}
\texttt{sage: (F.zero()).monomials()}
\texttt{[]}\texttt{\text{"# needs sage.modules\}}

\textbf{\texttt{support}}()

Return an iterable of the objects indexing the basis of \texttt{self.parent()} whose corresponding coefficients of \texttt{self} are non-zero.

This method returns these objects in an arbitrary order.

\textit{EXAMPLES:}
sage: # needs sage.modules
sage: F = CombinatorialFreeModule(QQ, ['a', 'b', 'c'])
sage: B = F.basis()
sage: f = B['a'] - 3*B['c']
sage: sorted(f.support())
['a', 'c']
sage: s = SymmetricFunctions(QQ).schur()       #...
sage: z = s([4]) + s([2,1]) + s([1,1,1]) + s([1])
sage: sorted(z.support())
[[1], [1, 1, 1], [2, 1], [4]]

support_of_term()
Return the support of self, where self is a monomial (possibly with coefficient).

EXAMPLES:

sage: X = CombinatorialFreeModule(QQ, [1,2,3,4]); X.rename("X")       #...
sage: X.monomial(2).support_of_term()       #...
sage: X.term(3, 2).support_of_term()       #...

An exception is raised if self has more than one term:

sage: (X.monomial(2) + X.monomial(3)).support_of_term()       #...
Traceback (most recent call last):
... 

tensor(*elements)
Return the tensor product of its arguments, as an element of the tensor product of the parents of those elements.

EXAMPLES:

sage: C = AlgebrasWithBasis(QQ)
sage: A = C.example()       #...
sage: a, b, c = A.algebra_generators()       #...
sage: a.tensor(b, c)       #...

FIXME: is this a policy that we want to enforce on all parents?
terms()
Return a list of the (non-zero) terms of self (in an arbitrary order).
See also:

monomials()

EXAMPLES:

```
sage: # needs sage.modules
sage: F = CombinatorialFreeModule(QQ, ['a', 'b', 'c'])
sage: B = F.basis()
sage: f = B['a'] + 2*B['c']
sage: f.terms()
[B['a'], 2*B['c']]
```

```
trailing_coefficient(*args, **kwds)

Return the trailing coefficient of self.

This is the coefficient of the monomial whose corresponding basis element is minimal. Note that this may not be the term which actually appears last when `self` is printed.

If the default term ordering is not what is desired, a comparison key `key(x)`, can be provided.

EXAMPLES:

```
sage: # needs sage.modules
sage: X = CombinatorialFreeModule(QQ, [1, 2, 3]); X.rename("X")
sage: x = 3*X.monomial(1) + 2*X.monomial(2) + X.monomial(3)
sage: x.trailing_coefficient()
3
sage: def key(x):
    return -x
sage: x.trailing_coefficient(key=key)
1
```

```
sage: s = SymmetricFunctions(QQ).schur()
# needs sage.combinat sage.modules
# needs sage.combinat sage.modules
sage: f.trailing_coefficient()
2
```
```
trailing_item(*args, **kwds)

Return the pair `(c, k)` where `c*self.parent().monomial(k)` is the trailing term of `self`.

This is the monomial whose corresponding basis element is minimal. Note that this may not be the term which actually appears last when `self` is printed.

If the default term ordering is not what is desired, a comparison key `key(x)`, can be provided.

EXAMPLES:

```
sage: # needs sage.modules
sage: X = CombinatorialFreeModule(QQ, [1, 2, 3]); X.rename("X")
sage: x = 3*X.monomial(1) + 2*X.monomial(2) + X.monomial(3)
sage: x.trailing_item()
(1, 3)
sage: def key(x):
    return -x
sage: x.trailing_item(key=key)
(3, 1)
```

```
sage: s = SymmetricFunctions(QQ).schur()
# needs sage.combinat sage.modules
```
```
trailing_monomial(*args, **kwds)

Return the trailing monomial of self.

This is the monomial whose corresponding basis element is minimal. Note that this may not be the term which actually appears last when self is printed.

If the default term ordering is not what is desired, a comparison key key(x), can be provided.

EXAMPLES:

sage: # needs sage.modules
sage: X = CombinatorialFreeModule(QQ, [1, 2, 3]); X.rename("X")
sage: x = 3*X.monomial(1) + 2*X.monomial(2) + X.monomial(3)
sage: x.trailing_monomial()
B[1]
sage: def key(x): return -x
sage: x.trailing_monomial(key=key)
B[3]

trailing_support(*args, **kwds)

Return the minimal element of the support of self. Note that this may not be the term which actually appears last when self is printed.

If the default ordering of the basis elements is not what is desired, a comparison key, key(x), can be provided.

EXAMPLES:

sage: X = CombinatorialFreeModule(QQ, [1, 2, 3]); X.rename("X")
needs sage.modules
sage: x = 3*X.monomial(1) + 2*X.monomial(2) + 4*X.monomial(3)
needs sage.modules
sage: x.trailing_support()
needs sage.modules
1
sage: def key(x): return -x
sage: x.trailing_support(key=key)
needs sage.modules
3
sage: s = SymmetricFunctions(QQ).schur()  # needs sage.combinat sage.modules
s[1]
trailing_term(*args, **kwds)

Return the trailing term of self.

This is the term whose corresponding basis element is minimal. Note that this may not be the term which actually appears last when self is printed.

If the default term ordering is not what is desired, a comparison key key(x), can be provided.

EXAMPLES:

```
sage: # needs sage.modules
sage: X = CombinatorialFreeModule(QQ, [1, 2, 3]); X.rename("X")
sage: x = 3*X.monomial(1) + 2*X.monomial(2) + X.monomial(3)
sage: x.trailing_term()
3*B[1]
sage: def key(x):
    return -x
sage: x.trailing_term(key=key)
B[3]
sage: s = SymmetricFunctions(QQ).schur() #...
sage: f.trailing_term() #...
sage: 2*s[1]
```

Filtered

alias of FilteredModulesWithBasis

FiniteDimensional

alias of FiniteDimensionalModulesWithBasis

Graded

alias of GradedModulesWithBasis

class Homsets(category, *args)

Bases: HomsetsCategory

class ParentMethods

Bases: object

class MorphismMethods

Bases: object

on_basis()

Return the action of this morphism on basis elements.

OUTPUT:
  • a function from the indices of the basis of the domain to the codomain

EXAMPLES:
```python
sage: # needs sage.modules
sage: X = CombinatorialFreeModule(QQ, [1,2,3]); X.rename("X")
```
```python
sage: Y = CombinatorialFreeModule(QQ, [1,2,3,4]); Y.rename("Y")
```
```python
sage: H = Hom(X, Y)
```
```python
sage: x = X.basis()
```
```python
sage: f = H(lambda x: Y.zero()).on_basis()
```
```python
sage: f(2)
0
```
```python
sage: f = lambda i: Y.monomial(i) + 2*Y.monomial(i+1)
```
```python
sage: g = H(on_basis=f).on_basis()
```
```python
sage: g(2)
```
```python
sage: g == f
True
```

```python
class ParentMethods

    Bases: object

    basis()

        Return the basis of self.

    EXAMPLES:

sage: F = CombinatorialFreeModule(QQ, ['a', 'b', 'c'])
```
```python
sage: F.basis()

Finite family {'a': B['a'], 'b': B['b'], 'c': B['c']}
```
```python
sage: QS3 = SymmetricGroupAlgebra(QQ, 3)
```
```python
sage: list(QS3.basis())

[[1, 2, 3], [1, 3, 2], [2, 1, 3], [2, 3, 1], [3, 1, 2], [3, 2, 1]]
```
```python
cardinality()

    Return the cardinality of self.

    EXAMPLES:

sage: # needs sage.groups sage.modules
sage: S = SymmetricGroupAlgebra(QQ, 4)
```
```python
sage: S.cardinality()
+Infinity
```
```python
sage: S = SymmetricGroupAlgebra(GF(2), 4)
```
```python
sage: S.cardinality()
16777216
```
```python
sage: S.cardinality().factor()
2^24
```
```python
sage: # needs sage.modules
sage: E.<x,y> = ExteriorAlgebra(QQ)
```
```python
sage: E.<x,y> = ExteriorAlgebra(GF(3))
```
```python
sage: E.cardinality()
81
```
sage: s = SymmetricFunctions(GF(2)).s()  # needs sage.combinat sage.modules
sage: s.cardinality()  # needs sage.combinat sage.modules
+Infinity

sage: M = CombinatorialFreeModule(QQ, [])
sage: M.dimension()
0
sage: M.cardinality()
1

dimension()
Return the dimension of self.

EXAMPLES:
sage: A.<x,y> = algebras.DifferentialWeyl(QQ)  # needs sage.modules
sage: A.dimension()  # needs sage.modules
+Infinity

echelon_form(elements, row_reduced=False, order=None)
Return a basis in echelon form of the subspace spanned by a finite set of elements.

INPUT:
• elements – a list or finite iterable of elements of self
• row_reduced – (default: False) whether to compute the basis for the row reduced echelon form
• order – (optional) either something that can be converted into a tuple or a key function

OUTPUT:
A list of elements of self whose expressions as vectors form a matrix in echelon form. If base_ring is specified, then the calculation is achieved in this base ring.

EXAMPLES:
sage: R.<x,y> = QQ[]
sage: C = CombinatorialFreeModule(R, ZZ, prefix='z')  # needs sage.modules
sage: z = C.basis()  # needs sage.modules
sage: C.echelon_form([z[0] - z[1], 2*z[1] - 2*z[2], z[0] - z[2]])  # needs sage.libs.singular sage.modules
[z[0] - z[2], z[1] - z[2]]

intersection(other)
Return the intersection of self with other.

EXAMPLES:
sage: X = CombinatorialFreeModule(QQ, range(4)); x = X.basis()
sage: U = X.submodule([x[0]-x[1], x[1]-x[2], x[2]-x[3]])
sage: F = CombinatorialFreeModule(QQ, ['a','b','c','d'])
sage: G = F.submodule([F.basis()['a']])
sage: X.intersection(X)  is  X
True
sage: X.intersection(U)  is  U
True
sage: X.intersection(F)
Traceback (most recent call last):
...  TypeError: other must be a submodule
sage: X.intersection(G)
Traceback (most recent call last):
...  ArithmeticError: this module must be the ambient

is_finite()

Return whether self is finite.

This is true if and only if self.basis().keys() and self.base_ring() are both finite.

EXAMPLES:

sage: GroupAlgebra(SymmetricGroup(2), IntegerModRing(10)).is_finite()  # needs sage.combinat  sage.groups  sage.modules
True
sage: GroupAlgebra(SymmetricGroup(2)).is_finite()  # needs sage.combinat  sage.groups  sage.modules
False
sage: GroupAlgebra(AbelianGroup(1), IntegerModRing(10)).is_finite()  # needs sage.groups  sage.modules
False

module_morphism(on_basis=None, matrix=None, function=None, diagonal=None, triangular=None, unitriangular=False, **keywords)

Construct a module morphism from self to codomain.

Let self be a module X with a basis indexed by I. This constructs a morphism \( f : X \to Y \) by linearity from a map \( I \to Y \) which is to be its restriction to the basis \( (x_i)_{i \in I} \) of \( X \). Some variants are possible too.

INPUT:

- **self** – a parent \( X \) in ModulesWithBasis(R) with basis \( x = (x_i)_{i \in I} \).

Exactly one of the four following options must be specified in order to define the morphism:
- **on_basis** – a function \( f \) from \( I \) to \( Y \)
- **diagonal** – a function \( d \) from \( I \) to \( R \)
- **function** – a function \( f \) from \( X \) to \( Y \)
- **matrix** – a matrix of size \( \dim Y \times \dim X \) (if the keyword side is set to 'left') or \( \dim Y \times \dim X \) (if this keyword is 'right')

Further options include:
- **codomain** – the codomain \( Y \) of the morphism (default: \( f.\text{codomain()} \) if it's defined; otherwise it must be specified)
- **category** – a category or None (default: None)
- **zero** – the zero of the codomain (default: \( \text{codomain.zero()} \)); can be used (with care) to define affine maps. Only meaningful with on_basis.
- **position** – a non-negative integer specifying which positional argument is used as the input of the function \( f \) (default: 0); this is currently only used with on_basis.
- **triangular** – (default: None) "upper" or "lower" or None:
  - "upper" - if the leading_support() of the image of the basis vector \( x_i \) is \( i \), or
- "lower" - if the `trailing_support()` of the image of the basis vector $x_i$ is $i$.
- `unitriangular` - (default: False) a boolean. Only meaningful for a triangular morphism. As a shorthand, one may use `unitriangular="lower"` for `triangular="lower", unitriangular=True`.
- `side` - “left” or “right” (default: “left”) Only meaningful for a morphism built from a matrix.

**EXAMPLES:**

With the `on_basis` option, this returns a function $g$ obtained by extending $f$ by linearity on the position-th positional argument. For example, for `position == 1` and a ternary function $f$, one has:

$$g(a, \sum \lambda_i x_i, c) = \sum \lambda_i f(a, i, c).$$

```python
sage: # needs sage.modules
sage: X = CombinatorialFreeModule(QQ, [1,2,3]); X.rename("X")
sage: Y = CombinatorialFreeModule(QQ, [1,2,3,4]); Y.rename("Y")
sage: def f(i):
    ....:     return Y.monomial(i) + 2*Y.monomial(i+1)
    sage: phi = X.module_morphism(f, codomain=Y)
    sage: phi(x[1] + x[3])
```

By default, the category is the first of `Modules(R).WithBasis().FiniteDimensional()`, `Modules(R).WithBasis()`, `Modules(R)`, and `CommutativeAdditiveMonoids()` that contains both the domain and the codomain:

```python
sage: phi.category_for()  # needs sage.modules
Category of finite dimensional vector spaces with basis over Rational Field
```

With the `zero` argument, one can define affine morphisms:

```python
sage: def f(i):
    ....:     return Y.monomial(i) + 2*Y.monomial(i+1)
    sage: phi = X.module_morphism(f, codomain=Y, zero=10*y[1])  # needs sage.modules
    sage: phi(x[1] + x[3])  # needs sage.modules
```

In this special case, the default category is `Sets()`:

```python
sage: phi.category_for()  # needs sage.modules
Category of sets
```

One can construct morphisms with the base ring as codomain:
sage: # needs sage.modules
sage: X = CombinatorialFreeModule(ZZ, [1, -1])
sage: phi = X.module_morphism(on_basis=lambda i: i, codomain=ZZ)
sage: phi(2 * X.monomial(1) + 3 * X.monomial(-1))
-1
sage: phi.category_for()
Category of commutative additive semigroups
sage: phi.category_for() # not implemented
Category of modules over Integer Ring

Or more generally any ring admitting a coercion map from the base ring:

sage: # needs sage.modules
sage: phi = X.module_morphism(on_basis=lambda i: i, codomain=RR)
sage: phi(2 * X.monomial(1) + 3 * X.monomial(-1))
-1.00000000000000
sage: phi.category_for()
Category of commutative additive semigroups
sage: phi.category_for() # not implemented
Category of modules over Integer Ring

sage: phi = X.module_morphism(on_basis=lambda i: i, codomain=Zmod(4))
# needs sage.modules
sage: phi(2 * X.monomial(1) + 3 * X.monomial(-1))
3
sage: phi.category_for()
Category of commutative additive semigroups
sage: phi.category_for() # not implemented
Traceback (most recent call last):
...
ValueError: codomain(=Ring of integers modulo 4) should be a module over the base ring of the domain(=Y)

On can also define module morphisms between free modules over different base rings; here we implement the natural map from $X = \mathbb{R}^2$ to $Y = \mathbb{C}$:

sage: # needs sage.modules
sage: X = CombinatorialFreeModule(RR, ['x', 'y'])
sage: Y = CombinatorialFreeModule(CC, ['z'])
sage: x = X.monomial('x')
sage: y = X.monomial('y')
sage: z = Y.monomial('z')
sage: def on_basis(a):
....:     if a == 'x':
....:         return CC(1) * z
....:     elif a == 'y':
....:         return CC(I) * z
sage: phi = X.module_morphism(on_basis=on_basis, codomain=Y)
sage: v = 3 * x + 2 * y; v
3.00000000000000*B['x'] + 2.00000000000000*B['y']
sage: phi(v) # needs sage.symbolic
(3.00000000000000+2.00000000000000*I)*B['z']
sage: phi.category_for()
Category of commutative additive semigroups
sage: phi.category_for() # not implemented

(continues on next page)
Category of vector spaces over Real Field with 53 bits of precision

```python
sage: # needs sage.modules
sage: Y = CombinatorialFreeModule(CC['q'], ['z'])
sage: z = Y.monomial('z')
sage: phi = X.module_morphism(on_basis=on_basis, codomain=Y)
sage: phi(v)  # needs sage.symbolic
(3.00000000000000+2.00000000000000*I)*B['z']
```

Of course, there should be a coercion between the respective base rings of the domain and the codomain for this to be meaningful:

```python
sage: Y = CombinatorialFreeModule(QQ, ['z'])  # needs sage.modules
sage: phi = X.module_morphism(on_basis=on_basis, codomain=Y)  # needs sage.modules
Traceback (most recent call last):
...  
ValueError: codomain(=Free module generated by {'z'} over Rational Field) should be a module over the base ring of the domain(=Free module generated by {'x', 'y'} over Real Field with 53 bits of precision)
```

```python
sage: Y = CombinatorialFreeModule(RR['q'], ['z'])  # needs sage.modules
sage: phi = Y.module_morphism(on_basis=on_basis, codomain=X)  # needs sage.modules
Traceback (most recent call last):
...  
ValueError: codomain(=Free module generated by {'x', 'y'} over Real Field with 53 bits of precision) should be a module over the base ring of the domain(=Free module generated by {'z'} over Univariate Polynomial Ring in q over Real Field with 53 bits of precision)
```

With the `diagonal=d` argument, this constructs the module morphism $g$ such that

\[ g(x_i) = d(i)y_i. \]

This assumes that the respective bases $x$ and $y$ of $X$ and $Y$ have the same index set $I$:

```python
sage: Y = CombinatorialFreeModule(RR['q'], ['z'])  # needs sage.modules
sage: phi = Y.module_morphism(diagonal=factorial, codomain=X)  # needs sage.modules
sage: x = X.basis()
sage: phi(x[1]), phi(x[2]), phi(x[3])
(B[1], 2*B[2], 6*B[3])
```

See also: `sage.modules.with_basis.morphism.DiagonalModuleMorphism`.

With the `matrix=m` argument, this constructs the module morphism whose matrix in the distinguished basis of $X$ and $Y$ is $m$:

```python
sage: X = CombinatorialFreeModule(ZZ, [1,2,3]); X.rename("X")
sage: from sage.arith.misc import factorial
sage: phi = X.module_morphism(diagonal=factorial, codomain=X)
sage: x = X.basis()
sage: phi(x[1]), phi(x[2]), phi(x[3])
(B[1], 2*B[2], 6*B[3])
```

(continues on next page)
sage: y = Y.basis()
sage: m = matrix([[0,1,2], [3,5,0]])
sage: phi = X.module_morphism(matrix=m, codomain=Y)
sage: phi(x[1])
3*B[4]
sage: phi(x[2])

See also: sage.modules.with_basis.morphism.ModuleMorphismFromMatrix.

With triangular="upper", the constructed module morphism is assumed to be upper triangular; that is its matrix in the distinguished basis of $X$ and $Y$ would be upper triangular with invertible elements on its diagonal. This is used to compute preimages and to invert the morphism:

sage: # needs sage.modules
sage: I = list(range(1, 200))
sage: X = CombinatorialFreeModule(QQ, I); X.rename("X"); x = X.basis()
...: Y = CombinatorialFreeModule(QQ, I); Y.rename("Y"); y = Y.basis()
...: f = Y.sum_of_monomials * divisors
...: phi = X.module_morphism(f, triangular="upper", codomain=Y)
...: phi(x[2])
...: phi(x[6])
...: phi(x[30])
...: phi.preimage(y[2])
...: phi.preimage(y[6])
...: phi.preimage(y[30])
...: (phi^-1)(y[30])

Since github issue #8678, one can also define a triangular morphism from a function:

sage: # needs sage.modules
sage: X = CombinatorialFreeModule(QQ, [0,1,2,3,4]); x = X.basis()
...: from sage.modules.with_basis.morphism import...
...: TriangularModuleMorphismFromFunction
...: def f(x): return x + X.term(0, sum(x.coefficients()))
...: phi = X.module_morphism(function=f, codomain=X,
...: triangular="upper")
...: phi(x[2] + 3*x[4])
...: phi.preimage(_)

For details and further optional arguments, see sage.modules.with_basis.morphism.TriangularModuleMorphism.

Warning: As a temporary measure, until multivariate morphisms are implemented, the constructed morphism is in $\text{Hom}(\text{codomain}, \text{domain}, \text{category})$. This is only correct for unary functions.
Todo:
• Should codomain be `self` by default in the diagonal, triangular, and matrix cases?
• Support for diagonal morphisms between modules not sharing the same index set

`monomial(i)`
Return the basis element indexed by `i`.

**INPUT:**
• `i` – an element of the index set

**EXAMPLES:**
```
sage: F = CombinatorialFreeModule(QQ, ['a', 'b', 'c'])  # needs sage.modules
sage: F.monomial('a')  # needs sage.modules
B['a']
```

F.monomial is in fact (almost) a map:
```
sage: F.monomial  # needs sage.modules
Term map from {'a', 'b', 'c'} to Free module generated by {'a', 'b', 'c'} over Rational Field
```

`monomial_or_zero_if_none(i)`

**EXAMPLES:**
```
sage: F = CombinatorialFreeModule(QQ, ['a', 'b', 'c'])  # needs sage.modules
sage: F.monomial_or_zero_if_none('a')  # needs sage.modules
B['a']
sage: F.monomial_or_zero_if_none(None)  # needs sage.modules
0
```

`quotient_module(submodule, check=True, already_echelonized=False, category=None)`
Construct the quotient module `self / submodule`.

**INPUT:**
• `submodule` – a submodule with basis of `self`, or something that can be turned into one via `self.submodule(submodule)`
• `check`, `already_echelonized` – passed down to `ModulesWithBasis.ParentMethods.submodule()`

**Warning:** At this point, this only supports quotients by free submodules admitting a basis in unitriangular echelon form. In this case, the quotient is also a free module, with a basis consisting of the retract of a subset of the basis of `self`.

**EXAMPLES:**
```
sage: # needs sage.modules
sage: X = CombinatorialFreeModule(QQ, range(3), prefix="x")
sage: x = X.basis()
```
Example:

```
sage: Y = X.quotient_module([x[0] - x[1], x[1] - x[2]],
...: already_echelonized=True)
sage: Y.print_options(prefix='y'); Y
Free module generated by {2} over Rational Field
sage: y = Y.basis()
y[2]
sage: y[2].lift()
x[2]
sage: Y.retract(x[0] + 2*x[1])
3*y[2]
```

```
sage: # needs sage.modules
sage: R.<a,b> = QQ[]
sage: C = CombinatorialFreeModule(R, range(3), prefix=x)
sage: x = C.basis()
sage: gens = [x[0] - x[1], 2*x[1] - 2*x[2], x[0] - x[2]]
sage: Y = C.quotient_module(gens)
```

See also:

- Modules.WithBasis.ParentMethods.submodule()
- Rings.ParentMethods.quotient()
- sage.modules.with_basis.subquotient.QuotientModuleWithBasis

### random_element (n=2)

Return a 'random' element of self.

**INPUT:**

- `n` - integer (default: 2); number of summands

**ALGORITHM:**

Return a sum of \( n \) terms, each of which is formed by multiplying a random element of the base ring by a random element of the group.

**EXAMPLES:**

```
sage: x = DihedralGroup(6).algebra(QQ).random_element() # needs sage.groups sage.modules
sage: x.parent() is DihedralGroup(6).algebra(QQ)
True
```

Note, this result can depend on the PRNG state in libgap in a way that depends on which packages are loaded, so we must re-seed GAP to ensure a consistent result for this example:

```
sage: libgap.set_seed(0) # needs sage.libs.gap
0
sage: m = SU(2, 13).algebra(QQ).random_element() # needs sage.groups sage.libs.pari sage.modules
sage: m.parent() is SU(2, 13).algebra(QQ)
True
sage: p = CombinatorialFreeModule(ZZ, Partitions(4)).random_element() # needs sage.combinat sage.modules
sage: p.parent() is CombinatorialFreeModule(ZZ, Partitions(4))
```

(continues on next page)
needs sage.combinat sage.modules
True

submodule (gens, check=True, already_echelonized=False, unitriangular=False, support_order=None, category=None, *args, **opts)

The submodule spanned by a finite set of elements.

INPUT:
- gens – a list or family of elements of self
- check – (default: True) whether to verify that the elements of gens are in self
- already_echelonized – (default: False) whether the elements of gens are already in (not necessarily reduced) echelon form
- unitriangular – (default: False) whether the lift morphism is unitriangular
- support_order – (optional) either something that can be converted into a tuple or a key function
- category – (optional) the category of the submodule

If already_echelonized is False, then the generators are put in reduced echelon form using echelonize(), and reindexed by 0, 1, ...

Warning: At this point, this method only works for finite dimensional submodules and if matrices can be echelonized over the base ring.

If in addition unitriangular is True, then the generators are made such that the coefficients of the pivots are 1, so that lifting map is unitriangular.

The basis of the submodule uses the same index set as the generators, and the lifting map sends \( y_i \) to \( \text{gens}[i] \).

See also:
- ModulesWithBasis.FiniteDimensional.ParentMethods.quotient_module()
- sage.modules.with_basis.subquotient.SubmoduleWithBasis

EXAMPLES:

We construct a submodule of the free \( \mathbb{Q} \)-module generated by \( x_0, x_1, x_2 \). The submodule is spanned by \( y_0 = x_0 - x_1 \) and \( y_1 = x_1 - x_2 \), and its basis elements are indexed by 0 and 1:

\[
\begin{align*}
\text{sage: } & \quad \# \text{ needs sage.modules} \\
\text{sage: } & \quad X = \text{CombinatorialialFreeModule}(\mathbb{Q}, \text{range}(3), \text{prefix}="x") \\
\text{sage: } & \quad x = X.basis() \\
\text{sage: } & \quad \text{gens} = [x[0] - x[1], x[1] - x[2]]; \text{gens} \\
& \quad [x[0] - x[1], x[1] - x[2]] \\
\text{sage: } & \quad Y = X.submodule(\text{gens}, \text{already_echelonized}=True) \\
\text{sage: } & \quad Y.print_options(\text{prefix}='y'); Y \\
\text{sage: } & \quad \text{Free module generated by \{0, 1\} over Rational Field} \\
\text{sage: } & \quad y = Y.basis() \\
\text{sage: } & \quad y[0] \\
\text{sage: } & \quad y[1] \\
\text{sage: } & \quad y[1].lift() \\
& \quad x[1] - x[2] \\
\text{sage: } & \quad Y.retract(x[0] - x[2]) \\
& \quad y[0] + y[1] \\
\text{sage: } & \quad Y.retract(x[0]) \\
\end{align*}
\]
By using a family to specify a basis of the submodule, we obtain a submodule whose index set coincides with the index set of the family:

```
sage: # needs sage.modules
sage: X = CombinatorialFreeModule(QQ, range(3), prefix="x")
sage: x = X.basis()
sage: gens = Family({1: x[0] - x[1], 3: x[1] - x[2]}); gens
Finite family {1: x[0] - x[1], 3: x[1] - x[2]}
sage: Y = X.submodule(gens, already_echelonized=True)
sage: Y.print_options(prefix='y'); Y
Free module generated by {1, 3} over Rational Field
sage: y = Y.basis()
sage: y[1]
y[1]
sage: y[1].lift()
x[0] - x[1]
sage: y[3].lift()
x[1] - x[2]
sage: Y.retract(x[0] - x[2])
y[1] + y[3]
sage: Y.retract(x[0])
Traceback (most recent call last):
... ValueError: x[0] is not in the image
```

It is not necessary that the generators of the submodule form a basis (an explicit basis will be computed):

```
sage: # needs sage.modules
sage: X = CombinatorialFreeModule(QQ, range(3), prefix="x")
sage: x = X.basis()
sage: gens = [x[0] - x[1], 2*x[1] - 2*x[2], x[0] - x[2]]; gens
[x[0] - x[1], 2*x[1] - 2*x[2], x[0] - x[2]]
sage: Y = X.submodule(gens, already_echelonized=False)
sage: Y.print_options(prefix='y')
sage: Y
Free module generated by {0, 1} over Rational Field
sage: [b.lift() for b in Y.basis()]
x[0] - x[2], x[1] - x[2]
```

We now implement by hand the center of the algebra of the symmetric group $S_3$:

```
sage: # needs sage.combinat sage.groups sage.modules
sage: S3 = SymmetricGroup(3)
sage: S3A = S3.algebra(QQ)
sage: basis = S3A.annihilator_basis(S3A.algebra_generators(),
...: S3A.bracket)
sage: basis
(((), (1,2,3) + (1,3,2), (2,3) + (1,2) + (1,3))
sage: center = S3A.submodule(basis,
...: category=AlgebrasWithBasis(QQ).Subobjects(),
...: already_echelonized=True)
sage: center
Free module generated by {0, 1, 2} over Rational Field
```

(continues on next page)
Of course, this center is best constructed using:

```
sage: center = S3A.center()  # needs sage.combinat sage.groups sage.modules
```

We can also automatically construct a basis such that the lift morphism is (lower) unitriangular:

```
sage: R.<a,b> = QQ[]
sage: C = CombinatorialFreeModule(R, range(3), prefix='x')
sage: x = C.basis()
sage: gens = [x[0] - x[1], 2*x[1] - 2*x[2], x[0] - x[2]]
sage: Y = C.submodule(gens, unitriangular=True)
sage: Y.lift.matrix()  
[ 1 0]
[ 0 1]
[-1 -1]
```

We now construct a (finite-dimensional) submodule of an infinite dimensional free module:

```
sage: C = CombinatorialFreeModule(QQ, ZZ, prefix='z')
sage: z = C.basis()
sage: gens = [z[0] - z[1], 2*z[1] - 2*z[2], z[0] - z[2]]
sage: Y = C.submodule(gens)
sage: [Y.lift(b) for b in Y.basis()]  
[z[0] - z[2], z[1] - z[2]]
```

**sum_of_monomials**

Return the sum of the basis elements with indices in `indices`.

**INPUT:**

- `indices` -- a list (or iterable) of indices of basis elements

**EXAMPLES:**

```
sage: F = CombinatorialFreeModule(QQ, ['a', 'b', 'c'])  # needs sage.modules
sage: F.sum_of_monomials(['a', 'b'])  # needs sage.modules
B['a'] + B['b']
sage: F.sum_of_monomials(['a', 'b', 'a'])  # needs sage.modules
2*B['a'] + B['b']
```
F.\texttt{sum\_of\_monomials} is in fact (almost) a map:

\begin{verbatim}
\begin{Verbatim}
sage: F.sum_of_monomials
\end{Verbatim}
\end{verbatim}

\texttt{sum\_of\_terms(terms)}

Construct a sum of terms of \texttt{self}.

\textbf{INPUT:}

\begin{itemize}
  \item \texttt{terms} – a list (or iterable) of pairs (index, coeff)
\end{itemize}

\textbf{OUTPUT:}

Sum of coeff \* B[index] over all (index, coeff) in \texttt{terms}, where B is the basis of \texttt{self}.

\textbf{EXAMPLES:}

\begin{verbatim}
\begin{Verbatim}
sage: m = matrix([[0,1], [1,1]])
\end{Verbatim}
\end{verbatim}

\begin{verbatim}
\begin{Verbatim}
sage: J.<a,b,c> = JordanAlgebra(m)
\end{Verbatim}
\end{verbatim}

\begin{verbatim}
\begin{Verbatim}
sage: J.sum_of_terms([(0, 2), (2, -3)])
\end{Verbatim}
\end{verbatim}

\begin{verbatim}
\begin{Verbatim}
sage: 2 + (0, -3)
\end{Verbatim}
\end{verbatim}

\texttt{tensor(*parents, **kwargs)}

Return the tensor product of the parents.

\textbf{EXAMPLES:}

\begin{verbatim}
\begin{Verbatim}
sage: C = AlgebrasWithBasis(QQ)
sage: A = C.example(); A.rename("A")
\end{Verbatim}
\end{verbatim}

\begin{verbatim}
\begin{Verbatim}
sage: A.tensor(A, A)
\end{Verbatim}
\end{verbatim}

\begin{verbatim}
\begin{Verbatim}
sage: A.rename(None)
\end{Verbatim}
\end{verbatim}

\texttt{term(index, coeff=None)}

Construct a term in \texttt{self}.

\textbf{INPUT:}

\begin{itemize}
  \item \texttt{index} – the index of a basis element
  \item \texttt{coeff} – an element of the coefficient ring (default: one)
\end{itemize}

\textbf{OUTPUT:}

coeff \* B[index], where B is the basis of \texttt{self}.

\textbf{EXAMPLES:}

\begin{verbatim}
\begin{Verbatim}
sage: m = matrix([[0,1], [1,1]])
\end{Verbatim}
\end{verbatim}

\begin{verbatim}
\begin{Verbatim}
sage: J.<a,b,c> = JordanAlgebra(m)
\end{Verbatim}
\end{verbatim}

\begin{verbatim}
\begin{Verbatim}
sage: J.term(1, -2)
\end{Verbatim}
\end{verbatim}

\begin{verbatim}
\begin{Verbatim}
0 + (-2, 0)
\end{Verbatim}
\end{verbatim}

Design: should this do coercion on the coefficient ring?
Super
alias of SuperModulesWithBasis

class TensorProducts (category, *args)
Bases: TensorProductsCategory

The category of modules with basis constructed by tensor product of modules with basis.

class ElementMethods
Bases: object

Implements operations on elements of tensor products of modules with basis.

apply_multilinear_morphism (f, codomain=None)

Return the result of applying the morphism induced by f to self.

INPUT:
• f – a multilinear morphism from the component modules of the parent tensor product to any module
• codomain – the codomain of f (optional)

By the universal property of the tensor product, f induces a linear morphism from self.parent() to the target module. Returns the result of applying that morphism to self.

The codomain is used for optimizations purposes only. If it's not provided, it's recovered by calling f on the zero input.

EXAMPLES:
We start with simple (admittedly not so interesting) examples, with two modules A and B:

```
sage: # needs sage.modules
sage: A = CombinatorialFreeModule(ZZ, [1,2], prefix="A")
sage: A.rename("A")
sage: B = CombinatorialFreeModule(ZZ, [3,4], prefix="B")
sage: B.rename("B")
```

and f the bilinear morphism \((a, b) \mapsto b \otimes a\) from \(A \times B\) to \(B \otimes A\):

```
sage: def f(a,b):
...:    return tensor([b,a])
```

Now, calling applying f on \(a \otimes b\) returns the same as \(f(a,b)\):

```
sage: def f(a,b):
...:    return sum(a.coefficients(), 0) * sum(b.coefficients(), 0)
sage: f(a, b)
```

\(f\) may be a bilinear morphism to any module over the base ring of A and B. Here the codomain is \(\mathbb{Z}\):

```
sage: def f(a,b):
...:    return sum(a.coefficients(), 0) * sum(b.coefficients(), 0)  
```

(continues on next page)
needs sage.modules

sage: tensor([a, b]).apply_multilinear_morphism(f)  #_

needs sage.modules

Mind the 0 in the sums above; otherwise $f$ would not return 0 in $\mathbb{Z}$:

sage: def f(a,b):
    ....:     return sum(a.coefficients()) * sum(b.coefficients())

sage: type(f(A.zero(), B.zero()))  #_

needs sage.modules

<... 'int'>

Which would be wrong and break this method:

sage: tensor([a, b]).apply_multilinear_morphism(f)  #_

needs sage.modules

Traceback (most recent call last):
...
AttributeError: 'int' object has no attribute 'parent'...

Here we consider an example where the codomain is a module with basis with a different base ring:

sage: # needs sage.modules
sage: C = CombinatorialFreeModule(QQ, [(1,3),(2,4)], prefix="C")
sage: C.rename("C")
sage: def f(a, b):
    ....:     return C.sum_of_terms([((1,3), QQ(a[1]*b[3])),
    ....:                              ((2,4), QQ(a[2]*b[4])))])
sage: f(a,b)
C[(1, 3)] - 4*C[(2, 4)]
sage: tensor([a, b]).apply_multilinear_morphism(f)
C[(1, 3)] - 4*C[(2, 4)]

We conclude with a real life application, where we check that the antipode of the Hopf algebra of Symmetric functions on the Schur basis satisfies its defining formula::

sage: # needs lrcalc_python sage.combinat sage.modules
sage: Sym = SymmetricFunctions(QQ)
sage: s = Sym.schur()
sage: def f(a, b): return a * b.antipode()
sage: x = 4 * s.an_element(); x
8*s[] + 8*s[1] + 12*s[2]
sage: x.coproduct().apply_multilinear_morphism(f)
8*s[]
sage: x.coproduct().apply_multilinear_morphism(f) == x.counit()
True

We recover the constant term of $x$, as desired.

Todo: Extract a method to linearize a multilinear morphism, and delegate the work there.
class ParentMethods
    Bases: object
    Implements operations on tensor products of modules with basis.

extra_super_categories()
    EXAMPLES:

    sage: ModulesWithBasis(QQ).TensorProducts().extra_super_categories()
    [Category of vector spaces with basis over Rational Field]
    sage: ModulesWithBasis(QQ).TensorProducts().super_categories()
    [Category of tensor products of modules with basis over Rational Field,
     Category of vector spaces with basis over Rational Field,
     Category of tensor products of vector spaces over Rational Field]

is_abelian()
    Return whether this category is abelian.
    This is the case if and only if the base ring is a field.
    EXAMPLES:

    sage: ModulesWithBasis(QQ).is_abelian()
    True
    sage: ModulesWithBasis(ZZ).is_abelian()
    False

4.120 Monoidal algebras

sage.categories.monoid_algebras.MonoidAlgebras(base_ring)
    The category of monoidal algebras over base_ring.
    EXAMPLES:

    sage: C = MonoidAlgebras(QQ); C
    Category of monoid algebras over Rational Field
    sage: sorted(C.super_categories(), key=str)
    [Category of bialgebras with basis over Rational Field,
     Category of semigroup algebras over Rational Field,
     Category of unital magma algebras over Rational Field]

    This is just an alias for:

    sage: C is Monoids().Algebras(QQ)
    True
4.121 Monoids

class sage.categories.monoids.Monoids(base_category)

    Bases: CategoryWithAxiom_singleton

The category of (multiplicative) monoids.

A monoid is a unital semigroup, that is a set endowed with a multiplicative binary operation $\ast$ which is associative and admits a unit (see Wikipedia article Monoid).

EXAMPLES:

```
sage: Monoids()
Category of monoids
sage: Monoids().super_categories()
[Category of semigroups, Category of unital magmas]
sage: Monoids().all_super_categories()
[Category of monoids, Category of semigroups, Category of unital magmas, Category of magmas, Category of sets, Category of sets with partial maps, Category of objects]
sage: Monoids().axioms()
frozenset({'Associative', 'Unital'})
sage: Semigroups().Unital()
Category of monoids
sage: Monoids().example()
An example of a monoid: the free monoid generated by ('a', 'b', 'c', 'd')
```

class Algebras(category, *args)

    Bases: AlgebrasCategory

class ElementMethods

    Bases: object

    is_central()

    Return whether the element self is central.

EXAMPLES:

```
sage: SG4 = SymmetricGroupAlgebra(ZZ,4)  # needs sage.groups sage.modules
sage: SG4(1).is_central()  # needs sage.groups sage.modules
True
sage: SG4(Permutation([1,3,2,4])).is_central()  # needs sage.groups sage.modules
False
sage: A = GroupAlgebras(QQ).example(); A  # needs sage.groups sage.modules
Algebra of Dihedral group of order 8 as a permutation group over Rational Field
sage: sum(A.basis()).is_central()  # needs sage.groups sage.modules
```

(continues on next page)
class ParentMethods

Bases: object

algebra_generators()

Return generators for this algebra.

For a monoid algebra, the algebra generators are built from the monoid generators if available and from the semigroup generators otherwise.

See also:

• Semigroups.Algebras.ParentMethods.algebra_generators()
• MagmaticAlgebras.ParentMethods.algebra_generators()

EXAMPLES:

sage: M = Monoids().example(); M
An example of a monoid:
the free monoid generated by ('a', 'b', 'c', 'd')
sage: M.monoid_generators()
Finite family {'a': 'a', 'b': 'b', 'c': 'c', 'd': 'd'}
sage: M.algebra(ZZ).algebra_generators() # needs sage.modules
Finite family {'a': B['a'], 'b': B['b'], 'c': B['c'], 'd': B['d']}

sage: Z12 = Monoids().Finite().example(); Z12
An example of a finite multiplicative monoid:
the integers modulo 12
sage: Z12.monoid_generators()
Traceback (most recent call last):
  ... AttributeError: IntegerModMonoid_with_category object has no attribute 'monoid_generators'...
sage: Z12.semigroup_generators()
Family (0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11)
sage: Z12.algebra(QQ).algebra_generators() # needs sage.modules
Family (B[0], B[1], B[2], B[3], B[4], B[5], B[6], B[7], B[8], B[9], ...
  B[10], B[11])

sage: A10 = AlternatingGroup(10) # needs sage.groups
sage: GroupAlgebras(QQ).example(A10).algebra_generators() # needs sage.groups sage.modules
Family ((8,9,10), (1,2,3,4,5,6,7,8,9))

sage: A = DihedralGroup(3).algebra(QQ); A # needs sage.groups sage.modules
Algebra of Dihedral group of order 6 as a permutation group over Rational Field
sage: A.algebra_generators() # needs sage.groups sage.modules
Family ((1,2,3), (1,3))
**one_basis()**

Return the unit of the monoid, which indexes the unit of this algebra, as per `AlgebrasWithBasis.ParentMethods.one_basis()`.

**EXAMPLES:**

```
sage: # needs sage.modules
sage: A = Monoids().example().algebra(ZZ)
sage: A.one_basis()
'

sage: A.one()
B[]

sage: A(3)
3*B[]
```

**extra_super_categories()**

The algebra of a monoid is a bialgebra and a monoid.

**EXAMPLES:**

```
sage: C = Monoids().Algebras(QQ)
sage: C.extra_super_categories()
[Category of bialgebras over Rational Field,
 Category of monoids]
sage: Monoids().Algebras(QQ).super_categories()
[Category of bialgebras with basis over Rational Field,
 Category of semigroup algebras over Rational Field,
 Category of unital magma algebras over Rational Field]
```

**class CartesianProducts**(category, *args)

Bases: `CartesianProductsCategory`

The category of monoids constructed as Cartesian products of monoids.

This construction gives the direct product of monoids. See Wikipedia article *Direct product* for more information.

**class ElementMethods**

Bases: `object`

**multiplicative_order()**

Return the multiplicative order of this element.

**EXAMPLES:**

```
sage: # needs sage.groups sage.modules
sage: G1 = SymmetricGroup(3)
sage: G2 = SL(2, 3)
sage: G = cartesian_product([G1, G2])
sage: G((G1.gen(0), G2.gen(1))).multiplicative_order()
12
```

**class ParentMethods**

Bases: `object`

**monoid_generators()**

Return the generators of `self`.

**EXAMPLES:**
An example with an infinitely generated group (a better output is needed):

```python
sage: N = Monoids().free(ZZ)  # needs sage.combinat
sage: C = cartesian_product([M, N])  # needs sage.combinat sage.groups
sage: C.monoid_generators()  # needs sage.combinat sage.groups
Lazy family (gen(i))_{i in The Cartesian product of (...)}
```

**extra_super_categories()**

A Cartesian product of monoids is endowed with a natural group structure.

**EXAMPLES:**

```python
sage: C = Monoids().CartesianProducts()

sage: C.extra_super_categories()
[Category of monoids]

sage: sorted(C.super_categories(), key=str)
[Category of Cartesian products of semigroups,
Category of Cartesian products of unital magmas,
Category of monoids]
```

### class Commutative (base_category)

Bases: `CategoryWithAxiom_singleton`

Category of commutative (abelian) monoids.

A monoid \( M \) is **commutative** if \( xy = yx \) for all \( x, y \in M \).

**static free** (`index_set=None, names=None, **kwds`)

Return a free abelian monoid on \( n \) generators or with the generators indexed by a set \( I \).

A free monoid is constructed by specifying either:
- the number of generators and/or the names of the generators, or
- the indexing set for the generators.

**INPUT:**
- `index_set` – (optional) an index set for the generators; if an integer, then this represents \( \{0, 1, \ldots, n - 1\} \)
- `names` – a string or list/tuple/iterable of strings (default: 'x'); the generator names or name prefix

**EXAMPLES:**

```python
sage: Monoids().Commutative().free(index_set=ZZ)  # needs sage.combinat
Free abelian monoid indexed by Integer Ring

sage: Monoids().Commutative().free(ZZ)  # needs sage.combinat
Free abelian monoid indexed by Integer Ring

sage: F.<x,y,z> = Monoids().Commutative().free(); F
```

(continues on next page)
class ElementMethods

Bases: object

inverse()

Return the multiplicative inverse of self.

This is an alias for inversion, which can also be invoked by \( -x \) for an element \( x \).

Nota Bene: Element classes should implement \( \texttt{__invert__} \) only.

EXAMPLES:

```python
sage: AA(sqrt(-2)).inverse()
1.414213562373095
```

is_one()

Return whether self is the one of the monoid.

The default implementation is to compare with self.one().

powers(n)

Return the list \([x^0, x^1, \ldots, x^{n-1}]\).

EXAMPLES:

```python
sage: A = Matrix([[1, 1], [-1, 0]])
```

Finite

alias of \texttt{FiniteMonoids}

Inverse

alias of \texttt{Groups}

class ParentMethods

Bases: object

prod(args)

n-ary product of elements of self.

INPUT:

- args -- a list (or iterable) of elements of self

Returns the product of the elements in args, as an element of self.

EXAMPLES:

```python
sage: S = Monoids().example()
sage: S.prod([S('a'), S('b')])
'ab'
```
semigroup_generators()

Return the generators of self as a semigroup.

The generators of a monoid \( M \) as a semigroup are the generators of \( M \) as a monoid and the unit.

EXAMPLES:

```python
sage: M = Monoids().free([1,2,3])  # needs sage.combinat
sage: M.semigroup_generators()      # needs sage.combinat
Family (1, F[1], F[2], F[3])
```

submonoid(generators, category=None)

Return the multiplicative submonoid generated by generators.

INPUT:
- generators – a finite family of elements of self, or a list, iterable, … that can be converted into one (see Family).
- category – a category

This is a shorthand for Semigroups.ParentMethods.subsemigroup() that specifies that this is a submonoid, and in particular that the unit is self.one().

EXAMPLES:

```python
sage: R = IntegerModRing(15)
sage: M = R.submonoid([R(3), R(5)]); M       # needs sage.combinat
A submonoid of (Ring of integers modulo 15) with 2 generators
sage: M.list()                               # needs sage.combinat
[1, 3, 5, 9, 0, 10, 12, 6]
```

Not the presence of the unit, unlike in:

```python
sage: S = R.subsemigroup([R(3), R(5)]); S     # needs sage.combinat
A subsemigroup of (Ring of integers modulo 15) with 2 generators
sage: S.list()                               # needs sage.combinat
[3, 5, 9, 0, 10, 12, 6]
```

This method is really a shorthand for subsemigroup:

```python
sage: M2 = R.subsemigroup([R(3), R(5)], one=R.one())  # needs sage.combinat
sage: M2.is(M)                                       # needs sage.combinat
True
```

class Subquotients(category, *args)

Bases: SubquotientsCategory

class ParentMethods

Bases: object

one()

Returns the multiplicative unit of this monoid, obtained by retracting that of the ambient monoid.
EXAMPLES:

```python
definition
sage: S = Monoids().Subquotients().example()  # todo: not implemented
sage: S.one()                                   # todo: not implemented
```

class WithRealizations (category, *args)

Bases: WithRealizationsCategory

class ParentMethods

Bases: object

one()

Return the unit of this monoid.

This default implementation returns the unit of the realization of self given by a_realization().

EXAMPLES:

```python
definition
sage: A = Sets().WithRealizations().example(); A  #...
# needs sage.modules
The subset algebra of {1, 2, 3} over Rational Field
sage: A.one.__module__  #...
# needs sage.modules
'sage.categories.monoids'
sage: A.one()  #...
# needs sage.modules
F[{}
```

static free (index_set=None, names=None, **kwds)

Return a free monoid on $n$ generators or with the generators indexed by a set $I$.

A free monoid is constructed by specifying either:

- the number of generators and/or the names of the generators
- the indexing set for the generators

INPUT:

- index_set – (optional) an index set for the generators; if an integer, then this represents \{0, 1, \ldots, n-1\}
- names – a string or list/tuple/iterable of strings (default: 'x'); the generator names or name prefix

EXAMPLES:

```python
definition
sage: Monoids().free(index_set=ZZ)  #...
# needs sage.combinat
Free monoid indexed by Integer Ring
sage: Monoids().free(ZZ)  #...
# needs sage.combinat
Free monoid indexed by Integer Ring
sage: F.<x,y,z> = Monoids().free(); F  #...
# needs sage.combinat
Free monoid indexed by { 'x', 'y', 'z' }
4.122 Number fields

class sage.categories.number_fields.NumberFields
    Bases: Category_singleton

The category of number fields.

EXAMPLES:

We create the category of number fields:

\begin{verbatim}
sage: C = NumberFields()
sage: C
Category of number fields
\end{verbatim}

By definition, it is infinite:

\begin{verbatim}
sage: NumberFields().Infinite() is NumberFields()
True
\end{verbatim}

Notice that the rational numbers \( \mathbb{Q} \) are considered as an object in this category:

\begin{verbatim}
sage: RationalField() in C
True
\end{verbatim}

However, we can define a degree 1 extension of \( \mathbb{Q} \), which is of course also in this category:

\begin{verbatim}
sage: x = PolynomialRing(RationalField(), 'x').gen()
sage: K = NumberField(x - 1, 'a'); K
Number Field in a with defining polynomial x - 1
\end{verbatim}

\begin{verbatim}
sage: K in C
True
\end{verbatim}

Number fields all lie in this category, regardless of the name of the variable:

\begin{verbatim}
sage: K = NumberField(x^2 + 1, 'a')
\end{verbatim}

\begin{verbatim}
sage: K in C
True
\end{verbatim}

class ElementMethods
    Bases: object

class ParentMethods
    Bases: object

    zeta_function (prec=53, max_imaginary_part=0, max_asymptotic_coeffs=40, algorithm='pari')

    Return the Dedekind zeta function of this number field.

    Actually, this returns an interface for computing with the Dedekind zeta function \( \zeta_F(s) \) of the number field \( F \).

    INPUT:
    • prec – optional integer (default 53) bits precision
    • max_imaginary_part – optional real number (default 0)
• max_asympt_coeffs – optional integer (default 40)
• algorithm – optional (default “pari”) either “gp” or “pari”

OUTPUT: The zeta function of this number field.

If algorithm is “gp”, this returns an interface to Tim Dokchitser’s gp script for computing with L-functions.

If algorithm is “pari”, this returns instead an interface to Pari’s own general implementation of L-functions.

EXAMPLES:

```python
doctest: K.<a> = NumberField(ZZ['x'].0^2 + ZZ['x'].0 - 1) #-- needs sage.rings.number_field
doctest: sage: Z = K.zeta_function(); Z #-- needs sage.rings.number_field sage.symbolic
PARI zeta function associated to Number Field in a
with defining polynomial x^2 + x - 1
doctest: sage: Z(-1) #-- needs sage.rings.number_field sage.symbolic
0.033333333333333

doctest: sage: x = polygen(QQ, 'x')
doctest: sage: L.<a, b, c> = NumberField([x^2 - 5, x^2 + 3, x^2 + 1]) #-- needs sage.rings.number_field
doctest: sage: Z = L.zeta_function() #-- needs sage.rings.number_field sage.symbolic
sage: sage: Z(5) #-- needs sage.rings.number_field sage.symbolic
1.00199015670185
```

Using the algorithm “pari”:

```python
doctest: sage: K.<a> = NumberField(ZZ['x'].0^2 + ZZ['x'].0 - 1) #-- needs sage.rings.number_field
doctest: sage: Z = K.zeta_function(algorithm="pari") #-- needs sage.rings.number_field sage.symbolic
sage: sage: Z(-1) #-- needs sage.rings.number_field sage.symbolic
0.033333333333333

doctest: sage: x = polygen(QQ, 'x')
doctest: sage: L.<a, b, c> = NumberField([x^2 - 5, x^2 + 3, x^2 + 1]) #-- needs sage.rings.number_field
doctest: sage: Z = L.zeta_function(algorithm="pari") #-- needs sage.rings.number_field sage.symbolic
sage: sage: Z(5) #-- needs sage.rings.number_field sage.symbolic
1.00199015670185
```

super_categories()
4.123 Objects

class sage.categories.objects.Objects
    Bases: Category_singleton

    The category of all objects the basic category

    EXAMPLES:

    sage: Objects()
    Category of objects
    sage: Objects().super_categories()
    []

class ParentMethods
    Bases: object

    Methods for all category objects

class SubcategoryMethods
    Bases: object

    Endsets()
    
    Return the category of endsets between objects of this category.

    EXAMPLES:

    sage: Sets().Endsets()
    Category of endsets of sets
    sage: Rings().Endsets()
    Category of endsets of unital magmas and additive unital additive magmas

    See also:

    • Homsets()

    Homsets()
    
    Return the category of homsets between objects of this category.

    EXAMPLES:

    sage: Sets().Homsets()
    Category of homsets of sets
    sage: Rings().Homsets()
    Category of homsets of unital magmas and additive unital additive magmas

    Note: Background

    Information, code, documentation, and tests about the category of homsets of a category Cs should go in the nested class Cs.Homsets. They will then be made available to homsets of any subcategory of Cs.

    Assume, for example, that homsets of Cs are Cs themselves. This information can be implemented in the method Cs.Homsets().extra_super_categories to make Cs.Homsets() a subcategory of Cs().
Methods about the homsets themselves should go in the nested class `Cs.Homsets`.

Methods about the morphisms can go in the nested class `Cs.Homsets.ElementMethods`. However it’s generally preferable to put them in the nested class `Cs.MorphismMethods`; indeed they will then apply to morphisms of all subcategories of `Cs`, and not only full subcategories.

See also:

`FunctorialConstruction`

Todo:
- Design a mechanism to specify that an axiom is compatible with taking subsets. Examples: `Finite`, `Associative`, `Commutative` (when meaningful), but not `Infinite` nor `Unital`.
- Design a mechanism to specify that, when $B$ is a subcategory of $A$, a $B$-homset is a subset of the corresponding $A$ homset. And use it to recover all the relevant axioms from homsets in super categories.
- For instances of redundant code due to this missing feature, see:
  - `AdditiveMonoids.Homsets.extra_super_categories()`
  - `HomsetsCategory.extra_super_categories()` (slightly different nature)
  - plus plenty of spots where this is not implemented.

```python
additional_structure()
```

Return `None`

Indeed, by convention, the category of objects defines no additional structure.

See also:

`Category.additiona1_structure()`

EXAMPLES:

```python
sage: Objects().additional_structure()
```

```python
super_categories()
```

EXAMPLES:

```python
sage: Objects().super_categories()
[ ]
```

### 4.124 Partially ordered monoids

```python
class sage.categories.partially_ordered_monoids.PartiallyOrderedMonoids
```

Bases: `Category_singleton`

The category of partially ordered monoids, that is partially ordered sets which are also monoids, and such that multiplication preserves the ordering: \( x \leq y \) implies \( x \cdot z < y \cdot z \) and \( z \cdot x < z \cdot y \).

See Wikipedia article `Ordered_monoid`

EXAMPLES:
sage: PartiallyOrderedMonoids()
Category of partially ordered monoids
sage: PartiallyOrderedMonoids().super_categories()
[Category of posets, Category of monoids]

class ElementMethods
   _bases: object

class ParentMethods
   _bases: object

super_categories()

EXAMPLES:

sage: PartiallyOrderedMonoids().super_categories()
[Category of posets, Category of monoids]

4.125 Permutation groups

class sage.categories.permutation_groups.PermutationGroups
    _bases: Category

The category of permutation groups.

A permutation group is a group whose elements are concretely represented by permutations of some set. In other words, the group comes endowed with a distinguished action on some set.

This distinguished action should be preserved by permutation group morphisms. For details, see Wikipedia article Permutation_group#Permutation_isomorphic_groups.

Todo: shall we accept only permutations with finite support or not?

EXAMPLES:

sage: PermutationGroups()
Category of permutation groups
sage: PermutationGroups().super_categories()
[Category of groups]

The category of permutation groups defines additional structure that should be preserved by morphisms, namely the distinguished action:

sage: PermutationGroups().additional_structure()
Category of permutation groups

Finite
    alias of FinitePermutationGroups

super_categories()
    Return a list of the immediate super categories of self.

    EXAMPLES:
4.126 Pointed sets

class sage.categories.pointed_sets.PointedSets

Bases: Category_singleton

The category of pointed sets.

EXAMPLES:

```
sage: PointedSets()
Category of pointed sets
```

```
sage: PointedSets().super_categories()
[Category of sets]
```

4.127 Polyhedral subsets of free ZZ, QQ or RR-modules.

class sage.categories.polyhedra.PolyhedralSets(R)

Bases: Category_over_base_ring

The category of polyhedra over a ring.

EXAMPLES:

We create the category of polyhedra over Q:

```
sage: PolyhedralSets(QQ)
Category of polyhedral sets over Rational Field
```

```
sage: PolyhedralSets(QQ).super_categories()
[Category of commutative magmas, Category of additive monoids]
```

4.128 Posets

class sage.categories.posets.Posets

Bases: Category

The category of posets i.e. sets with a partial order structure.

EXAMPLES:
The partial order is implemented by the mandatory method \texttt{le()}:

\begin{verbatim}
sage: x = P(Set([1,3])); y = P(Set([1,2,3]))
sage: P.le(x, y) True
sage: P.le(x, x) True
sage: P.le(y, x) False
\end{verbatim}

The other comparison methods are called \texttt{lt()}, \texttt{ge()}, \texttt{gt()}, following Python's naming convention in operator. Default implementations are provided:

\begin{verbatim}
sage: P.lt(x, x) False
sage: P.ge(y, x) True
\end{verbatim}

Unless the poset is a facade (see \texttt{SetsFacade}), one can compare directly its elements using the usual Python operators:

\begin{verbatim}
sage: D = Poset((divisors(30), attrcall("divides")), facade = False)
sage: D(3) <= D(6) True
sage: D(3) <= D(3) True
sage: D(3) <= D(5) False
sage: D(3) < D(3) False
sage: D(10) >= D(5) True
\end{verbatim}

At this point, this has to be implemented by hand. Once github issue \#10130 will be resolved, this will be automatically provided by this category:

\begin{verbatim}
sage: # not implemented
sage: x < y True
sage: x < x False
sage: x <= x True
sage: y >= x True
\end{verbatim}

See also:

\texttt{Poset()}, \texttt{FinitePosets}, \texttt{LatticePosets}
class ElementMethods
    Bases: object

Finite
    alias of FinitePosets
class ParentMethods
    Bases: object

CartesianProduct
    alias of CartesianProductPoset
directed_subset (elements, direction)
    Return the order filter or the order ideal generated by a list of elements.
    If direction is ‘up’, the order filter (upper set) is being returned.
    If direction is ‘down’, the order ideal (lower set) is being returned.
    INPUT:
    • elements – a list of elements.
    • direction – ‘up’ or ‘down’.
    EXAMPLES:
    sage: B = posets.BooleanLattice(4)
    sage: B.directed_subset([3, 8], 'up')
    [3, 7, 8, 9, 10, 11, 12, 13, 14, 15]
    sage: B.directed_subset([7, 10], 'down')
    [0, 1, 2, 3, 4, 5, 6, 7, 8, 10]

ge (x, y)
    Return whether \(x \geq y\) in the poset self.
    INPUT:
    • x, y – elements of self.
    This default implementation delegates the work to le().
    EXAMPLES:
    sage: D = Poset((divisors(30), attrcall("divides")))
    sage: D.ge(6, 3)
    True
    sage: D.ge(3, 3)
    True
    sage: D.ge(3, 5)
    False
gt (x, y)
    Return whether \(x > y\) in the poset self.
    INPUT:
    • x, y – elements of self.
    This default implementation delegates the work to lt().
    EXAMPLES:
    sage: D = Poset((divisors(30), attrcall("divides")))
    sage: D.gt(3, 6)
    False
    (continues on next page)
is_antichain_of_poset(o)

Return whether an iterable o is an antichain of self.

INPUT:
• o – an iterable (e.g., list, set, or tuple) containing some elements of self

OUTPUT:
True if the subset of self consisting of the entries of o is an antichain of self, and False otherwise.

EXAMPLES:

sage: P = Poset((divisors(12), attrcall("divides")),
....: facade=True, linear_extension=True)
sage: sorted(P.list())
[1, 2, 3, 4, 6, 12]
sage: P.is_antichain_of_poset([1, 3])
False
sage: P.is_antichain_of_poset([3, 1])
False
sage: P.is_antichain_of_poset([1, 1, 3])
False
sage: P.is_antichain_of_poset([])
True
sage: P.is_antichain_of_poset([1])
True
sage: P.is_antichain_of_poset([1, 1])
True
sage: P.is_antichain_of_poset([3, 4])
True
sage: P.is_antichain_of_poset([3, 4, 12])
False
sage: P.is_antichain_of_poset([6, 4])
True
sage: P.is_antichain_of_poset(i for i in divisors(12)
....: if (2 < i and i < 6))
True
sage: P.is_antichain_of_poset(i for i in divisors(12)
....: if (2 <= i and i < 6))
False

sage: Q = Poset({2: [3, 1], 3: [4], 1: [4]})
sage: Q.is_antichain_of_poset({1, 2})
False
sage: Q.is_antichain_of_poset({2, 4})
False
sage: Q.is_antichain_of_poset({4, 2})
False
sage: Q.is_antichain_of_poset({2, 2})
True
sage: Q.is_antichain_of_poset({3, 4})
False
sage: Q.is_antichain_of_poset({3, 1})

(continues on next page)
An infinite poset:

```python
sage: from sage.categories.examples.posets import...
˓→FiniteSetsOrderedByInclusion
sage: R = FiniteSetsOrderedByInclusion()
˓→set([3, 1, 2]),
˓→set([1, 4]), R(set([4, 5])))
True
sage: R.is_antichain_of_poset([R(set([3, 1, 2, 4])),
˓→set([1, 4]), R(set([4, 5])))
False
```

### is_chain_of_poset (o, ordered=False)

Return whether an iterable o is a chain of self, including a check for o being ordered from smallest to largest element if the keyword ordered is set to True.

**INPUT:**

- o – an iterable (e.g., list, set, or tuple) containing some elements of self
- ordered – a Boolean (default: False) which decides whether the notion of a chain includes being ordered

**OUTPUT:**

If ordered is set to False, the truth value of the following assertion is returned: The subset of self formed by the elements of o is a chain in self.

If ordered is set to True, the truth value of the following assertion is returned: Every element of the list o is (strictly!) smaller than its successor in self. (This makes no sense if ordered is a set.)

**EXAMPLES:**

```python
sage: P = Poset((divisors(12), attrcall("divides")),
˓→set([1], 3])
True
sage: P.is_chain_of_poset([3, 1])
True
sage: P.is_chain_of_poset([3, 1], ordered=True)
True
sage: P.is_chain_of_poset([3, 1], ordered=True)
False
sage: P.is_chain_of_poset([])
True
sage: P.is_chain_of_poset([], ordered=True)
True
sage: P.is_chain_of_poset((2, 12, 6))
True
sage: P.is_chain_of_poset((2, 6, 12), ordered=True)
True
sage: P.is_chain_of_poset((2, 12, 6), ordered=True)
True
```
Examples with infinite posets:

```python
sage: from sage.categories.examples.posets import FiniteSetsOrderedByInclusion
sage: R = FiniteSetsOrderedByInclusion()
```

```python
sage: R.is_chain_of_poset([R(set([3, 1, 2])), ....: R(set([1, 4])), ....: R(set([4, 5]))])
False
```

```python
sage: R.is_chain_of_poset([R(set([3, 1, 2])), ....: R(set([1, 2])), ....: R(set([1]))], ordered=True)
False
```

```python
sage: R.is_chain_of_poset([R(set([3, 1, 2])), ....: R(set([1, 2])), R(set([1]))])
True
```

```python
sage: from sage.categories.examples.posets import PositiveIntegersOrderedByDivisibilityFacade
sage: T = PositiveIntegersOrderedByDivisibilityFacade()
```

```python
sage: T.is_chain_of_poset((T(3), T(4), T(7)))
False
```

```python
sage: T.is_chain_of_poset((T(3), T(6), T(3)))
True
```

```python
sage: T.is_chain_of_poset((T(3), T(6), T(3)), ordered=True)
False
```

```python
sage: T.is_chain_of_poset((T(3), T(3), T(6)))
True
```

```python
sage: T.is_chain_of_poset((T(3), T(3), T(6)), ordered=True)
False
```

```python
sage: T.is_chain_of_poset((T(3), T(6)), ordered=True)
True
```

```python
sage: T.is_chain_of_poset(), ordered=True)
```

(continues on next page)
True
sage: T.is_chain_of_poset((T(3),), ordered=True)
True
sage: T.is_chain_of_poset((T(q) for q in divisors(27)))
True
sage: T.is_chain_of_poset((T(q) for q in divisors(18)))
False

is_order_filter(o)
Return whether o is an order filter of self, assuming self has no infinite ascending path.

INPUT:
• o—a list (or set, or tuple) containing some elements of self

EXAMPLES:

sage: P = Poset((divisors(12), attrcall("divides")),
              facade=True, linear_extension=True)
sage: sorted(P.list())
[1, 2, 3, 4, 6, 12]
sage: P.is_order_filter([4, 12])
True
sage: P.is_order_filter([])
True
sage: P.is_order_filter({3, 4, 12})
False
sage: P.is_order_filter({3, 6, 12})
True

is_order_ideal(o)
Return whether o is an order ideal of self, assuming self has no infinite descending path.

INPUT:
• o—a list (or set, or tuple) containing some elements of self

EXAMPLES:

sage: P = Poset((divisors(12), attrcall("divides")),
              facade=True, linear_extension=True)
sage: sorted(P.list())
[1, 2, 3, 4, 6, 12]
sage: P.is_order_ideal([1, 3])
True
sage: P.is_order_ideal([])
True
sage: P.is_order_ideal({1, 3})
True
sage: P.is_order_ideal([1, 3, 4])
False

le(x, y)
Return whether x \leq y in the poset self.

INPUT:
• x, y—elements of self.

EXAMPLES:
```python
sage: D = Poset((divisors(30), attrcall("divides")))
sage: D.le( 3, 6 )
True
sage: D.le( 3, 3 )
True
sage: D.le( 3, 5 )
False
```

**lower_covers (x)**

Return the lower covers of $x$, that is, the elements $y$ such that $y < x$ and there exists no $z$ such that $y < z < x$.

**EXAMPLES:**

```python
sage: D = Poset((divisors(30), attrcall("divides")))
sage: D.lower_covers(15)
[3, 5]
```

**lt (x, y)**

Return whether $x < y$ in the poset self.

**INPUT:**

- $x, y$ – elements of self.

This default implementation delegates the work to `le()`.

**EXAMPLES:**

```python
sage: D = Poset((divisors(30), attrcall("divides")))
sage: D.lt( 3, 6 )
True
sage: D.lt( 3, 3 )
False
sage: D.lt( 3, 5 )
False
```

**order_filter (elements)**

Return the order filter generated by a list of elements.

A subset $I$ of a poset is said to be an order filter if, for any $x$ in $I$ and $y$ such that $y \geq x$, then $y$ is in $I$.

This is also called the upper set generated by these elements.

**EXAMPLES:**

```python
sage: B = posets.BooleanLattice(4)
sage: B.order_filter([3,8])
[3, 7, 8, 9, 10, 11, 12, 13, 14, 15]
```

**order_ideal (elements)**

Return the order ideal in self generated by the elements of an iterable elements.

A subset $I$ of a poset is said to be an order ideal if, for any $x$ in $I$ and $y$ such that $y \leq x$, then $y$ is in $I$.

This is also called the lower set generated by these elements.

**EXAMPLES:**

```python
```
sage: B = posets.BooleanLattice(4)
sage: B.order_ideal([7,10])
[0, 1, 2, 3, 4, 5, 6, 7, 8, 10]

order_ideal_toggle(I, v)

Return the result of toggling the element v in the order ideal I.

If v is an element of a poset P, then toggling the element v is an automorphism of the set J(P) of all order ideals of P. It is defined as follows: If I is an order ideal of P, then the image of I under toggling the element v is

- the set I ∪ {v}, if v /∈ I but every element of P smaller than v is in I;
- the set I \ {v}, if v ∈ I but no element of P greater than v is in I;
- I otherwise.

This image always is an order ideal of P.

EXAMPLES:

sage: P = Poset({1: [2,3], 2: [4], 3: []})
sage: I = Set({1, 2})
sage: I in P.order_ideals_lattice()  # needs sage.modules
True
sage: P.order_ideal_toggle(I, 1)
{1, 2}
sage: P.order_ideal_toggle(I, 2)
{1}
sage: P.order_ideal_toggle(I, 3)
{1, 2, 3}
sage: P.order_ideal_toggle(I, 4)
{1, 2, 4}
sage: P4 = Posets(4)
sage: all(all(all(P.order_ideal_toggle(P.order_ideal_toggle(I, i), i) == I
.... # needs sage.modules
.... for i in range(4))
.... for I in P.order_ideals_lattice(facade=True))
.... for P in P4)
True

order_ideal_toggles(I, vs)

Return the result of toggling the elements of the list (or iterable) vs (one by one, from left to right) in the order ideal I.

See order_ideal_toggle() for a definition of toggling.

EXAMPLES:

sage: P = Poset({1: [2,3], 2: [4], 3: []})
sage: I = Set({1, 2})
sage: P.order_ideal_toggles(I, [1,2,3,4])
{1, 3}
sage: P.order_ideal_toggles(I, (1,2,3,4))
{1, 3}

principal_lower_set(x)

Return the order ideal generated by an element x.

This is also called the lower set generated by this element.

EXAMPLES:
```
sage: B = posets.BooleanLattice(4)
sage: B.principal_order_ideal(6)
[0, 2, 4, 6]
```

**principal_order_filter** *(x)*

Return the order filter generated by an element *x*.

This is also called the upper set generated by this element.

**EXAMPLES:**
```
sage: B = posets.BooleanLattice(4)
sage: B.principal_order_filter(2)
[2, 3, 6, 7, 10, 11, 14, 15]
```

```
sage: B = posets.BooleanLattice(4)
sage: B.principal_order_ideal(6)
[0, 2, 4, 6]
```

```
sage: B = posets.BooleanLattice(4)
sage: B.principal_order_ideal(6)
[0, 2, 4, 6]
```

```
sage: B = posets.BooleanLattice(4)
sage: B.principal_order_filter(2)
[2, 3, 6, 7, 10, 11, 14, 15]
```

**upper_covers** *(x)*

Return the upper covers of *x*, that is, the elements *y* such that *x < y* and there exists no *z* such that *x < z < y*.

**EXAMPLES:**
```
sage: D = Poset((divisors(30), attrcall("divides")))
sage: D.upper_covers(3)
[6, 15]
```

```
sage: Posets().example()
An example of a poset: sets ordered by inclusion
```

```
sage: Posets().example("facade")
An example of a facade poset: the positive integers ordered by divisibility
```

```
```
super_categories()

Return a list of the (immediate) super categories of self, as per Category.super_categories().

EXAMPLES:

    sage: Posets().super_categories()
    [Category of sets]

4.129 Principal ideal domains

class sage.categories.principal_ideal_domains.PrincipalIdealDomains

Bases: Category_singleton

The category of (constructive) principal ideal domains

By constructive, we mean that a single generator can be constructively found for any ideal given by a finite set of generators. Note that this constructive definition only implies that finitely generated ideals are principal. It is not clear what we would mean by an infinitely generated ideal.

EXAMPLES:

    sage: PrincipalIdealDomains()
    Category of principal ideal domains
    sage: PrincipalIdealDomains().super_categories()
    [Category of unique factorization domains]

See also Wikipedia article Principal_ideal_domain

class ElementMethods

    Bases: object

class ParentMethods

    Bases: object

additional_structure()

Return None.

Indeed, the category of principal ideal domains defines no additional structure: a ring morphism between two principal ideal domains is a principal ideal domain morphism.

EXAMPLES:

    sage: PrincipalIdealDomains().additional_structure()

super_categories()

EXAMPLES:

    sage: PrincipalIdealDomains().super_categories()
    [Category of unique factorization domains]
4.130 Quotient fields

class sage.categories.quotient_fields.QuotientFields
   Bases: Category_singleton

   The category of quotient fields over an integral domain

   EXAMPLES:

   sage: QuotientFields()
   Category of quotient fields
   sage: QuotientFields().super_categories()
   [Category of fields]

class ElementMethods
   Bases: object

   denominator()

   Constructor for abstract methods

   EXAMPLES:

   sage: def f(x):
   ....:     "doc of f"
   ....:     return 1
   sage: x = abstract_method(f); x
   <abstract method f at ...>
   sage: x.__doc__
   'doc of f'
   sage: x.__name__
   'f'
   sage: x.__module__
   '__main__'

derivative(*args)

   The derivative of this rational function, with respect to variables supplied in args.

   Multiple variables and iteration counts may be supplied; see documentation for the global derivative() function for more details.

   See also:

   _derivative()

   EXAMPLES:

   sage: F.<x> = Frac(QQ['x'])
   sage: (1/x).derivative()
   -1/x^2
   sage: (x+1/x).derivative(x, 2)
   2/x^3
   sage: F.<x,y> = Frac(QQ['x,y'])
   sage: (1/(x*y)).derivative(x,y)
   2/(x^3 + 3*x^2*y + 3*x*y^2 + y^3)
factor(*args, **kwds)

Return the factorization of self over the base ring.

INPUT:

• *args - Arbitrary arguments suitable over the base ring
• **kwds - Arbitrary keyword arguments suitable over the base ring

OUTPUT:

• Factorization of self over the base ring

EXAMPLES:

```
sage: K.<x> = QQ[]
sage: f = (x^3+x)/(x-3)
sage: f.factor()
needs sage.libs.pari
(x - 3)^-1 * x * (x^2 + 1)
```

Here is an example to show that github issue #7868 has been resolved:

```
sage: R.<x,y> = GF(2)[]
sage: f = x*y/(x+y)
sage: f.factor()
needs sage.rings.finite_rings
(x + y)^-1 * y * x
```

gcd(other)

Greatest common divisor

**Note:** In a field, the greatest common divisor is not very informative, as it is only determined up to a unit. But in the fraction field of an integral domain that provides both gcd and lcm, it is possible to be a bit more specific and define the gcd uniquely up to a unit of the base ring (rather than in the fraction field).

AUTHOR:

• Simon King (2011-02): See github issue #10771

EXAMPLES:

```
sage: # needs sage.libs.pari
sage: R.<x> = QQ['x']
sage: p = (1+x)^3*(1+2*x^2)/(1-x^5)
sage: q = (1+x)^2*(1+3*x^2)/(1-x^4)
sage: factor(p)
(-2) * (x - 1)^-1 * (x + 1)^3 * (x^2 + 1/2) * (x^4 + x^3 + x^2 + x + 1)^-1
sage: factor(q)
(-3) * (x - 1)^-1 * (x + 1) * (x^2 + 1)^-1 * (x^2 + 1/3)
sage: gcd(p, q)
(x + 1)/(x^7 + x^5 - x^2 - 1)
sage: factor(gcd(p, q))
(x - 1)^-1 * (x + 1) * (x^2 + 1)^-1 * (x^4 + x^3 + x^2 + x + 1)^-1
sage: factor(gcd(p, 1 + x))
(x - 1)^-1 * (x + 1) * (x^4 + x^3 + x^2 + x + 1)^-1
sage: factor(gcd(1 + x, q))
(x - 1)^-1 * (x + 1) * (x^2 + 1)^-1
```

lcm(other)

Least common multiple
In a field, the least common multiple is not very informative, as it is only determined up to a unit. But in the fraction field of an integral domain that provides both gcd and lcm, it is reasonable to be a bit more specific and to define the least common multiple so that it restricts to the usual least common multiple in the base ring and is unique up to a unit of the base ring (rather than up to a unit of the fraction field).

The least common multiple is easily described in terms of the prime decomposition. A rational number can be written as a product of primes with integer (positive or negative) powers in a unique way. The least common multiple of two rational numbers \(x\) and \(y\) can then be defined by specifying that the exponent of every prime \(p\) in \(\text{lcm}(x, y)\) is the supremum of the exponents of \(p\) in \(x\), and the exponent of \(p\) in \(y\) (where the primes that does not appear in the decomposition of \(x\) or \(y\) are considered to have exponent zero).

AUTHOR:

- Simon King (2011-02): See github issue #10771

EXAMPLES:

```sage
sage: lcm(2/3, 1/5)
2
```

Indeed \(2/3 = 2^13^{-1}5^0\) and \(1/5 = 2^03^05^{-1}\), so \(\text{lcm}(2/3, 1/5) = 2^13^05^0 = 2\).

```sage
sage: lcm(1/3, 1/5) 1
sage: lcm(1/3, 1/6) 1/3
```

Some more involved examples:

```sage
sage: # needs sage.libs.pari
sage: R.<x> = QQ[]
sage: p = (1+x)^3*(1+2*x^2)/(1-x^5)
sage: q = (1+x)^2*(1+3*x^2)/(1-x^4)
sage: factor(p)
(-2) * (x - 1)^-1 * (x + 1)^3 * (x^2 + 1/2) * (x^4 + x^3 + x^2 + x + 1)^-1
sage: factor(q)
(-3) * (x - 1)^-1 * (x + 1) * (x^2 + 1)^-1 * (x^2 + 1/3)
sage: factor(lcm(p, q))
(x - 1)^-1 * (x + 1)^3 * (x^2 + 1/2) * (x^4 + x^3 + x^2 + x + 1)^-1
sage: factor(lcm(p, 1 + x))
(x + 1)^3 * (x^2 + 1/2)
sage: factor(lcm(1 + x, q))
(x + 1) * (x^2 + 1/3)
sage: factor(lcm(1 + x, q))
(x + 1) * (x^2 + 1/3)
```

calculator

Constructor for abstract methods

EXAMPLES:

```sage
sage: def f(x):
....:     "doc of f"
....:     return 1
sage: x = abstract_method(f); x
<abstract method f at ...>
sage: x.__doc__
'doc of f'
sage: x.__name__
'f'
sage: x.__module__
'__main__'
```

calculator

Decompose fraction field element into a whole part and a list of fraction field elements over prime power denominators.
The sum will be equal to the original fraction.

**INPUT:**
- `decompose_powers` — boolean (default: True); whether to decompose prime power denominators as opposed to having a single term for each irreducible factor of the denominator

**OUTPUT:**
Partial fraction decomposition of `self` over the base ring.

**AUTHORS:**

**EXAMPLES:**

```python
sage: # needs sage.libs.pari
sage: S.<t> = QQ[]
sage: q = 1/(t+1) + 2/(t+2) + 3/(t-3); q
t + 4*t + 6) / (t^3 - 7*t - 6)
sage: whole, parts = q.partial_fraction_decomposition(); parts
[3/(t - 3), 1/(t + 1), 2/(t + 2)]
sage: sum(parts) == q
True
sage: q = 1/(t^3+1) + 2/(t^2+2) + 3/(t-3)^5
sage: whole, parts = q.partial_fraction_decomposition(); parts
[1/3/(t + 1), 3/(t^5 - 15*t^4 + 90*t^3 - 270*t^2 + 405*t - 243),
(-1/3*t + 2/3)/(t^2 - t + 1), 2/(t^2 + 2)]
sage: sum(parts) == q
True
sage: q = 2*t / (t + 3)^2
sage: q.partial_fraction_decomposition()
(0, [2/(t + 3), -6/(t^2 + 6*t + 9)])
sage: for p in q.partial_fraction_decomposition()[1]:
    print(p.factor())
(2) * (t + 3)^-1
(-6) * (t + 3)^-2
sage: q.partial_fraction_decomposition(decompose_powers=False)
(0, [2*t/(t^2 + 6*t + 9)])
```

We can decompose over a given algebraic extension:

```python
sage: R.<x> = QQ[sqrt(2)]
# needs sage.rings.number_field sage.symbolic
sage: r = 1/(x^4+1)
# needs sage.rings.number_field sage.symbolic
sage: r.partial_fraction_decomposition()  # needs sage.rings.number_field sage.symbolic
(0,
[(-1/4*sqrt2*x + 1/2)/(x^2 - sqrt2*x + 1),
(1/4*sqrt2*x + 1/2)/(x^2 + sqrt2*x + 1)])
sage: R.<x> = QQ[I]
# of QQ[sqrt(-1)]
# needs sage.rings.number_field sage.symbolic
sage: r = 1/(x^4+1)
# needs sage.rings.number_field sage.symbolic
sage: r.partial_fraction_decomposition()  # needs sage.rings.number_field sage.symbolic
(0, [(-1/2*I)/(x^2 - I), 1/2*I/(x^2 + I)])
```

We can also ask Sage to find the least extension where the denominator factors in linear terms:
 sage: # needs sage.rings.number_field
 sage: R.<x> = QQ[]
 sage: r = 1/(x^4+2)
 sage: N = r.denominator().splitting_field('a'); N
 Number Field in a with defining polynomial x^8 - 8*x^6 + 28*x^4 + 16*x^2...
 sage: R1.<x1> = N[]
 sage: r1 = 1/(x1^4+2)
 sage: r1.partial_fraction_decomposition()
 (0,
  [(-1/224*a^6 + 13/448*a^4 - 5/56*a^2 - 25/224)/(x1 - 1/28*a^6 + 13/56*a^4...
  → 4 - 5/7*a^2 - 25/28),
   (1/224*a^6 - 13/448*a^4 + 5/56*a^2 + 25/224)/(x1 + 1/28*a^6 - 13/56*a^4...
  → 5/7*a^2 + 25/28),
   (-5/1344*a^7 + 43/1344*a^5 - 85/672*a^3 - 31/672*a)/(x1 - 5/168*a^7 +...
  → 43/168*a^5 - 85/84*a^3 - 31/84*a),
   (5/1344*a^7 - 43/1344*a^5 + 85/672*a^3 + 31/672*a)/(x1 + 5/168*a^7 - 43/
  → 168*a^5 + 85/84*a^3 + 31/84*a)])

Or we may work directly over an algebraically closed field:

 sage: R.<x> = QQbar[]
 sage: r = 1/(x^4+1)
 sage: r.partial_fraction_decomposition()
 (0,
  [(-0.1767766952966369? - 0.1767766952966369?*I)/(x - 0.7071067811865475?...
  → 0.7071067811865475?*I),
   (-0.1767766952966369? + 0.1767766952966369?*I)/(x - 0.7071067811865475?...
  → 0.7071067811865475?*I),
   (0.1767766952966369? - 0.1767766952966369?*I)/(x + 0.7071067811865475?...
  → 0.7071067811865475?*I),
   (0.1767766952966369? + 0.1767766952966369?*I)/(x + 0.7071067811865475?...
  → 0.7071067811865475?*I)])

We do the best we can over inexact fields:

 sage: R.<x> = RealField(20)[]
 sage: q = 1/(x^2 + x + 2)^2 + 1/(x-1); q
 (x^4 + 2.0000*x^3 + 5.0000*x^2 + 5.0000*x + 3.0000)/(x^5 + x^4 + 3.0000*x^3 - x^2 - 4.0000)
 sage: whole, parts = q.partial_fraction_decomposition(); parts
 [1.0000/(x - 1.0000),
  1.0000/(x^4 + 2.0000*x^3 + 5.0000*x^2 + 4.0000*x + 4.0000)]
 sage: sum(parts)
 (x^4 + 2.0000*x^3 + 5.0000*x^2 + 5.0000*x + 3.0000)/(x^5 + x^4 + 3.0000*x^3 - x^2 - 4.0000)

```
xgcd(other)
```

Return a triple \((g, s, t)\) of elements of that field such that \(g\) is the greatest common divisor of \(s\) and \(t\).
Note: In a field, the greatest common divisor is not very informative, as it is only determined up to a unit. But in the fraction field of an integral domain that provides both \( \text{xgcd} \) and \( \text{lcm} \), it is possible to be a bit more specific and define the gcd uniquely up to a unit of the base ring (rather than in the fraction field).

EXAMPLES:

```python
sage: QQ(3).xgcd(QQ(2))
(1, 1, -1)
sage: QQ(3).xgcd(QQ(1/2))
(1/2, 0, 1)
sage: QQ(1/3).xgcd(QQ(2))
(1/3, 1, 0)
sage: QQ(3/2).xgcd(QQ(5/2))
(1/2, 2, -1)
sage: R.<x> = QQ['x']
sage: p = (1+x)^3*(1+2*x^2)/(1-x^5)
sage: q = (1+x)^2*(1+3*x^2)/(1-x^4)
sage: factor(p)  # needs sage.libs.pari
(-2) * (x - 1)^-1 * (x + 1)^3 * (x^2 + 1/2) * (x^4 + x^3 + x^2 + x + 1)^-1
sage: factor(q)  # needs sage.libs.pari
(-3) * (x - 1)^-1 * (x + 1) * (x^2 + 1)^-1 * (x^2 + 1/3)
sage: g, s, t = xgcd(p, q)
sage: g
(x + 1)/(x^7 + x^5 - x^2 - 1)
sage: g == s*p + t*q
True
```

An example without a well defined gcd or \( \text{xgcd} \) on its base ring:

```python
sage: # needs sage.rings.number_field
sage: K = QuadraticField(5)
sage: O = K.maximal_order()
sage: R = PolynomialRing(O, 'x')
sage: F = R.fraction_field()
sage: x = F.gen(0)
sage: x.gcd(x+1)
1
sage: x.xgcd(x+1)
(1, 1/x, 0)
sage: zero = F.zero()
sage: zero.gcd(x)
1
sage: zero.xgcd(x)
(1, 0, 1/x)
sage: zero.xgcd(zero)
(0, 0, 0)
```

```
class ParentMethods:
    Bases: object

    super_categories()  

    EXAMPLES:
```
4.131 Quantum Group Representations

AUTHORS:

- Travis Scrimshaw (2018): initial version

```python
class sage.categories.quantum_group_representations.QuantumGroupRepresentations(base, name=None):
    Bases: Category_module
    The category of quantum group representations.

    class ParentMethods
        Bases: object
        cartan_type()
            Return the Cartan type of self.

            EXAMPLES:
```sage: # needs sage.combinat sage.modules
sage: from sage.algebras.quantum_groups.representations import MinusculeRepresentation
sage: C = crystals.Tableaux(['C',4], shape=[1])
sage: R = ZZ['q'].fraction_field()
sage: V = MinusculeRepresentation(R, C)
sage: V.cartan_type()
['C', 4]

```python
    index_set()
        Return the index set of self.

        EXAMPLES:
```sage: # needs sage.combinat sage.modules
sage: from sage.algebras.quantum_groups.representations import MinusculeRepresentation
sage: C = crystals.Tableaux(['C',4], shape=[1])
sage: R = ZZ['q'].fraction_field()
sage: V = MinusculeRepresentation(R, C)
sage: V.index_set()
(1, 2, 3, 4)

```python
    q()
        Return the quantum parameter q of self.

        EXAMPLES:
```sage: # needs sage.combinat sage.modules
sage: from sage.algebras.quantum_groups.representations import MinusculeRepresentation
sage: C = crystals.Tableaux(['C',4], shape=[1])
sage: R = ZZ['q'].fraction_field()
```
class **TensorProducts** *(category, *args)*  
Bases: **TensorProductsCategory**  
The category of quantum group representations constructed by tensor product of quantum group representations.

**Warning:** We use the reversed coproduct in order to match the tensor product rule on crystals.

class **ParentMethods**  
Bases: object  

cartan_type()  

Return the Cartan type of self.

EXAMPLES:

```python  
sage: # needs sage.combinat sage.modules  
sage: from sage.algebras.quantum_groups.representations import...  
˓→MinusculeRepresentation  
sage: C = crystals.Tableaux(['C',2], shape=[1])  
sage: R = ZZ['q'].fraction_field()  
sage: V = MinusculeRepresentation(R, C)  
sage: T = tensor([V,V])  
sage: T.cartan_type()  
['C', 2]  
```

extra_super_categories()  

EXAMPLES:

```python  
sage: from sage.categories.quantum_group_representations import...  
˓→QuantumGroupRepresentations  
sage: Cat = QuantumGroupRepresentations(ZZ['q'].fraction_field())  
sage: Cat.TensorProducts().extra_super_categories()  
[Category of quantum group representations over  
Fraction Field of Univariate Polynomial Ring in q over Integer Ring]  
```

class **WithBasis** *(base_category)*  
Bases: **CategoryWithAxiom_over_base_ring**  
The category of quantum group representations with a distinguished basis.

class **ElementMethods**  
Bases: object  

\[ K(i, power=1) \]

Return the action of \( K_i \) on self to the power power.

**INPUT:**
- \( i \) – an element of the index set  
- \( power \) – (default: 1) the power of \( K_i \)

**EXAMPLES:**
```
sage: # needs sage.combinat sage.modules
sage: from sage.algebras.quantum_groups.representations import AdjointRepresentation
sage: K = crystals.KirillovReshetikhin(['D',4,2], 1,1)
sage: R = ZZ['q'].fraction_field()
sage: V = AdjointRepresentation(R, K)
sage: v = V.an_element(); v
2*B[[]] + 2*B([[1]]) + 3*B([[2]])
sage: v.K(0)
2*B[[]] + 2/q^2*B([[1]]) + 3*B([[2]])
sage: v.K(1)
2*B[[]] + 2*q^2*B([[1]]) + 3/q^2*B([[2]])
sage: v.K(1, 2)
2*B[[]] + 2*q^4*B([[1]]) + 3/q^4*B([[2]])
sage: v.K(1, -1)
2*B[[]] + 2/q^2*B([[1]]) + 3*q^2*B([[2]])
```

\(e(i)\)

Return the action of \(e_i\) on \(self\).

**INPUT:**

- \(i\) – an element of the index set

**EXAMPLES:**

```
sage: # needs sage.combinat sage.modules
sage: from sage.algebras.quantum_groups.representations import AdjointRepresentation
sage: C = crystals.Tableaux(['G',2], shape=[1,1])
sage: R = ZZ['q'].fraction_field()
sage: V = AdjointRepresentation(R, C)
sage: v = V.an_element(); v
2*B[[1], [2]] + 2*B[[1], [3]] + 3*B[[2], [3]]
sage: v.e(1)
((3*q^4+3*q^2+3)/q)*B[[1], [3]]
sage: v.e(2)
2*B[[1], [2]]
```

\(f(i)\)

Return the action of \(f_i\) on \(self\).

**INPUT:**

- \(i\) – an element of the index set

**EXAMPLES:**

```
sage: # needs sage.combinat sage.modules
sage: from sage.algebras.quantum_groups.representations import AdjointRepresentation
sage: K = crystals.KirillovReshetikhin(['D',4,1], 2,1)
sage: R = ZZ['q'].fraction_field()
sage: V = AdjointRepresentation(R, K)
sage: v = V.an_element(); v
2*B[[]] + 2*B[[[1], [2]]] + 3*B[[[1], [3]]]
sage: v.f(0)
((2*q^2+2)/q)*B[[[1], [2]]]
sage: v.f(1)
3*B[[[2], [3]]]
sage: v.f(2)
```

(continues on next page)
class ParentMethods
Bases: object
tensor(*factors)

Return the tensor product of self with the representations factors.

EXAMPLES:

sage: # needs sage.combinat sage.modules
sage: from sage.algebras.quantum_groups.representations import (....:
......: MinusculeRepresentation, AdjointRepresentation)
sage: R = ZZ['q'].fraction_field()
sage: CM = crystals.Tableaux(['D',4], shape=[1])
sage: CA = crystals.Tableaux(['D',4], shape=[1,1])
sage: V = MinusculeRepresentation(R, CM)
sage: V.tensor(V, V)
V((1, 0, 0, 0)) # V((1, 0, 0, 0)) # V((1, 0, 0, 0))
sage: A = MinusculeRepresentation(R, CA)
sage: V.tensor(A)
V((1, 0, 0, 0)) # V((1, 1, 0, 0))
sage: B = crystals.Tableaux(['A',2], shape=[1])
sage: W = MinusculeRepresentation(R, B)
sage: tensor([W,V])
Traceback (most recent call last):
... ValueError: all factors must be of the same Cartan type
sage: tensor([V,A,W])
Traceback (most recent call last):
... ValueError: all factors must be of the same Cartan type

class TensorProducts (category, *args)
Bases: TensorProductsCategory

The category of quantum group representations with a distinguished basis constructed by tensor product of quantum group representations with a distinguished basis.

class ParentMethods
Bases: object

K_on_basis(i, b, power=1)

Return the action of $K_i$ on the basis element indexed by $b$ to the power power.

INPUT:
• i – an element of the index set
• b – an element of basis keys
• power – (default: 1) the power of $K_i$

EXAMPLES:

sage: # needs sage.combinat sage.modules
sage: from sage.algebras.quantum_groups.representations import (....: MinusculeRepresentation, AdjointRepresentation)
sage: R = ZZ['q'].fraction_field()
sage: CM = crystals.Tableaux(['D',4], shape=[1])
sage: CA = crystals.Tableaux(['D',4], shape=[1,1])
sage: V = MinusculeRepresentation(R, CM)
sage: V.tensor(V, V)
V((1, 0, 0, 0)) # V((1, 0, 0, 0)) # V((1, 0, 0, 0))
sage: A = MinusculeRepresentation(R, CA)
sage: V.tensor(A)
V((1, 0, 0, 0)) # V((1, 1, 0, 0))
sage: B = crystals.Tableaux(['A',2], shape=[1])
sage: W = MinusculeRepresentation(R, B)
sage: tensor([W,V])
Traceback (most recent call last):
... ValueError: all factors must be of the same Cartan type
sage: tensor([V,A,W])
Traceback (most recent call last):
... ValueError: all factors must be of the same Cartan type
....: MinusculeRepresentation, AdjointRepresentation)

```python
sage: CM = crystals.Tableaux(['A', 2], shape=[1])
sage: VM = MinusculeRepresentation(R, CM)
sage: VA = AdjointRepresentation(R, CA)
sage: v = tensor([sum(VM.basis()), VA.module_generator()]); v
```

```latex
\begin{align*}
4*B[[1]] & \# B[[1], [2]] + 4*B[[1]] & \# B[[1], [3]]
+ 6*B[[1]] & \# B[[2], [3]] + 4*B[[2]] & \# B[[1], [2]]
+ 4*B[[2]] & \# B[[1], [3]] & + 6*B[[2]] & \# B[[2], [3]]
+ 6*B[[3]] & \# B[[1], [2]] & + 6*B[[3]] & \# B[[1], [3]]
+ 9*B[[3]] & \# B[[2], [3]]
\end{align*}
```

```python
sage: v.K(1) # indirect doctest
```

```latex
\begin{align*}
q^2*B[[1]] & \# B[[1], [2]]
+ B[[2]] & \# B[[1], [2]]
+ q*B[[3]] & \# B[[1], [2]]
\end{align*}
```

```python
sage: v.K(2, -1) # indirect doctest
```

```latex
\begin{align*}
1/q*B[[1]] & \# B[[1], [2]] + 1/q^2*B[[2]] & \# B[[1], [2]]
+ B[[3]] & \# B[[1], [2]]
\end{align*}
```

### e_on_basis(i, b)

Return the action of $e_i$ on the basis element indexed by $b$.

**INPUT:**

- $i$ – an element of the index set
- $b$ – an element of basis keys

**EXAMPLES:**

```python
sage: # needs sage.combinat sage.modules
sage: from sage.algebras.quantum_groups.representations import (....: MinusculeRepresentation, AdjointRepresentation)

sage: v = tensor([VM.an_element(), VA.an_element()]); v
```

```latex
\begin{align*}
4*B[[1]] & \# B[[1], [2]] + 4*B[[1]] & \# B[[1], [3]]
+ 6*B[[1]] & \# B[[2], [3]] + 4*B[[2]] & \# B[[1], [2]]
+ 4*B[[2]] & \# B[[1], [3]] & + 6*B[[2]] & \# B[[2], [3]]
+ 6*B[[3]] & \# B[[1], [2]] & + 6*B[[3]] & \# B[[1], [3]]
+ 9*B[[3]] & \# B[[2], [3]]
\end{align*}
```

```python
sage: v.e(1) # indirect doctest
```

```latex
\begin{align*}
4*B[[1]] & \# B[[1], [2]]
+ ((4*q+6)/q)*B[[1]] & \# B[[1], [3]] + 6*B[[1]] & \# B[[2], [3]]
+ 6*q*B[[2]] & \# B[[1], [3]] & + 9*B[[3]] & \# B[[1], [3]]
+ 9*B[[3]] & \# B[[2], [3]]
\end{align*}
```

```python
sage: v.e(2) # indirect doctest
```

```latex
\begin{align*}
4*B[[1]] & \# B[[1], [2]]
+ ((6*q+4)/q)*B[[2]] & \# B[[1], [2]] + 6*B[[2]] & \# B[[1], [3]]
+ 9*B[[2]] & \# B[[2], [3]] & + 6*q*B[[3]] & \# B[[1], [2]]
+ 6*B[[3]] & \# B[[1], [2]]
\end{align*}
```

```python
sage: v.e(3) # indirect doctest
```

```latex
\begin{align*}
0
\end{align*}
```

```python
sage: v.e(4) # indirect doctest
```

```latex
\begin{align*}
0
\end{align*}
```
\textbf{\texttt{f_on_basis}} \((i,b)\)

Return the action of \(f_i\) on the basis element indexed by \(b\).

\textbf{INPUT:}

- \(i\) – an element of the index set
- \(b\) – an element of basis keys

\textbf{EXAMPLES:}

\begin{verbatim}
sage: # needs sage.combinat sage.modules
sage: from sage.algebras.quantum_groups.representations import (...
  MinusculeRepresentation, AdjointRepresentation)

sage: R = ZZ['q'].fraction_field()
sage: KM = crystals.KirillovReshetikhin(['B',3,1], 3,1)
sage: VM = MinusculeRepresentation(R, KM)
sage: KA = crystals.KirillovReshetikhin(['B',3,1], 2,1)
sage: VA = AdjointRepresentation(R, KA)
sage: v = tensor([VM.an_element(), VA.an_element()]); v
   4*B[[++, [1]]] # B[[1], [2]]
   + 6*B[[++, [1]]] # B[[1], [3]]
   + 4*B[[++, [2]]] # B[[1], [3]]
   + 6*B[[++, [2]]] # B[[1], [3]]
   + 6*B[[++, [3]]] # B[[1], [3]]
   + 6*B[[++, [2]]] # B[[1], [3]]
   + 6*B[[++, [2]]] # B[[1], [3]]
   + 9*B[[++, [3]]] # B[[1], [3]]

sage: v.f(0)  # indirect doctest
   ((4*q^4+4)/q^2)*B[[++, [1]]] # B[[1], [2]]
   + ((4*q^4+4)/q^2)*B[[++, [1]]] # B[[1], [2]]
   + ((4*q^4+4)/q^2)*B[[++, [1]]] # B[[1], [2]]
   + ((6*q^4+6)/q^2)*B[[++, [1]]] # B[[1], [2]]

sage: v.f(1)  # indirect doctest
   6*B[[++, [1]]] # B[[2], [3]]
   + 6*B[[++, [1]]] # B[[2], [3]]
   + 9*B[[++, [1]]] # B[[2], [3]]
   + 6*B[[++, [1]]] # B[[2], [3]]
   + 6*B[[++, [1]]] # B[[2], [3]]
   + 9*B[[++, [1]]] # B[[2], [3]]
   + 6*B[[++, [1]]] # B[[2], [3]]
   + 9*B[[++, [1]]] # B[[2], [3]]

sage: v.f(2)  # indirect doctest
   4*B[[++, [1]]] # B[[1], [2]]
   + 4*B[[++, [1]]] # B[[1], [2]]
   + 4*B[[++, [1]]] # B[[1], [2]]
   + 4*B[[++, [1]]] # B[[1], [2]]
   + 4*B[[++, [1]]] # B[[1], [2]]
   + 4*B[[++, [1]]] # B[[1], [2]]
   + 4*B[[++, [1]]] # B[[1], [2]]
   + 4*B[[++, [1]]] # B[[1], [2]]

sage: v.f(3)  # indirect doctest
   6*B[[+, [1]]] # B[[1], [0]]
   + 4*B[[+, [1]]] # B[[1], [0]]
   + 4*B[[+, [1]]] # B[[1], [0]]
   + 6*B[[+, [1]]] # B[[1], [0]]
   + 6*B[[+, [1]]] # B[[1], [0]]
   + 9*B[[+, [1]]] # B[[1], [0]]
   + 6*B[[+, [1]]] # B[[1], [0]]
   + 6*B[[+, [1]]] # B[[1], [0]]
   + 9*B[[+, [1]]] # B[[1], [0]]

extra_super_categories()

\textbf{EXAMPLES:}

\begin{verbatim}
sage: from sage.categories.quantum_group_representations import 
  QuantumGroupRepresentations

sage: Cat = QuantumGroupRepresentations(ZZ['q'].fraction_field())
sage: Cat.WithBasis().TensorProducts().extra_super_categories()
(continues on next page)
\end{verbatim}
example()

Return an example of a quantum group representation as per Category.example.

EXAMPLES:

```sage
from sage.categories.quantum_group_representations import QuantumGroupRepresentations
sage: Cat = QuantumGroupRepresentations(ZZ['q'].fraction_field())
sage: Cat.example()  # needs sage.combinat sage.modules
V((2, 1, 0))
```

super_categories()

Return the super categories of self.

EXAMPLES:

```sage
from sage.categories.quantum_group_representations import QuantumGroupRepresentations
sage: QuantumGroupRepresentations(ZZ['q'].fraction_field()).super_categories()
[Category of vector spaces over Fraction Field of Univariate Polynomial Ring in q over Integer Ring]
```

### 4.132 Regular Crystals

**class sage.categories.regular_crystals.RegularCrystals**

Bases: `Category_singleton`

The category of regular crystals.

A crystal is called *regular* if every vertex \( b \) satisfies

\[
\varepsilon_i(b) = \max\{k \mid e_i^k(b) \neq 0\} \quad \text{and} \quad \varphi_i(b) = \max\{k \mid f_i^k(b) \neq 0\}.
\]

**Note:** Regular crystals are sometimes referred to as *normal*. When only one of the conditions (on either \( \varphi_i \) or \( \varepsilon_i \)) holds, these crystals are sometimes called *seminormal* or *semiregular*.

EXAMPLES:

```sage
C = RegularCrystals()
sage: C
Category of regular crystals
sage: C.super_categories()
[Category of crystals]
sage: C.example()
Highest weight crystal of type A_3 of highest weight omega_1
```

**class ElementMethods**

Bases: `object`
demazure_operator_simple\( (i, \text{ring}=\text{None}) \)

Return the Demazure operator \( D_i \) applied to self.

**INPUT:**
- \( i \) – an element of the index set of the underlying crystal
- \( \text{ring} \) – (default: \( \mathbb{Q} \)) a ring

**OUTPUT:**
An element of the ring-free module indexed by the underlying crystal.

Let \( r = (\text{wt}(b), \alpha_i^\vee) \), then \( D_i(b) \) is defined as follows:
- If \( r \geq 0 \), this returns the sum of the elements obtained from self by application of \( f_i^k \) for \( 0 \leq k \leq r \).
- If \( r < 0 \), this returns the opposite of the sum of the elements obtained by application of \( e_i^k \) for \( 0 < k < -r \).

**REFERENCES:**
- [Li1995]
- [Ka1993]

**EXAMPLES:**

```python
sage: T = crystals.Tableaux(['A',2], shape=[2,1])
sage: t = T(rows=[[1,2],[2]])
sage: t.demazure_operator_simple(2)
B[[[1, 2]], [[2]]] + B[[[1, 3], [2]]] + B[[[1, 3], [3]]]
sage: t.demazure_operator_simple(2).parent()
Algebra of The crystal of tableaux of type ['A', 2] and shape(s) [[2, 1]]
   over Integer Ring

sage: t.demazure_operator_simple(1)
0

sage: K = crystals.KirillovReshetikhin(['A',2,1],2,1)
sage: t = K(rows=[[3],[2]])
sage: t.demazure_operator_simple(0)
B[[[1, 2]]] + B[[[2, 3]]]
```

dual_equivalence_class \( (\text{index_set}=\text{None}) \)

Return the dual equivalence class indexed by \( \text{index_set} \) of self.

The dual equivalence class of an element \( b \in B \) is the set of all elements of \( B \) reachable from \( b \) via sequences of \( i \)-elementary dual equivalence relations (i.e., \( i \)-elementary dual equivalence transformations and their inverses) for \( i \) in the index set of \( B \).

For this to be well-defined, the element \( b \) has to be of weight 0 with respect to \( I \); that is, we need to have \( \varepsilon_j(b) = \varphi_j(b) \) for all \( j \in I \).

See [As2008]. See also dual_equivalence_graph() for a definition of \( i \)-elementary dual equivalence transformations.

**INPUT:**
- \( \text{index_set} \) – (optional) the index set \( I \) (default: the whole index set of the crystal); this has to be a subset of the index set of the crystal (as a list or tuple)

**OUTPUT:**
The dual equivalence class of self indexed by the subset \( \text{index_set} \). This class is returned as an undirected edge-colored multigraph. The color of an edge is the index \( i \) of the dual equivalence relation it encodes.

See also:
- `dual_equivalence_graph()`
- `sage.combinat.partition.Partition.dual_equivalence_graph()

**EXAMPLES:**

```python
sage: T = crystals.Tableaux(['A', 3], shape=[2,2])
sage: G = T(2,1,4,3).dual_equivalence_class()
sage: G.edges(sort=True)
[([[[1, 3], [2, 4]], [[1, 2], [3, 4]], 2),
  ([[1, 3], [2, 4]], [[1, 2], [3, 4]], 3))]
sage: T = crystals.Tableaux(['A',4], shape=[3,2])
sage: G = T(2,1,4,3,5).dual_equivalence_class()
sage: G.edges(sort=True)
[([[1, 3, 5], [2, 4]], [[1, 3, 4], [2, 5]], 4),
  ([[1, 3, 5], [2, 4]], [[1, 2, 5], [3, 4]], 2),
  ([[1, 3, 5], [2, 4]], [[1, 2, 5], [3, 4]], 3),
  ([[1, 3, 4], [2, 5]], [[1, 2, 4], [3, 5]], 2),
  ([[1, 3, 5], [2, 4]], [[1, 2, 3], [4, 5]], 3),
  ([[1, 2, 4], [3, 5]], [[1, 2, 3], [4, 5]], 4)]
```

**epsilon**(i)

Return $\varepsilon_i$ of self.

**EXAMPLES:**

```python
sage: C = crystals.Letters(['A',5])
sage: C(1).epsilon(1)
0
sage: C(2).epsilon(1)
1
```

**phi**(i)

Return $\varphi_i$ of self.

**EXAMPLES:**

```python
sage: C = crystals.Letters(['A',5])
sage: C(1).phi(1)
1
sage: C(2).phi(1)
0
```

**stembridgeDel_depth**(i,j)

Return the difference in the $j$-depth of self and $f_i$ of self, where $i$ and $j$ are in the index set of the underlying crystal. This function is useful for checking the Stembridge local axioms for crystal bases.

The $i$-depth of a crystal node $x$ is $\varepsilon_i(x)$.

**EXAMPLES:**

```python
sage: T = crystals.Tableaux(['A',2], shape=[2,1])
sage: t = T(rows=[[1,1],[2]])
sage: t.stembridgeDel_depth(1,2)
0
sage: s = T(rows=[[1,3],[3]])
sage: s.stembridgeDel_depth(1,2)
-1
```
**stembridgeDel_rise** *(i, j)*

Return the difference in the *j*-rise of `self` and \( f_i \) of `self`, where *i* and *j* are in the index set of the underlying crystal. This function is useful for checking the Stembridge local axioms for crystal bases.

The *i*-rise of a crystal node \( x \) is \( \varphi_i(x) \).

**EXAMPLES:**

```python
sage: T = crystals.Tableaux(['A', 2], shape=[2, 1])
sage: t = T(rows=[[1, 1], [2]])
sage: t.stembridgeDel_rise(1, 2)
-1
sage: s = T(rows=[[1, 3], [3]])
sage: s.stembridgeDel_rise(1, 2)
0
```

**stembridgeDelta_depth** *(i, j)*

Return the difference in the *j*-depth of `self` and \( e_i \) of `self`, where *i* and *j* are in the index set of the underlying crystal. This function is useful for checking the Stembridge local axioms for crystal bases.

The *i*-depth of a crystal node \( x \) is \( -\varepsilon_i(x) \).

**EXAMPLES:**

```python
sage: T = crystals.Tableaux(['A', 2], shape=[2, 1])
sage: t = T(rows=[[1, 2], [2]])
sage: t.stembridgeDelta_depth(1, 2)
0
sage: s = T(rows=[[2, 3], [3]])
sage: s.stembridgeDelta_depth(1, 2)
-1
```

**stembridgeDelta_rise** *(i, j)*

Return the difference in the *j*-rise of `self` and \( e_i \) of `self`, where *i* and *j* are in the index set of the underlying crystal. This function is useful for checking the Stembridge local axioms for crystal bases.

The *i*-rise of a crystal node \( x \) is \( \varphi_i(x) \).

**EXAMPLES:**

```python
sage: T = crystals.Tableaux(['A', 2], shape=[2, 1])
sage: t = T(rows=[[1, 2], [2]])
sage: t.stembridgeDelta_rise(1, 2)
-1
sage: s = T(rows=[[2, 3], [3]])
sage: s.stembridgeDelta_rise(1, 2)
0
```

**stembridgeTriple** *(i, j)*

Let \( A \) be the Cartan matrix of the crystal, \( x \) a crystal element, and let *i* and *j* be in the index set of the crystal. Further, set \( b = \text{stembridgeDelta_depth}(x, i, j) \) and \( c = \text{stembridgeDelta_rise}(x, i, j) \). If \( x.e(i) \) is non-empty, this function returns the triple \( (A_{ij}, b, c) \); otherwise it returns None. By the Stembridge local characterization of crystal bases, one should have \( A_{ij} = b + c \).

**EXAMPLES:**

```python
```
```python
sage: T = crystals.Tableaux(['A',2], shape=[2,1])
sage: t = T(rows=[[1,1],[2]])
sage: t.stembridgeTriple(1,2)
(-1, 0, -1)
sage: s = T(rows=[[1,2],[2]])
sage: s.stembridgeTriple(1,2)
(-2, 0, -2)
sage: u = T(rows=[[0,2],[1]])
sage: u.stembridgeTriple(1,2)
(-2, -1, -1)
```

**weight()**

Return the weight of this crystal element.

**EXAMPLES:**

```python
sage: C = crystals.Letters(['A',5])
sage: C(1).weight()
(1, 0, 0, 0, 0, 0)
```

**class MorphismMethods**

**Bases:** object

**is_isomorphism()**

Check if *self* is a crystal isomorphism, which is true if and only if this is a strict embedding with the same number of connected components.

**EXAMPLES:**

```python
sage: A21 = RootSystem(['A',2,1])
sage: La = A21.weight_space(extended=True).fundamental_weights()
sage: B = crystals.LSPaths(La[0])
sage: C = crystals.GeneralizedYoungWalls(2, La[0])
sage: H = Hom(B, C)
sage: from sage.categories.highest_weight_crystals import *
˓→HighestWeightCrystalMorphism
sage: class Psi(HighestWeightCrystalMorphism):
˓→    def is_strict(self):
˓→        return True
sage: psi = Psi(H, C.module_generators); psi
['A', 2, 1] Crystal morphism:
    From: The crystal of LS paths of type ['A', 2, 1] and weight Lambda[0]
    To: Highest weight crystal of generalized Young walls of Cartan type ['A', 2, 1] and highest weight Lambda[0]
    Defn: (Lambda[0],) |--> []
sage: psi.is_isomorphism()
True
```

**class ParentMethods**

**Bases:** object

4.132. Regular Crystals
demazure_operator \((element, reduced\_word)\)

Returns the application of Demazure operators \(D_i\) for \(i\) from \(reduced\_word\) on \(element\).

INPUT:
- element – an element of a free module indexed by the underlying crystal
- reduced_word – a reduced word of the Weyl group of the same type as the underlying crystal

OUTPUT:
- an element of the free module indexed by the underlying crystal

EXAMPLES:

```
sage: T = crystals.Tableaux(['A',2], shape=[2,1])
sage: C = CombinatorialFreeModule(QQ, T)
sage: t = T.highest_weight_vector()
sage: b = 2*C(t)
sage: T.demazure_operator(b,[1,2,1])
2*B[[[1, 1], [2]]] + 2*B[[[1,1, 2], [2]]] + 2*B[[[1, 3], [2]]]
+ 2*B[[[1, 1], [3]]] + 2*B[[[1, 2], [3]]] + 2*B[[[1, 3], [3]]]
+ 2*B[[[2, 2], [3]]] + 2*B[[[2, 3], [3]]]
```

The Demazure operator is idempotent:

```
sage: T = crystals.Tableaux('A1', shape=[4])
sage: C = CombinatorialFreeModule(QQ, T)
sage: b = C(T.module_generators[0]); b
B[[1, 1, 1, 1]]
sage: e = T.demazure_operator(b,[1]); e
B[[1, 1, 1, 1]] + B[[1, 1, 2, 2]] + B[[1, 2, 2, 2]] + B[[2, 2, 2, 2]]
```

```
sage: all(T.demazure_operator(T.demazure_operator(C(t),[1]),[1]) == T.demazure_operator(C(t),[1]) for t in T)
True
```

demazure_subcrystal \((element, reduced\_word, only\_support=True)\)

Return the subcrystal corresponding to the application of Demazure operators \(D_i\) for \(i\) from \(reduced\_word\) on \(element\).

INPUT:
- element – an element of a free module indexed by the underlying crystal
- reduced_word – a reduced word of the Weyl group of the same type as the underlying crystal
- only_support – (default: True) only include arrows corresponding to the support of \(reduced\_word\)

OUTPUT:
- the Demazure subcrystal

EXAMPLES:

```
sage: T = crystals.Tableaux(['A',2], shape=[2,1])
sage: t = T.highest_weight_vector()
sage: S = T.demazure_subcrystal(t, [1,2])
sage: list(S)
[[[1, 1], [2]], [[1, 2], [2]], [[1, 1], [3]],
 [[1, 2], [3]], [[2, 2], [3]]]
sage: S = T.demazure_subcrystal(t, [2,1])
sage: list(S)
```

(continues on next page)
We construct an example where we don’t only want the arrows indicated by the support of the reduced word:

```python
sage: K = crystals.KirillovReshetikhin(['A',1,1], 1, 2)
sage: mg = K.module_generator()
sage: S = K.demazure_subcrystal(mg, [1])
sage: S.digraph().edges(sort=True)
[([[1, 1]], [[1, 2]], 1), ([[1, 2]], [[2, 2]], 1)]
sage: S = K.demazure_subcrystal(mg, [1], only_support=False)
sage: S.digraph().edges(sort=True)
[([[1, 1]], [[1, 2]], 1),
 [[[1, 2]], [[1, 1]], 0),
 [[[1, 2]], [[2, 2]], 1),
 [[[2, 2]], [[1, 2]], 0)]
```

**dual_equivalence_graph** (*X=None, index_set=None, directed=True*)

Return the dual equivalence graph indexed by `index_set` on the subset `X` of `self`.

Let \( b \in B \) be an element of weight 0, so \( \varepsilon_j(b) = \varphi_j(b) \) for all \( j \in I \), where \( I \) is the indexing set. We say \( b' \) is an \( i \)-elementary dual equivalence transformation of \( b \) (where \( i \in I \)) if
- \( \varepsilon_i(b) = 1 \) and \( \varepsilon_{i-1}(b) = 0 \), and
- \( b' = f_{i-1}f_ie_i^{-1}e_ib \).

We can do the inverse procedure by interchanging \( i \) and \( i-1 \) above.

**Note:** If the index set is not an ordered interval, we let \( i - 1 \) mean the index appearing before \( i \) in \( I \).

This definition comes from [As2008] Section 4 (where our \( \varphi_j(b) \) and \( \varepsilon_j(b) \) are denoted by \( \epsilon(b, j) \) and \( -\delta(b, j) \), respectively).

The dual equivalence graph of \( B \) is defined to be the colored graph whose vertices are the elements of \( B \) of weight 0, and whose edges of color \( i \) (for \( i \in I \)) connect pairs \( \{b, b'\} \) such that \( b' \) is an \( i \)-elementary dual equivalence transformation of \( b \).

**Note:** This dual equivalence graph is a generalization of \( G(X) \) in [As2008] Section 4 except we do not require \( \varepsilon_i(b) = 0, 1 \) for all \( i \).

This definition can be generalized by choosing a subset \( X \) of the set of all vertices of \( B \) of weight 0, and restricting the dual equivalence graph to the vertex set \( X \).

**INPUT:**
- \( X \) – (optional) the vertex set \( X \) (default: the whole set of vertices of `self` of weight 0)
- `index_set` – (optional) the index set \( I \) (default: the whole index set of `self`); this has to be a subset of the index set of `self` (as a list or tuple)
- `directed` – (default: `True`) whether to have the dual equivalence graph be directed, where the head of an edge \( b \to b' \) is \( b \) and the tail is \( b' = f_{i-1}f_ie_i^{-1}e_ib \)

**See also:**
- `sage.combinat.partition.Partition.dual_equivalence_graph()`

**EXAMPLES:**
sage: T = crystals.Tableaux(['A',3], shape=[2,2])
sage: G = T.dual_equivalence_graph()
sage: G.edges(sort=True)
[([[1, 3], [2, 4]], [[1, 2], [3, 4]], 2),
 ([[1, 2], [3, 4]], [[1, 3], [2, 4]], 3)]
sage: T = crystals.Tableaux(['A',4], shape=[3,2])
sage: G = T.dual_equivalence_graph()
sage: G.edges(sort=True)
[([[1, 3, 5], [2, 4]], [[1, 3, 4], [2, 5]], 4),
 ([[1, 3, 5], [2, 4]], [[1, 2, 5], [3, 4]], 2),
 ([[1, 3, 4], [2, 5]], [[1, 2, 4], [3, 5]], 2),
 ([[1, 2, 5], [3, 4]], [[1, 3, 5], [2, 4]], 3),
 ([[1, 2, 4], [3, 5]], [[1, 2, 3], [4, 5]], 3),
 ([[1, 2, 3], [4, 5]], [[1, 2, 4], [3, 5]], 4)]
sage: T = crystals.Tableaux(['A',4], shape=[3,1])
sage: G = T.dual_equivalence_graph(index_set=[1,2,3])
sage: G.vertices(sort=True)
[[[1, 3, 4], [2]], [[1, 2, 4], [3]], [[1, 2, 3], [4]]]
sage: G.edges(sort=True)
[([[1, 3, 4], [2]], [[1, 2, 4], [3]], 2),
 ([[1, 2, 4], [3]], [[1, 2, 3], [4]], 3)]

class TensorProducts

Bases: TensorProductsCategory

The category of regular crystals constructed by tensor product of regular crystals.

extra_super_categories()

EXAMPLES:

sage: RegularCrystals().TensorProducts().extra_super_categories()
[Category of regular crystals]

additional_structure()

Return None.

Indeed, the category of regular crystals defines no new structure: it only relates \(\varepsilon_a\) and \(\varphi_a\) to \(e_a\) and \(f_a\) respectively.

See also:

Category.additional_structure()

Todo: Should this category be a CategoryWithAxiom?

EXAMPLES:

sage: RegularCrystals().additional_structure()

example (n=3)

Returns an example of highest weight crystals, as per Category.example().

EXAMPLES:

sage: B = RegularCrystals().example(); B
Highest weight crystal of type A_3 of highest weight omega_1
super_categories()

EXAMPLES:

```
sage: RegularCrystals().super_categories()
[Category of crystals]
```

## 4.133 Regular Supercrystals

```python
class sage.categories.regular_supercrystals.RegularSuperCrystals
    Bases: Category_singleton

The category of crystals for super Lie algebras.

EXAMPLES:
```
sage: from sage.categories.regular_supercrystals import RegularSuperCrystals
sage: C = RegularSuperCrystals()
sage: C
Category of regular super crystals
sage: C.super_categories()
[Category of finite super crystals]
```

Parents in this category should implement the following methods:

- either an attribute `_cartan_type` or a method `cartan_type`
- `module_generators`: a list (or container) of distinct elements that generate the crystal using $f_i$ and $e_i$

Furthermore, their elements $x$ should implement the following methods:

- $x.e(i)$ (returning $e_i(x)$)
- $x.f(i)$ (returning $f_i(x)$)
- $x.weight()$ (returning $\text{wt}(x)$)

EXAMPLES:
```
sage: from sage.misc.abstract_method import abstract_methods_of_class
sage: from sage.categories.regular_supercrystals import RegularSuperCrystals
sage: abstract_methods_of_class(RegularSuperCrystals().element_class)
{optional: [], required: ['e', 'f', 'weight']}
```

```python
class ElementMethods
    Bases: object

    epsilon(i)
    Return $\varepsilon_i$ of self.

    EXAMPLES:
```
sage: C = crystals.Tableaux(['A', [1,2]], shape=[2,1])
sage: c = C.an_element(); c
[-2, -2], [-1]
sage: c.epsilon(2)
0
sage: c.epsilon(0)
0
```

(continues on next page)
sage: c.epsilon(-1)
0
phi(i)
Return \( \varphi_i \) of self.

EXAMPLES:

sage: C = crystals.Tableaux(['A', [1,2]], shape=[2,1])
sage: c = C.an_element(); c
[[-2, -2], [-1]]
sage: c.phi(1)
0
sage: c.phi(2)
0
sage: c.phi(0)
1

class TensorProducts(category, *args)
Bases: TensorProductsCategory
The category of regular crystals constructed by tensor product of regular crystals.

extra_super_categories()
EXAMPLES:

sage: from sage.categories.regular_supercrystals import RegularSuperCrystals
sage: RegularSuperCrystals().TensorProducts().extra_super_categories()
[Category of regular super crystals]

super_categories()
EXAMPLES:

sage: from sage.categories.regular_supercrystals import RegularSuperCrystals
sage: C = RegularSuperCrystals()
sage: C.super_categories()
[Category of finite super crystals]

4.134 Right modules

class sage.categories.right_modules.RightModules(base, name=None)
Bases: Category_over_base_ring
The category of right modules right modules over an rng (ring not necessarily with unit), i.e. an abelian group with right multiplication by elements of the rng

EXAMPLES:

sage: RightModules(QQ)
Category of right modules over Rational Field
sage: RightModules(QQ).super_categories()
[Category of commutative additive groups]
class ElementMethods
    Bases: object

class ParentMethods
    Bases: object

super_categories()
    EXAMPLES:

    sage: RightModules(QQ).super_categories()
    [Category of commutative additive groups]

4.135 Ring ideals

class sage.categories.ring_ideals.RingIdeals(R)
    Bases: Category_ideal

    The category of two-sided ideals in a fixed ring.

    EXAMPLES:

    sage: Ideals(Integers(200))
    Category of ring ideals in Ring of integers modulo 200
    sage: C = Ideals(IntegerRing()); C
    Category of ring ideals in Integer Ring
    sage: I = C([8,12,18])
    sage: I
    Principal ideal (2) of Integer Ring

    See also: CommutativeRingIdeals.

Todo:

- If useful, implement RingLeftIdeals and RingRightIdeals of which RingIdeals would be a subcategory.

- Make RingIdeals(R), return CommutativeRingIdeals(R) when R is commutative.

super_categories()
    EXAMPLES:

    sage: RingIdeals(ZZ).super_categories()
    [Category of modules over Integer Ring]
    sage: RingIdeals(QQ).super_categories()
    [Category of vector spaces over Rational Field]
4.136 Rings

class sage.categories.rings.Rings(base_category):
    """Category of rings"""
    Bases: CategoryWithAxiom_singleton

    The category of rings

    Associative rings with unit, not necessarily commutative

    EXAMPLES:

    sage: Rings()
    Category of rings
    sage: sorted(Rings().super_categories(), key=str)
    [Category of rngs, Category of semirings]
    sage: sorted(Rings().axioms())
    ['AdditiveAssociative', 'AdditiveCommutative', 'AdditiveInverse',
     'AdditiveUnital', 'Associative', 'Distributive', 'Unital']
    sage: Rings() is (CommutativeAdditiveGroups() & Monoids()).Distributive()
    True
    sage: Rings() is Rngs().Unital()
    True
    sage: Rings() is Semirings().AdditiveInverse()
    True

Todo: (see github issue #sage_trac/wiki/CategoriesRoadMap)

    * Make Rings() into a subcategory or alias of Algebras(ZZ);
    * A parent P in the category Rings() should automatically be in the category Algebras(P).

Commutative
    alias of CommutativeRings

Division
    alias of DivisionRings

class ElementMethods
    Bases: object

    inverse_of_unit()
    """Return the inverse of this element if it is a unit."

    OUTPUT:

    An element in the same ring as this element.

    EXAMPLES:

    sage: R.<x> = ZZ[]
    sage: S = R.quo(x^2 + x + 1)
    # needs sage.libs.pari
    sage: S(1).inverse_of_unit()  # needs sage.libs.pari
    1
This method fails when the element is not a unit:

```
sage: 2.inverse_of_unit()
Traceback (most recent call last):
...
ArithmeticError: inverse does not exist
```

The inverse returned is in the same ring as this element:

```
sage: a = -1
sage: a.parent()
Integer Ring
sage: a.inverse_of_unit().parent()
Integer Ring
```

Note that this is often not the case when computing inverses in other ways:

```
sage: (-a).parent()
Rational Field
sage: (1/a).parent()
Rational Field
```

```
is_unit()
Return whether this element is a unit in the ring.

Note: This is a generic implementation for (non-commutative) rings which only works for the one
element, its additive inverse, and the zero element. Most rings should provide a more specialized imple-
mentation.

EXAMPLES:

```
sage: # needs sage.modules
sage: MS = MatrixSpace(ZZ, 2)
sage: MS.one().is_unit()
True
sage: MS.zero().is_unit()
False
sage: MS([1,2,3,4]).is_unit()
False
```

```
class MorphismMethods
Bases: object

extend_to_fraction_field()
Return the extension of this morphism to fraction fields of the domain and the codomain.

EXAMPLES:

```
sage: S.<x> = QQ[]
sage: f = S.hom([x + 1]); f
Ring endomorphism of Univariate Polynomial Ring in x over Rational Field
  Defn: x |--> x + 1
sage: g = f.extend_to_fraction_field(); g
#-˓needs sage.libs.singular
Ring endomorphism of Fraction Field of Univariate Polynomial Ring in x
(continues on next page)
over Rational Field

Defn: \( x \mapsto x + 1 \)

\[ \text{sage: } g(x) \text{ #...} \]

\( \text{needs sage.libs.singular} \)

\[ x + 1 \]

\[ \text{sage: } g(1/x) \text{ #...} \]

\( \text{needs sage.libs.singular} \)

\[ 1/(x + 1) \]

If this morphism is not injective, it does not extend to the fraction field and an error is raised:

\[ \text{sage: } f = \text{GF}(5).\text{coerce_map_from}(\mathbb{Z}) \]

\[ \text{sage: } f.\text{extend_to_fraction_field()} \]

Traceback (most recent call last):
  ...

ValueError: the morphism is not injective

**is_injective()**

Return whether or not this morphism is injective.

**EXAMPLES:**

\[ \text{sage: } \# \text{ needs sage.libs.singular} \]

\[ \text{sage: } R.\langle x,y \rangle = \mathbb{Q}[\]

\[ \text{sage: } R.\text{hom}([x, y^2], R).\text{is_injective()} \]

True

\[ \text{sage: } R.\text{hom}([x, x^2], R).\text{is_injective()} \]

False

\[ \text{sage: } S.\langle u,v \rangle = R.\text{quotient}(x^3*y) \]

\[ \text{sage: } R.\text{hom}([v, u], S).\text{is_injective()} \]

False

\[ \text{sage: } S.\text{hom}([-u, v], S).\text{is_injective()} \]

True

\[ \text{sage: } S.\text{cover()}.\text{is_injective()} \]

False

If the domain is a field, the homomorphism is injective:

\[ \text{sage: } K.\langle x \rangle = \text{FunctionField}(\mathbb{Q}) \]

\[ \text{sage: } L.\langle y \rangle = \text{FunctionField}(\mathbb{Q}) \]

\[ \text{sage: } f = K.\text{hom}([y]); f \]

Function Field morphism:
  From: Rational function field in x over Rational Field
  To: Rational function field in y over Rational Field
  Defn: x \mapsto y

\[ \text{sage: } f.\text{is_injective()} \]

True

Unless the codomain is the zero ring:

\[ \text{sage: } \text{codomain} = \text{Integers}(1) \]

\[ \text{sage: } f = \text{QQ.\text{hom}([\text{Zmod}(1)(0)], \text{check=False})} \]

\[ \text{sage: } f.\text{is_injective()} \]

False

Homomorphism from rings of characteristic zero to rings of positive characteristic can not be injective:
A morphism whose domain is an order in a number field is injective if the codomain has characteristic zero:

```
sage: K.<x> = FunctionField(QQ)
sage: f = ZZ.hom(K); f
Composite map:
  From: Integer Ring
  To: Rational function field in x over Rational Field
  Defn: Conversion via FractionFieldElement_1poly_field map:
    From: Integer Ring
    To: Fraction Field of Univariate Polynomial Ring in x over Rational Field
    then
    Isomorphism:
    From: Fraction Field of Univariate Polynomial Ring in x over Rational Field
    To: Rational function field in x over Rational Field
sage: f.is_injective()
True
```

A coercion to the fraction field is injective:

```
sage: R = ZpFM(3)
  # needs sage.rings.padics
sage: R.fraction_field().coerce_map_from(R).is_injective()
True
```

---

**NoZeroDivisors**

alias of **Domains**

**class ParentMethods**

Bases: object

```
  bracket (x, y)
  
  Return the Lie bracket \([x, y] = xy - yx\) of \(x\) and \(y\).

  INPUT:
  * x, y – elements of self
  
  EXAMPLES:

  sage: # needs sage.combinat sage.modules
  sage: F = AlgebrasWithBasis(QQ).example()
sage: F
  An example of an algebra with basis:
  the free algebra on the generators ('a', 'b', 'c') over Rational Field
sage: a, b, c = F.algebra_generators()
sage: F.bracket(a, b)
B[word: ab] - B[word: ba]
```
This measures the default of commutation between $x$ and $y$. $F$ endowed with the bracket operation is a Lie algebra; in particular, it satisfies Jacobi’s identity:

```python
sage: (F.bracket(F.bracket(a,b), c) + F.bracket(F.bracket(b,c), a))  
˓→needs sage.combinat sage.modules
....: + F.bracket(F.bracket(c,a), b))
0
```

**characteristic()**

Return the characteristic of this ring.

**EXAMPLES:**

```python
sage: QQ.characteristic() 0
sage: GF(19).characteristic() 19
sage: Integers(8).characteristic() 8
sage: Zp(5).characteristic() ˓→needs sage.rings.padics
0
```

**free_module**(base=None, basis=None, map=True)

Return a free module $V$ over the specified subring together with maps to and from $V$.

The default implementation only supports the case that the base ring is the ring itself.

**INPUT:**
- base – a subring $R$ so that this ring is isomorphic to a finite-rank free $R$-module $V$
- basis – (optional) a basis for this ring over the base
- map – boolean (default True), whether to return $R$-linear maps to and from $V$

**OUTPUT:**
- A finite-rank free $R$-module $V$
- An $R$-module isomorphism from $V$ to this ring (only included if map is True)
- An $R$-module isomorphism from this ring to $V$ (only included if map is True)

**EXAMPLES:**

```python
sage: # needs sage.modules
sage: R.<x> = QQ[]
```

```python
sage: V, from_V, to_V = R.free_module(R)
```

```python
sage: v = to_V(1 + x); v
(1 + x)
```

```python
sage: from_V(v)
1 + x
```

```python
sage: W, from_W, to_W = R.free_module(R, basis=(1 - x))
```

```python
sage: W is V
True
```

```python
sage: w = to_W(1 + x); w
(1 - x^2)
```

```python
sage: from_W(w)
1 + x + O(x^20)
```

**ideal**(args, **kwds)

Create an ideal of this ring.

**Note:** The code is copied from the base class `Ring`. This is because there are rings that do not inherit
from that class, such as matrix algebras. See github issue #7797.

INPUT:

- An element or a list/tuple/sequence of elements.
- coerce (optional bool, default True): First coerce the elements into this ring.
- side, optional string, one of "twosided" (default), "left", "right": determines whether
  the resulting ideal is twosided, a left ideal or a right ideal.

EXAMPLES:

```python
sage: # needs sage.modules
sage: MS = MatrixSpace(QQ, 2, 2)
sage: isinstance(MS, Ring)
False
sage: MS in Rings()
True
sage: MS.ideal(2)
Twosided Ideal
  (  [2 0]
    [0 2]
  )
of Full MatrixSpace of 2 by 2 dense matrices over Rational Field
sage: MS.ideal([MS.0, MS.1], side='right')
Right Ideal
  (  [1 0]
    [0 0],
  [0 1]
    [0 0]
  )
of Full MatrixSpace of 2 by 2 dense matrices over Rational Field
```

ideal_monoid()

The monoid of the ideals of this ring.

**Note:** The code is copied from the base class of rings. This is since there are rings that do not inherit
from that class, such as matrix algebras. See github issue #7797.

EXAMPLES:

```python
sage: # needs sage.modules
sage: MS = MatrixSpace(QQ, 2, 2)
sage: isinstance(MS, Ring)
False
sage: MS in Rings()
True
sage: MS.ideal_monoid()
Monoid of ideals of Full MatrixSpace of 2 by 2 dense matrices
  over Rational Field
```

Note that the monoid is cached:
is_commutative()
Return whether the ring is commutative.

The answer is True only if the category is a sub-category of CommutativeRings.

It is recommended to use instead R in Rings().Commutative().

EXAMPLES:

```
sage: Q.<i,j,k> = QuaternionAlgebra(QQ, -1, -1)  
    # needs sage.combinat sage.modules
sage: Q.is_commutative()  
    # needs sage.combinat sage.modules
False
```

is_ring()
Return True, since this in an object of the category of rings.

EXAMPLES:

```
sage: Parent(QQ,category=Rings()).is_ring()  
True
```

is_zero()
Return True if this is the zero ring.

EXAMPLES:

```
sage: Integers(1).is_zero()  
True
sage: Integers(2).is_zero()  
False
sage: QQ.is_zero()  
False
sage: R.<x> = ZZ[]
sage: R.quo(1).is_zero()  
True
sage: R.<x> = GF(101)[]
sage: R.quo(77).is_zero()  
True
```

quo(I, names=None, **kwds)
Quotient of a ring by a two-sided ideal.

Note: This is a synonym for quotient().

EXAMPLES:

```
sage: MS = MatrixSpace(QQ, 2)  
    # needs sage.modules
```

MS is not an instance of :class:`Ring`.

However it is an instance of the parent class of the category of rings. The quotient method is inherited from there:

```python
sage: isinstance(MS, sage.rings.ring.Ring)  # needs sage.modules
False
sage: isinstance(MS, Rings().parent_class)  # needs sage.modules
True
sage: MS.quo(I, names=['a', 'b', 'c', 'd'])  # needs sage.modules
Quotient of Full MatrixSpace of 2 by 2 dense matrices over Rational Field by the ideal

\[
\begin{pmatrix}
1 & 0 \\
0 & 0
\end{pmatrix},
\begin{pmatrix}
0 & 1 \\
0 & 0
\end{pmatrix},
\begin{pmatrix}
0 & 0 \\
1 & 0
\end{pmatrix},
\begin{pmatrix}
0 & 0 \\
0 & 1
\end{pmatrix}
\]
```

A test with a subclass of :class:`Ring`:

```python
sage: R.<x,y> = PolynomialRing(QQ, 2)
sage: S.<a,b> = R.quo((x^2, y))
sage: S
Quotient of Multivariate Polynomial Ring in x, y over Rational Field by the ideal (x^2, y)
sage: S.gens()
(a, 0)
sage: a == b
False
```

.. automodule:: sage.rings.quotient_ring_element
   :members:

`quotient`: \( (I, \text{names}=\text{None}, **\text{kwds}) \)

Quotient of a ring by a two-sided ideal.

**INPUT:**

- \( I \) – A twosided ideal of this ring.
- \( \text{names} \) – (optional) names of the generators of the quotient (if there are multiple generators, you can specify a single character string and the generators are named in sequence starting with 0).
- further named arguments that may be passed to the quotient ring constructor.

**EXAMPLES:**

Usually, a ring inherits a method `sage.rings.ring.Ring.quotient()`. So, we need a bit of effort to make the following example work with the category framework:
An example with polynomial rings:

```python
sage: R.<x> = PolynomialRing(ZZ)
sage: I = R.ideal([4 + 3*x + x^2, 1 + x^2])
sage: S = R.quotient(I, 'a')
sage: S.gens()
a
sage: # needs sage.libs.singular
sage: R.<x,y> = PolynomialRing(QQ, 2)
sage: S.<a,b> = R.quotient((x^2, y))
sage: S.quotient_ring(I, names=None, **kwds)
Quotient of a ring by a two-sided ideal.
```

Note: This is a synonym for `quotient()`.  

quotient_ring(I, names=None, **kwds)  
Quotient of a ring by a two-sided ideal.
INPUT:
• I – an ideal of $R$
• names – (optional) names of the generators of the quotient. (If there are multiple generators, you can specify a single character string and the generators are named in sequence starting with 0.)
• further named arguments that may be passed to the quotient ring constructor.

OUTPUT:
• $R/I$ – the quotient ring of $R$ by the ideal $I$

EXAMPLES:

```python
sage: MS = MatrixSpace(QQ, 2)  # needs sage.modules
sage: I = MS * MS.gens() * MS  # needs sage.modules
```

MS is not an instance of `Ring`, but it is an instance of the parent class of the category of rings. The quotient method is inherited from there:

```python
sage: isinstance(MS, sage.rings.ring.Ring)  # needs sage.modules
False
sage: isinstance(MS, Rings().parent_class)  # needs sage.modules
True
sage: MS.quotient_ring(I, names=['a','b','c','d'])  # needs sage.modules
```

A test with a subclass of `Ring`:

```python
sage: R.<x> = PolynomialRing(ZZ)
sage: I = R.ideal([4 + 3*x + x^2, 1 + x^2])
sage: S = R.quotient_ring(I, 'a')
sage: S.gens()
(a,)
```

```python
sage: R.<x,y> = PolynomialRing(QQ,2)
sage: S.<a,b> = R.quotient_ring((x^2, y))
sage: S
Quotient of Multivariate Polynomial Ring in x, y over Rational Field by the ideal (x^2, y)
sage: S.gens()
(a, 0)
```

(continues on next page)
class SubcategoryMethods
    Bases: object

    Division()
    Return the full subcategory of the division objects of self.

    A ring satisfies the division axiom if all non-zero elements have multiplicative inverses.

    EXAMPLES:

    sage: Rings().Division()
    Category of division rings
    sage: Rings().Commutative().Division()
    Category of fields

    NoZeroDivisors()
    Return the full subcategory of the objects of self having no nonzero zero divisors.

    A zero divisor in a ring \( R \) is an element \( x \in R \) such that there exists a nonzero element \( y \in R \) such that \( x \cdot y = 0 \) or \( y \cdot x = 0 \) (see Wikipedia article Zero_divisor).

    EXAMPLES:

    sage: Rings().NoZeroDivisors()
    Category of domains

4.137 Rngs

class sage.categories.rngs.Rngs(base_category)
    Bases: CategoryWithAxiom_singleton
    The category of rngs.

    An rng \((S, +, *)\) is similar to a ring but not necessarily unital. In other words, it is a combination of a commutative additive group \((S, +)\) and a multiplicative semigroup \((S, *)\), where * distributes over +.

    EXAMPLES:

    sage: C = Rngs(); C
    Category of rngs
    sage: sorted(C.super_categories(), key=str)
    ['Category of associative additive commutative additive associative additive unital distributive magmas and additive magmas, Category of commutative additive groups']
    sage: C.axioms()
    ['AdditiveAssociative', 'AdditiveCommutative', 'AdditiveInverse', 'AdditiveUnital', 'Associative', 'Distributive']
    sage: C.is (CommutativeAdditiveGroups() & Semigroups()).Distributive()
    True
    sage: C.Unital()
    Category of rings
**4.138 R-trivial semigroups**

```python
class sage.categories.r_trivial_semigroups.RTrivialSemigroups(base_category):
    Bases: CategoryWithAxiom

    Commutative_extra_super_categories()
    Implement the fact that a commutative $R$-trivial semigroup is $J$-trivial.
    EXAMPLES:
    sage: Semigroups().RTrivial().Commutative_extra_super_categories()
    [Category of j trivial semigroups]

    extra_super_categories()
    Implement the fact that a $R$-trivial semigroup is $H$-trivial.
    EXAMPLES:
    sage: Semigroups().RTrivial().extra_super_categories()
    [Category of h trivial semigroups]
```

**4.139 Schemes**

```python
class sage.categories.schemes.AbelianVarieties(base):
    Bases: Schemes_over_base

    The category of abelian varieties over a given field.
    EXAMPLES:
    sage: AbelianVarieties(QQ)
    Category of abelian varieties over Rational Field
    sage: AbelianVarieties ZZ
    Traceback (most recent call last):
    ...
    ValueError: category of abelian varieties is only defined over fields

class Homsets(category, *args):
    Bases: HomsetsCategory

    Overloaded Homsets class to register the homset as an additive abelian group.
    EXAMPLES:
    sage: AbelianVarieties(QQ).Homsets().is_
    ...
    subcategory(CommutativeAdditiveGroups())
    True
```
class Endset(base_category)
    
    Overloaded Endset class to register the endset as a ring.
    
sage: AbelianVarieties(QQ).Endsets().is_subcategory(Rings()) True

extra_super_categories()
    Register the endset as a ring.

EXAMPLES:

    sage: End(EllipticCurve(j=1)) in Rings()
    True

extra_super_categories()
    Register the homset as an additive abelian group.

EXAMPLES:

    sage: Hom(EllipticCurve(j=1), EllipticCurve(j=2)) in...
    ...CommutativeAdditiveGroups()
    True

super_categories()

EXAMPLES:

    sage: AbelianVarieties(QQ).super_categories()
    [Category of schemes over Rational Field,
     Category of commutative additive groups]

class sage.categories.schemes.Schemes
    
    The category of all schemes.

    EXAMPLES:

    sage: Schemes()
    Category of schemes

Schemes can also be used to construct the category of schemes over a given base:

    sage: Schemes(Spec(ZZ))
    Category of schemes over Integer Ring

    sage: Schemes(ZZ)
    Category of schemes over Integer Ring

Todo: Make Schemes() a singleton category (and remove Schemes from the workaround in
category_types.Category_over_base._test_category_over_bases()).
This is currently incompatible with the dispatching below.

super_categories()

EXAMPLES:
4.140 Semigroups

class sage.categories.semigroups.Semigroups(base_category)

Bases: CategoryWithAxiom_singleton

The category of (multiplicative) semigroups.

A semigroup is an associative magma, that is a set endowed with a multiplicative binary operation \(*\) which is associative (see Wikipedia article Semigroup).

The operation \(*\) is not required to have a neutral element. A semigroup for which such an element exists is a monoid.

EXAMPLES:

```python
sage: C = Semigroups(); C
Category of semigroups
sage: C.super_categories()
[Category of magmas]
sage: C.all_super_categories()
[Category of semigroups, Category of magmas, Category of sets, Category of sets with partial maps, Category of objects]
sage: C.axioms()
frozenset({'Associative'})
sage: C.example()
An example of a semigroup: the left zero semigroup
```

class Algebras(category, *args)

Bases: AlgebrasCategory
class ParentMethods
    Bases: object

algebra_generators()
    The generators of this algebra, as per MagmaticAlgebras.ParentMethods.
    algebra_generators().
    They correspond to the generators of the semigroup.
    EXAMPLES:

    sage: M = FiniteSemigroups().example(); M
    An example of a finite semigroup:
    the left regular band generated by ('a', 'b', 'c', 'd')
    sage: M.semigroup_generators()
    Family ('a', 'b', 'c', 'd')
    sage: M.algebra(ZZ).algebra_generators()  # needs sage.modules
    Family (B['a'], B['b'], B['c'], B['d'])

    gen (i=0)
    Return the i-th generator of self.
    EXAMPLES:

    sage: A = GL(3, GF(7)).algebra(ZZ)  # needs sage.modules
    sage: A.gen(0)  # needs sage.groups sage.libs.pari sage.modules
    [3 0 0]
    [0 1 0]
    [0 0 1]

gens()
    Return the generators of self.
    EXAMPLES:

    sage: a, b = SL2Z.algebra(ZZ).gens(); a, b  # needs sage.groups sage.modules
    ([ 0 -1]
     [ 1 0],
    [1 1]
    [0 1])
    sage: 2*a + b  # needs sage.groups sage.modules
    2*[ 0 -1]
    [ 1 0]  +
    [1 1]
    [0 1]

ngens()
    Return the number of generators of self.
    EXAMPLES:
sage: SL2Z.algebra(ZZ).ngens()                      # needs sage.groups sage.modules
2

sage: DihedralGroup(4).algebra(RR).ngens()        # needs sage.groups sage.modules
2

product_on_basis\((g1, g2)\)
Product, on basis elements, as per `MagmaticAlgebras.WithBasis.ParentMethods.product_on_basis()`.

The product of two basis elements is induced by the product of the corresponding elements of the group.

EXAMPLES:

sage: S = FiniteSemigroups().example(); S
An example of a finite semigroup:
the left regular band generated by \('a', 'b', 'c', 'd'\)
sage: A = S.algebra(QQ)                           # needs sage.modules
sage: a, b, c, d = A.algebra_generators()         # needs sage.modules
sage: a * b + b * d * c * d                      # needs sage.modules
B['ab'] + B['bdc']

regular_representation\((side='left')\)
Return the regular representation of \(\text{self}\).

INPUT:
• \textit{side} – (default: "left") whether this is the "left" or "right" regular representation

EXAMPLES:

sage: G = groups.permutation.Dihedral(4)
sage: A = G.algebra(QQ)                           # needs sage.modules
sage: V = A.regular_representation()              # needs sage.modules
sage: V == G.regular_representation(QQ)           # needs sage.modules
True

trivial_representation\((side='twosided')\)
Return the trivial representation of \(\text{self}\).

INPUT:
• \textit{side} – ignored

EXAMPLES:

sage: G = groups.permutation.Dihedral(4)
sage: A = G.algebra(QQ)                           # needs sage.modules
sage: V = A.trivial_representation()              # needs sage.modules

extra_super_categories()
Implement the fact that the algebra of a semigroup is indeed a (not necessarily unital) algebra.

EXAMPLES:

```
sage: Semigroups().Algebras(QQ).extra_super_categories()
[Category of semigroups]
sage: Semigroups().Algebras(QQ).super_categories()
[Category of associative algebras over Rational Field,
 Category of magma algebras over Rational Field]
```

Aperiodic
alias of AperiodicSemigroups

class CartesianProducts(category, *args)
Bases: CartesianProductsCategory
extra_super_categories()
Implement the fact that a Cartesian product of semigroups is a semigroup.

EXAMPLES:

```
sage: Semigroups().CartesianProducts().extra_super_categories()
[Category of semigroups]
sage: Semigroups().CartesianProducts().super_categories()
[Category of semigroups, Category of Cartesian products of magmas]
```

class ElementMethods
Bases: object

Finite
alias of FiniteSemigroups

FinitelyGeneratedAsMagma
alias of FinitelyGeneratedSemigroups

HTrivial
alias of HTrivialSemigroups

JTrivial
alias of JTrivialSemigroups

LTrivial
alias of LTrivialSemigroups

class ParentMethods
Bases: object
cayley_graph (side='right', simple=False, elements=None, generators=None, connecting_set=None)
Return the Cayley graph for this finite semigroup.

INPUT:
• side – “left”, “right”, or “twosided”: the side on which the generators act (default:”right”)
• simple – boolean (default:False): if True, returns a simple graph (no loops, no labels, no multiple edges)
• generators – a list, tuple, or family of elements of self (default: self.
  semigroup_generators())
• connecting_set – alias for generators; deprecated
• elements – a list (or iterable) of elements of self

OUTPUT:
• DiGraph

EXAMPLES:

We start with the (right) Cayley graphs of some classical groups:

```
sage: # needs sage.graphs sage.groups
sage: D4 = DihedralGroup(4); D4
Dihedral group of order 8 as a permutation group
sage: G = D4.cayley_graph()
sage: show(G, color_by_label=True, edge_labels=True) # needs sage.plot
....
sage: A5 = AlternatingGroup(5); A5
Alternating group of order 5!/2 as a permutation group
sage: G = A5.cayley_graph()
sage: G.show3d(color_by_label=True, edge_size=0.01, # needs sage.plot
    ....:    edge_size2=0.02, vertex_size=0.03)
sage: G.show3d(vertex_size=0.03, # long time (less than a minute),...
    ....:    edge_size=0.01, edge_size2=0.02,
    ....:    vertex_colors={(1,1,1): G.vertices(sort=True)},
    ....:    bgcolor=(0,0,0), color_by_label=True,
    ....:    xres=700, yres=700, iterations=200)
sage: G.num_edges() 
120
```

```
sage: # needs sage.combinat sage.graphs sage.groups
sage: M = Monoids().example(); M
An example of a monoid:
(continues on next page)
```

Alternative generators may be specified:

```
sage: # needs sage.graphs sage.groups
sage: G = A5.cayley_graph(generators=[A5.gens()[0]])
sage: G.num_edges() 
60
sage: g = PermutationGroup([(i + 1, j + 1)
    ....:    for i in range(5)
    ....:    for j in range(5) if j != i])
sage: g.cayley_graph(generators=[(1,2), (2,3)])
Digraph on 120 vertices
```

If `elements` is specified, then only the subgraph induced and those elements is returned. Here we use it to display the Cayley graph of the free monoid truncated on the elements of length at most 3:

```
sage: # needs sage.combinat sage.graphs
sage: M = Monoids().example(); M
An example of a monoid:
```

(continues on next page)

4.140. Semigroups 721
the free monoid generated by ('a', 'b', 'c', 'd')

```
sage: elements = [M.prod(w) for w in sum((list(Words(M.semigroup_generators(), k)) for k in range(4)), [])]
sage: G = M.cayley_graph(elements=elements)
sage: G.num_verts(), G.num_edges()
(85, 84)
sage: G.show3d(color_by_label=True, edge_size=0.001, vertex_size=0.01)  # needs sage.plot
```

We now illustrate the `side` and `simple` options on a semigroup:

```
sage: S = FiniteSemigroups().example(alphabet=('a', 'b'))
sage: g = S.cayley_graph(simple=True)  # needs sage.graphs
sage: g.vertices(sort=True)  # needs sage.graphs
['a', 'ab', 'b', 'ba']
sage: g.edges(sort=True)  # needs sage.graphs
[('a', 'ab', None), ('b', 'ba', None)]
sage: g = S.cayley_graph(side="left", simple=True)  # needs sage.graphs
sage: g.vertices(sort=True)  # needs sage.graphs
['a', 'ab', 'b', 'ba']
sage: g.edges(sort=True)  # needs sage.graphs
[('a', 'ba', None), ('ab', 'ba', None), ('b', 'ab', None), ('ba', 'ab', None)]
sage: g = S.cayley_graph(side="twosided", simple=True)  # needs sage.graphs
sage: g.vertices(sort=True)  # needs sage.graphs
['a', 'ab', 'b', 'ba']
sage: g.edges(sort=True)  # needs sage.graphs
[('a', 'ab', None), ('a', 'ba', None), ('ab', 'ba', None), ('b', 'ab', None), ('b', 'ba', None), ('ba', 'ab', None)]
sage: g = S.cayley_graph(side="twosided")  # needs sage.graphs
sage: g.vertices(sort=True)  # needs sage.graphs
['a', 'ab', 'b', 'ba']
sage: g.edges(sort=True)  # needs sage.graphs
[('a', 'a', (0, left')), ('a', 'a', (0, right)), ('a', 'ab', (1, right ˓→)), ('a', 'ba', (1, left ˓→)), ('ab', 'ab', (0, left ˓→)), ('ab', 'ab', (0, ˓→)), ('ab', 'ab', (1, right ˓→)), ('ab', 'ba', (1, right ˓→)), ('ab', 'ba', (1, right')), ('b', 'ab', (0, left ˓→)), ('b', 'ab', (0, right))]
```

(continued from previous page)
Todo:
• Add more options for constructing subgraphs of the Cayley graph, handling the standard use cases when exploring large/infinite semigroups (a predicate, generators of an ideal, a maximal length in term of the generators)
• Specify good default layout/plot/latex options in the graph
• Generalize to combinatorial modules with module generators / operators

AUTHORS:
• Bobby Moretti (2007-08-10)
• Robert Miller (2008-05-01): editing
• Nicolas M. Thiery (2008-12): extension to semigroups, side, simple, and elements options, …

magma_generators()
An alias for `semigroup_generators()`.

EXAMPLES:

```python
sage: S = Semigroups().example("free"); S
An example of a semigroup: the free semigroup generated by ('a', 'b', 'c', 'd')
sage: S.magma_generators()
Family ('a', 'b', 'c', 'd')
sage: S.semigroup_generators()
Family ('a', 'b', 'c', 'd')
```

prod(args)
Return the product of the list of elements `args` inside `self`.

EXAMPLES:

```python
sage: S = Semigroups().example("free")
sage: S.prod([S('a'), S('b'), S('c')])
'abc'
sage: S.prod([])
Traceback (most recent call last):
  ...
AssertionError: Cannot compute an empty product in a semigroup
```

regular_representation(base_ring=None, side='left')
Return the regular representation of `self` over `base_ring`.
• side – (default: "left") whether this is the "left" or "right" regular representation

EXAMPLES:

```python
sage: G = groups.permutation.Dihedral(4)  #...
  ← needs sage.groups
sage: G.regular_representation()
  ← needs sage.groups
```

(continues on next page)
Left Regular Representation of Dihedral group of order 8 as a permutation group over Integer Ring

**semigroup_generators()**

Return distinguished semigroup generators for self.

**OUTPUT:** a family

This method is optional.

**EXAMPLES:**

```
sage: S = Semigroups().example("free"); S
An example of a semigroup: the free semigroup generated by ('a', 'b', 'c', 'd')
sage: S.semigroup_generators()
Family ('a', 'b', 'c', 'd')
```

**subsemigroup** *(generators, one=None, category=None)*

Return the multiplicative subsemigroup generated by *generators*.

**INPUT:**

- *generators* – a finite family of elements of self, or a list, iterable, … that can be converted into one (see Family).
- *one* – a unit for the subsemigroup, or None.
- *category* – a category

This implementation lazily constructs all the elements of the semigroup, and the right Cayley graph relations between them, and uses the latter as an automaton.

See `AutomaticSemigroup` for details.

**EXAMPLES:**

```
sage: R = IntegerModRing(15)
sage: M = R.subsemigroup([R(3), R(5)]); M
A subsemigroup of (Ring of integers modulo 15) with 2 generators
sage: M.list()
[3, 5, 9, 0, 10, 12, 6]
```

By default, *M* is just in the category of subsemigroups:

```
sage: M in Semigroups().Subobjects()
True
```

In the following example, we specify that *M* is a submonoid of the finite monoid *R* (it shares the same unit), and a group by itself:

```
sage: M = R.subsemigroup([R(-1)],
    ..., category=Monoids().Finite().Subobjects() & Groups()); M
A submonoid of (Ring of integers modulo 15) with 1 generators
sage: M.list()
[1, 14]
```
In the following example, $M$ is a group; however, its unit does not coincide with that of $R$, so $M$ is only a subsemigroup, and we need to specify its unit explicitly:

```python
sage: M = R.subsemigroup([R(5)], one=R(10),
....:    category=Semigroups().Finite().Subobjects() & Groups()); M
A subsemigroup of (Ring of integers modulo 15) with 1 generators
sage: M in Groups()
True
sage: M.list()
[10, 5]
sage: M.one()
10
```

Todo:
- Fix the failure in TESTS by providing a default implementation of `__invert__` for finite groups (or even finite monoids).
- Provide a default implementation of `one` for a finite monoid, so that we would not need to specify it explicitly?

```python
def trivial_representation(base_ring=None, side='twosided')
    return self.trivial_representation(base_ring=base_ring, side=side)
```

```python
class Quotients(category, *args)
    Bases: QuotientsCategory
```
semigroup_generators()

Return semigroup generators for self by retracting the semigroup generators of the ambient semigroup.

EXAMPLES:

```python
sage: S = FiniteSemigroups().Quotients().example().semigroup_generators() # todo: not implemented
```

element()

Return an example of quotient of a semigroup, as per Category.example().

EXAMPLES:

```python
sage: Semigroups().Quotients().example()
An example of a (sub)quotient semigroup: a quotient of the left zero...
```

RTrivial

alias of RTrivialSemigroups

class SubcategoryMethods

Bases: object

Aperiodic()

Return the full subcategory of the aperiodic objects of self.

A (multiplicative) semigroup $S$ is aperiodic if for any element $s \in S$, the sequence $s, s^2, s^3, ...$ eventually stabilizes.

In terms of variety, this can be described by the equation $s^2 s = s$.

EXAMPLES:

```python
sage: Semigroups().Aperiodic()
Category of aperiodic semigroups
```

An aperiodic semigroup is $H$-trivial:

```python
sage: Semigroups().Aperiodic().axioms()
frozenset({'Aperiodic', 'Associative', 'HTrivial'})
```

In the finite case, the two notions coincide:

```python
sage: Semigroups().Aperiodic().Finite() is Semigroups().HTrivial().Finite()
True
```

See also:

- Wikipedia article Aperiodic_semigroup
- Semigroups.SubcategoryMethods.RTrivial
- Semigroups.SubcategoryMethods.LTrivial
- Semigroups.SubcategoryMethods.JTrivial
- Semigroups.SubcategoryMethods.Aperiodic

HTrivial()

Return the full subcategory of the $H$-trivial objects of self.
Let \( S \) be (multiplicative) semigroup. Two elements of \( S \) are in the same \( H \)-class if they are in the same \( L \)-class and in the same \( R \)-class.

The semigroup \( S \) is \( H \)-trivial if all its \( H \)-classes are trivial (that is of cardinality 1).

**EXAMPLES:**

```python
sage: C = Semigroups().HTrivial(); C
Category of h trivial semigroups
sage: Semigroups().HTrivial().Finite().example()
NotImplemented
```

See also:

- Wikipedia article Green%27s_relations
- Semigroups.SubcategoryMethods.RTrivial
- Semigroups.SubcategoryMethods.LTrivial
- Semigroups.SubcategoryMethods.JTrivial
- Semigroups.SubcategoryMethods.Aperiodic

**JTrivial()**

Return the full subcategory of the \( J \)-trivial objects of \( self \).

Let \( S \) be (multiplicative) semigroup. The \( J \)-preorder \( \leq_J \) on \( S \) is defined by:

\[
x \leq_J y \iff x \in S y S
\]

The \( J \)-classes are the equivalence classes for the associated equivalence relation. The semigroup \( S \) is \( J \)-trivial if all its \( J \)-classes are trivial (that is of cardinality 1), or equivalently if the \( J \)-preorder is in fact a partial order.

**EXAMPLES:**

```python
sage: C = Semigroups().JTrivial(); C
Category of j trivial semigroups
```

A semigroup is \( J \)-trivial if and only if it is \( L \)-trivial and \( R \)-trivial:

```python
sage: sorted(C.axioms())
['Associative', 'HTrivial', 'JTrivial', 'LTrivial', 'RTrivial']
sage: Semigroups().LTrivial().RTrivial()
Category of j trivial semigroups
```

For a commutative semigroup, all three axioms are equivalent:

```python
sage: Semigroups().Commutative().LTrivial()
Category of commutative j trivial semigroups
sage: Semigroups().Commutative().RTrivial()
Category of commutative j trivial semigroups
```

See also:

- Wikipedia article Green%27s_relations
- Semigroups.SubcategoryMethods.LTrivial
- Semigroups.SubcategoryMethods.RTrivial
- Semigroups.SubcategoryMethods.HTrivial

**LTrivial()**

Return the full subcategory of the \( L \)-trivial objects of \( self \).
Let $S$ be (multiplicative) semigroup. The $L$-preorder $\leq_L$ on $S$ is defined by:

$$x \leq_L y \iff x \in Sy$$

The $L$-classes are the equivalence classes for the associated equivalence relation. The semigroup $S$ is $L$-trivial if all its $L$-classes are trivial (that is of cardinality 1), or equivalently if the $L$-preorder is in fact a partial order.

EXAMPLES:

```
sage: C = Semigroups().LTrivial(); C
Category of l trivial semigroups
```

A $L$-trivial semigroup is $H$-trivial:

```
sage: sorted(C.axioms())
['Associative', 'HTrivial', 'LTrivial']
```

See also:

- Wikipedia article Green%27s_relations
- Semigroups.SubcategoryMethods.RTrivial
- Semigroups.SubcategoryMethods.JTrivial
- Semigroups.SubcategoryMethods.HTrivial

RTrivial() 
Return the full subcategory of the $R$-trivial objects of self.

Let $S$ be (multiplicative) semigroup. The $R$-preorder $\leq_R$ on $S$ is defined by:

$$x \leq_R y \iff x \in yS$$

The $R$-classes are the equivalence classes for the associated equivalence relation. The semigroup $S$ is $R$-trivial if all its $R$-classes are trivial (that is of cardinality 1), or equivalently if the $R$-preorder is in fact a partial order.

EXAMPLES:

```
sage: C = Semigroups().RTrivial(); C
Category of r trivial semigroups
```

An $R$-trivial semigroup is $H$-trivial:

```
sage: sorted(C.axioms())
['Associative', 'HTrivial', 'RTrivial']
```

See also:

- Wikipedia article Green%27s_relations
- Semigroups.SubcategoryMethods.LTrivial
- Semigroups.SubcategoryMethods.JTrivial
- Semigroups.SubcategoryMethods.HTrivial

```python
class Subquotients(category, *args)
    Bases: SubquotientsCategory
    The category of subquotient semi-groups.
    EXAMPLES:
```

Chapter 4. Individual Categories
sage: Semigroups().Subquotients().all_super_categories()

[Category of subquotients of semigroups,
 Category of semigroups,
 Category of subquotients of magmas,
 Category of magmas,
 Category of subquotients of sets,
 Category of sets,
 Category of sets with partial maps,
 Category of objects]

[Category of subquotients of semigroups,
 Category of semigroups,
 Category of subquotients of magmas,
 Category of magmas,
 Category of subquotients of sets,
 Category of sets,
 Category of sets with partial maps,
 Category of objects]

example()

Returns an example of subquotient of a semigroup, as per Category.example().

EXAMPLES:

sage: Semigroups().Subquotients().example()
An example of a (sub)quotient semigroup: a quotient of the left zero...

Unital

alias of Monoids

eexample(choice='leftzero', **kwds)

Returns an example of a semigroup, as per Category.example().

INPUT:

- choice – str (default: 'leftzero'). Can be either 'leftzero' for the left zero semigroup, or 'free' for the free semigroup.

- **kwds – keyword arguments passed onto the constructor for the chosen semigroup.

EXAMPLES:

sage: Semigroups().example(choice='leftzero')
An example of a semigroup: the left zero semigroup
sage: Semigroups().example(choice='free')
An example of a semigroup: the free semigroup generated by (\texttt{a}', \texttt{b}', \texttt{c}', \texttt{d} →')
sage: Semigroups().example(choice='free', alphabet=(\texttt{a}', \texttt{b}'))
An example of a semigroup: the free semigroup generated by (\texttt{a}', \texttt{b}')
4.141 Semirings

```
class sage.categories.semirings.Semirings(base_category):
    Bases: CategoryWithAxiom_singleton

    The category of semirings.

    A semiring \((S, +, \ast)\) is similar to a ring, but without the requirement that each element must have an additive inverse. In other words, it is a combination of a commutative additive monoid \((S, +)\) and a multiplicative monoid \((S, \ast)\), where \(\ast\) distributes over \(+\).

    See also:
    Wikipedia article Semiring

    EXAMPLES:

    sage: Semirings()
    Category of semirings
    sage: Semirings().super_categories()
    [Category of associative additive commutative additive associative additive_unital distributive magmas and additive magmas, Category of monoids]
    sage: sorted(Semirings().axioms())
    ['AdditiveAssociative', 'AdditiveCommutative', 'AdditiveUnital', 'Associative', 'Distributive', 'Unital']
    sage: Semirings() is (CommutativeAdditiveMonoids() & Monoids()).Distributive()
    True
    sage: Semirings().AdditiveInverse()
    Category of rings
```

4.142 Semisimple Algebras

```
class sage.categories.semisimple_algebras.SemisimpleAlgebras(base, name=None):
    Bases: Category_over_base_ring

    The category of semisimple algebras over a given base ring.

    EXAMPLES:

    sage: from sage.categories.semisimple_algebras import SemisimpleAlgebras
    sage: C = SemisimpleAlgebras(QQ); C
    Category of semisimple algebras over Rational Field
    sage: C is SemisimpleAlgebras(QQ); C
    True
    sage: C.super_categories()
    [Category of algebras over Rational Field]
```

This category is best constructed as:

```
sage: D = Algebras(QQ).Semisimple(); D
Category of semisimple algebras over Rational Field
sage: D is C
True
sage: C.super_categories()
[Category of algebras over Rational Field]
```
Typically, finite group algebras are semisimple:

```sage
dihedral_group(5).algebra(QQ) in SemisimpleAlgebras #...

← needs sage.groups

True
```

Unless the characteristic of the field divides the order of the group:

```sage
dihedral_group(5).algebra(IntegerModRing(5)) in SemisimpleAlgebras #...

← needs sage.groups

False
```

```sage
dihedral_group(5).algebra(IntegerModRing(7)) in SemisimpleAlgebras #...

← needs sage.groups

True
```

See also:

Wikipedia article Semisimple_algebra

class **FiniteDimensional**(base_category)

    Bases: CategoryWithAxiom_over_base_ring

    WithBasis

        alias of FiniteDimensionalSemisimpleAlgebrasWithBasis

class **ParentMethods**

    Bases: object

    ```radical_basis(**keywords)```

        Return a basis of the Jacobson radical of this algebra.

            • keywords – for compatibility; ignored.

        OUTPUT: the empty list since this algebra is semisimple.

        EXAMPLES:

```sage
A = SymmetricGroup(4).algebra(QQ) #...

← needs sage.groups

sage: A.radical_basis() #...

← needs sage.groups

()`

```

```sage
super_categories()

EXAMPLES:

```sage
Algebras(QQ).Semisimple().super_categories()

[Category of algebras over Rational Field]`
### 4.143 Sets

**exception** `sage.categories.sets_cat.EmptySetError`

Bases: `ValueError`

Exception raised when some operation can't be performed on the empty set.

**EXAMPLES:**

```python
sage: def first_element(st):
    ....:     if not st: raise EmptySetError("no elements")
    ....:     else: return st[0]
sage: first_element(Set((1,2,3)))
1
sage: first_element(Set([]))
Traceback (most recent call last):
  ... 
EmptySetError: no elements
```

**class** `sage.categories.sets_cat.Sets`

Bases: `Category_singleton`

The category of sets.

The base category for collections of elements with = (equality).

This is also the category whose objects are all parents.

**EXAMPLES:**

```python
sage: Sets()
Category of sets
sage: Sets().super_categories()
[Category of sets with partial maps]
sage: Sets().all_super_categories()
[Category of sets, Category of sets with partial maps, Category of objects]
```

Let us consider an example of set:

```python
sage: P = Sets().example("inherits")
sage: P
Set of prime numbers
```

See `P??` for the code.

P is in the category of sets:

```python
sage: P.category()
Category of sets
```

and therefore gets its methods from the following classes:

```python
sage: for cl in P.__class__.mro(): print(cl)
<class 'sage.categories.examples.sets_cat.PrimeNumbers_Inherits_with_category'>
<class 'sage.categories.examples.sets_cat.PrimeNumbers_Inherits'>
<class 'sage.categories.examples.sets_cat.PrimeNumbers_Abstract'>
<class 'sage.structure.unique_representation.UniqueRepresentation'>
<class 'sage.structure.unique_representation.CachedRepresentation'>
<class 'sage.misc.fast_methods.WithEqualityById'>
```

(continues on next page)
We run some generic checks on P:

```python
sage: TestSuite(P).run(verbosity=True)  # needs sage.libs.pari
running __test_an_element() ... pass
running __test_category() ... pass
running __test_category() ... pass
running __test_construction() ... pass
running __test_elements() ... pass
    Running the test suite of self.an_element()
running __test_category() ... pass
running __test_eq() ... pass
running __test_new() ... pass
running __test_not_implemented_methods() ... pass
running __test_pickling() ... pass
    pass
running __test_elements_eq_reflexive() ... pass
running __test_elements_eq_symmetric() ... pass
running __test_elements_eq_transitive() ... pass
running __test_elements_neq() ... pass
running __test_eq() ... pass
running __test_new() ... pass
running __test_not_implemented_methods() ... pass
running __test_pickling() ... pass
running __test_some_elements() ... pass
```

Now, we manipulate some elements of P:

```python
sage: P.an_element()
47
sage: x = P(3)
sage: x.parent()
Set of prime numbers
sage: x in P, 4 in P
(True, False)
sage: x.is_prime()
True
```

They get their methods from the following classes:

```python
sage: for cl in x.__class__.mro(): print(cl)
<class 'sage.categories.examples.sets_cat.PrimeNumbers_Inherits_with_category.Element_class'>
<class 'sage.categories.examples.sets_cat.PrimeNumbers_Inherits.Element'>
<class 'sage.rings.integer.IntegerWrapper'>
<class 'sage.rings.integer.Integer'>
<class 'sage.structure.element.EuclideanDomainElement'>
<class 'sage.structure.element.PrincipalIdealDomainElement'>
<class 'sage.structure.element.DedekindDomainElement'>
```
class Algebras(category, *args)
    Bases: AlgebrasCategory

class ParentMethods
    Bases: object

    construction()
    Return the functorial construction of self.

    EXAMPLES:

    sage: A = GroupAlgebra(KleinFourGroup(), QQ)
    # needs sage.groups sage.modules
    sage: F, arg = A.construction(); F, arg
    # needs sage.groups sage.modules
    (GroupAlgebraFunctor, Rational Field)
    sage: F(arg) is A
    # needs sage.groups sage.modules
    True

    This also works for structures such as monoid algebras (see github issue #27937):

    sage: A = FreeAbelianMonoid('x,y').algebra(QQ)
    # needs sage.groups sage.modules
    sage: F, arg = A.construction(); F, arg
    # needs sage.groups sage.modules
    (The algebra functorial construction, Free abelian monoid on 2 generators (x, y))
    sage: F(arg) is A
    # needs sage.groups sage.modules
    True

    extra_super_categories()

    EXAMPLES:

    sage: Sets().Algebras(ZZ).super_categories()
    [Category of modules with basis over Integer Ring]

    sage: Sets().Algebras(QQ).extra_super_categories()
    [Category of vector spaces with basis over Rational Field]

    sage: Sets().example().algebra(ZZ).categories()
    # needs sage.modules
class CartesianProducts(category, *args)

Bases: CartesianProductsCategory

EXAMPLES:

sage: C = Sets().CartesianProducts().example()
sage: C
The Cartesian product of (Set of prime numbers (basic implementation),
An example of an infinite enumerated set: the non negative integers,
An example of a finite enumerated set: \{1,2,3\})
sage: C.category()
Category of Cartesian products of sets
sage: C.categories()
[Category of Cartesian products of sets, Category of sets,
  Category of sets with partial maps,
  Category of objects]
sage: TestSuite(C).run()

class ElementMethods

Bases: object

cartesian_factors()

Return the Cartesian factors of self.

EXAMPLES:

sage: # needs sage.modules
sage: F = CombinatorialFreeModule(ZZ, [4,5]); F.rename("F")
sage: G = CombinatorialFreeModule(ZZ, [4,6]); G.rename("G")
sage: H = CombinatorialFreeModule(ZZ, [4,7]); H.rename("H")
sage: S = cartesian_product([F, G, H])
  
  x = S.monomial((0,4)) + 2 * S.monomial((0,5))
  + 3 * S.monomial((1,6)) + 4 * S.monomial((2,4))
  + 5 * S.monomial((2,7))
  x.cartesian_factors()
sage: [s.parent() for s in x.cartesian_factors()]
[F, G, H]
sage: S.zero().cartesian_factors()
(0, 0, 0)
sage: [s.parent() for s in S.zero().cartesian_factors()]
[F, G, H]

cartesian_projection(i)

Return the projection of self onto the i-th factor of the Cartesian product.

INPUT:

• i – the index of a factor of the Cartesian product

EXAMPLES:
sage: # needs sage.modules
sage: F = CombinatorialFreeModule(ZZ, [4, 5]); F.rename("F")
sage: G = CombinatorialFreeModule(ZZ, [4, 6]); G.rename("G")
sage: S = cartesian_product([F, G])
sage: x = (S.monomial((0,4)) + 2 * S.monomial((0,5))
    + 3 * S.monomial((1,6)))
sage: x.cartesian_projection(0)
sage: x.cartesian_projection(1)
3*B[6]

class ParentMethods
Bases: object

an_element()

EXAMPLES:

sage: C = Sets().CartesianProducts().example(); C
The Cartesian product of (Set of prime numbers (basic implementation),
An example of an infinite enumerated set: the non negative integers,
An example of a finite enumerated set: {1,2,3})
sage: C.an_element()
(47, 42, 1)

cardinality()

Return the cardinality of self.

EXAMPLES:

sage: E = FiniteEnumeratedSet([1,2,3])
sage: C = cartesian_product([E, SymmetricGroup(4)])
# needs sage.groups
sage: C.cardinality()
72
sage: E = FiniteEnumeratedSet([])
sage: C = cartesian_product([E, ZZ, QQ])
sage: C.cardinality()
0
sage: C = cartesian_product([ZZ, QQ])
sage: C.cardinality()
+Infinity
sage: cartesian_product([GF(5), Permutations(10)]).cardinality()
18144000
sage: cartesian_product([GF(71)]*20).cardinality() == 71**20
True

cartesian_factors()

Return the Cartesian factors of self.

EXAMPLES:

sage: cartesian_product([QQ, ZZ, ZZ]).cartesian_factors()
(Rational Field, Integer Ring, Integer Ring)
**cartesian_projection** (*i*)

Return the natural projection onto the *i*-th Cartesian factor of `self`.

**INPUT:**

- *i* – the index of a Cartesian factor of `self`

**EXAMPLES:**

```python
sage: C = Sets().CartesianProducts().example(); C
The Cartesian product of (Set of prime numbers (basic implementation),
An example of an infinite enumerated set: the non negative integers,
An example of a finite enumerated set: (1,2,3))
sage: x = C.an_element(); x
(47, 42, 1)
sage: pi = C.cartesian_projection(1)
sage: pi(x)
42
```

**construction** ()

The construction functor and the list of Cartesian factors.

**EXAMPLES:**

```python
sage: C = cartesian_product([QQ, ZZ, ZZ])
sage: C.construction()
(The cartesian_product functorial construction,
Rational Field, Integer Ring, Integer Ring)
```

**is_empty** ()

Return whether this set is empty.

**EXAMPLES:**

```python
sage: S1 = FiniteEnumeratedSet([1,2,3])
sage: S2 = Set([])
sage: cartesian_product([S1,ZZ]).is_empty()
False
sage: cartesian_product([S1,S2,S1]).is_empty()
True
```

**is_finite** ()

Return whether this set is finite.

**EXAMPLES:**

```python
sage: E = FiniteEnumeratedSet([1,2,3])
sage: C = cartesian_product([E, SymmetricGroup(4)])
# needs sage.groups
sage: C.is_finite()
# needs sage.groups
True
sage: cartesian_product([ZZ,ZZ]).is_finite()
False
sage: cartesian_product([ZZ, Set(), ZZ]).is_finite()
True
```

**random_element** (*args*)

Return a random element of this Cartesian product.
The extra arguments are passed down to each of the factors of the Cartesian product.

EXAMPLES:

```python
sage: C = cartesian_product([Permutations(10)]*5)
sage: C.random_element()  # random
([2, 9, 4, 7, 1, 8, 6, 10, 5, 3],
 [8, 6, 5, 7, 1, 4, 9, 3, 10, 2],
 [5, 10, 3, 8, 2, 9, 1, 4, 7, 6],
 [9, 6, 10, 3, 2, 1, 5, 8, 7, 4],
 [8, 5, 2, 9, 10, 3, 7, 1, 4, 6])
```

```python
sage: C = cartesian_product([ZZ]*10)
sage: c1 = C.random_element()
sage: c1  # random
(3, 1, 4, 1, 1, -3, 0, -4, -17, 2)
sage: c2 = C.random_element(4,7)
sage: c2  # random
(6, 5, 6, 4, 5, 6, 6, 4, 5, 5)
sage: all(4 <= i < 7 for i in c2)
True
```

`extra_super_categories()`

A Cartesian product of sets is a set.

EXAMPLES:

```python
sage: Sets().CartesianProducts().extra_super_categories()
[Category of sets]
sage: Sets().CartesianProducts().super_categories()
[Category of sets]
```

class ElementMethods

Bases: object

`cartesian_product(*elements)`

Return the Cartesian product of its arguments, as an element of the Cartesian product of the parents of those elements.

EXAMPLES:

```python
sage: C = AlgebrasWithBasis(QQ)
sage: A = C.example()  # needs sage.combinat, sage.modules
sage: a, b, c = A.algebra_generators()  # needs sage.combinat, sage.modules
sage: a.cartesian_product(b, c)  # needs sage.combinat, sage.modules
B[(0, word: a)] + B[(1, word: b)] + B[(2, word: c)]
```

FIXME: is this a policy that we want to enforce on all parents?
Enumerated
   alias of EnumeratedSets

Facade
   alias of FacadeSets

Finite
   alias of FiniteSets

class Infinite(base_category)
   Bases: CategoryWithAxiom_singleton

class ParentMethods
   Bases: object

   cardinality()
   Count the elements of the enumerated set.

   EXAMPLES:

   sage: NN = InfiniteEnumeratedSets().example()
sage: NN.cardinality()
+Infinity

   is_empty()
   Return whether this set is empty.
   Since this set is infinite this always returns False.

   EXAMPLES:

   sage: C = InfiniteEnumeratedSets().example()
sage: C.is_empty()
False

   is_finite()
   Return whether this set is finite.
   Since this set is infinite this always returns False.

   EXAMPLES:

   sage: C = InfiniteEnumeratedSets().example()
sage: C.is_finite()
False

class IsomorphicObjects(category, *args)
   Bases: IsomorphicObjectsCategory

   A category for isomorphic objects of sets.

   EXAMPLES:

   sage: Sets().IsomorphicObjects()
   Category of isomorphic objects of sets
   sage: Sets().IsomorphicObjects().all_super_categories()
   [Category of isomorphic objects of sets,
   Category of subobjects of sets, Category of quotients of sets,
   Category of subquotients of sets,
   ]
class ParentMethods
    Bases: object

Metric
    alias of MetricSpaces

class MorphismMethods
    Bases: object

    image(domain_subset=None)
    Return the image of the domain or of domain_subset.

    EXAMPLES:

    sage: # needs sage.combinat
    sage: P = Partitions(6)
    sage: H = Hom(P, ZZ)
    sage: f = H(ZZ.sum)
    sage: X = f.image()
    # needs sage.libs.flint
    sage: list(X)
    # needs sage.libs.flint
    [6]

    is_injective()
    Return whether this map is injective.

    EXAMPLES:

    sage: f = ZZ.hom(GF(3)); f
    Natural morphism:
    From: Integer Ring
    To:   Finite Field of size 3
    sage: f.is_injective()
    False

class ParentMethods
    Bases: object

    CartesianProduct
        alias of CartesianProduct

    algebra(base_ring, category=None, **kwds)
    Return the algebra of self over base_ring.

    INPUT:
    • self – a parent $S$
    • base_ring – a ring $K$
    • category – a super category of the category of $S$, or None

    This returns the space of formal linear combinations of elements of $S$ with coefficients in $K$, endowed with whatever structure can be induced from that of $S$. See the documentation of sage.categories.algebra_functor for details.
EXAMPLES:

If \( S \) is a group, the result is its group algebra \( KS \):

```sage
sage: # needs sage.groups sage.modules
sage: S = DihedralGroup(4); S
Dihedral group of order 8 as a permutation group
sage: A = S.algebra(QQ); A
Algebra of Dihedral group of order 8 as a permutation group
   over Rational Field
sage: A.category()
Category of finite group algebras over Rational Field
sage: a = A.an_element(); a
() + (1,3) + 2*(1,3)(2,4) + 3*(1,4,3,2)
```

This space is endowed with an algebra structure, obtained by extending by bilinearity the multiplication of \( G \) to a multiplication on \( RG \):

```sage
sage: a * a
# needs sage.groups sage.modules
6*() + 4*(2,4) + 3*(1,2)(3,4) + 12*(1,2,3,4) + 2*(1,3)
   + 13*(1,3)(2,4) + 6*(1,4,3,2) + 3*(1,4)(2,3)
```

If \( S \) is a monoid, the result is its monoid algebra \( KS \):

```sage
sage: S = Monoids().example(); S
An example of a monoid: the free monoid generated by ('a', 'b', 'c', 'd')
sage: A = S.algebra(QQ); A
# needs sage.modules
Algebra of
   An example of a monoid: the free monoid generated by ('a', 'b', 'c', 'd')
   over Rational Field
sage: A.category()
# needs sage.modules
Category of monoid algebras over Rational Field
```

Similarly, we can construct algebras for additive magmas, monoids, and groups.

One may specify for which category one takes the algebra; here we build the algebra of the additive group \( GF_3 \):

```sage
sage: # needs sage.modules
sage: from sage.categories.additive_groups import AdditiveGroups
sage: S = GF(7)
sage: A = S.algebra(QQ, category=AdditiveGroups()); A
Algebra of Finite Field of size 7 over Rational Field
sage: A.category()
Category of finite dimensional additive group algebras
   over Rational Field
sage: a = A(S(1))
sage: a
1
sage: 1 + a * a * a
0 + 3
```

Note that the category keyword needs to be fed with the structure on \( S \) to be used, not the induced structure on the result.
an_element()
Return a (preferably typical) element of this parent.
This is used both for illustration and testing purposes. If the set self is empty, an_element() should raise the exception EmptySetError.
This default implementation calls __an_element__() and caches the result. Any parent should implement either an_element() or __an_element__().
EXAMPLES:

```
sage: CDF.an_element()
→ # needs sage.rings.complex_double
1.0*I
sage: ZZ[['t']].an_element()
t
```
cartesian_product (*parents, **kwargs)
Return the Cartesian product of the parents.
INPUT:
• parents – a list (or other iterable) of parents.
• category – (default: None) the category the Cartesian product belongs to. If None is passed, then category_from_parents() is used to determine the category.
• extra_category – (default: None) a category that is added to the Cartesian product in addition to the categories obtained from the parents.
• other keyword arguments will passed on to the class used for this Cartesian product (see also CartesianProduct).
OUTPUT:
The Cartesian product.
EXAMPLES:

```
sage: C = AlgebrasWithBasis(QQ)
sage: A = C.example(); A.rename("A")  #...
→ needs sage.combinat sage.modules
sage: A.cartesian_product(A, A)  #...
→ needs sage.combinat sage.modules
A (+) A (+) A
sage: ZZ.cartesian_product(GF(2), FiniteEnumeratedSet([1,2,3]))
The Cartesian product of (Integer Ring, Finite Field of size 2, {1, 2, 3})
```
construction()
Return a pair (functor, parent) such that functor(parent) returns self. If self does not have a functorial construction, return None.
EXAMPLES:

```
sage: QQ.construction()
(FractionField, Integer Ring)
sage: f, R = QQ['x'].construction()
sage: f
```

(continues on next page)
is_parent_of(element)

Return whether self is the parent of element.

INPUT:

- element – any object

EXAMPLES:

```
sage: S = ZZ
sage: S.is_parent_of(1)
True
sage: S.is_parent_of(2/1)
False
```

This method differs from __contains__() because it does not attempt any coercion:

```
sage: 2/1 in S, S.is_parent_of(2/1)
(True, False)
sage: int(1) in S, S.is_parent_of(int(1))
(True, False)
```

some_elements()

Return a list (or iterable) of elements of self.

This is typically used for running generic tests (see TestSuite).

This default implementation calls an_element().

EXAMPLES:

```
sage: S = Sets().example(); S
Set of prime numbers (basic implementation)
sage: S.an_element()
47
sage: S.some_elements()
[47]
sage: S = Set([])
sage: list(S.some_elements())
[]
```

This method should return an iterable, not an iterator.

class Quotients(category, *args)

Bases: QuotientsCategory

A category for quotients of sets.

See also:

Sets().Quotients()

EXAMPLES:
class ParentMethods
    Bases: object

class Realizations(*category, *args)
    Bases: RealizationsCategory

class ParentMethods
    Bases: object

    realization_of()
    Return the parent this is a realization of.

    EXAMPLES:

    sage: A = Sets().WithRealizations().example(); A
    # needs sage.modules
    The subset algebra of {1, 2, 3} over Rational Field
    sage: In = A.In(); In
    # needs sage.modules
    The subset algebra of {1, 2, 3} over Rational Field in the In basis
    sage: In.realization_of()
    # needs sage.modules
    The subset algebra of {1, 2, 3} over Rational Field

class SubcategoryMethods
    Bases: object

    Algebras(*base_ring)
    Return the category of objects constructed as algebras of objects of self over base_ring.

    INPUT:
    * base_ring – a ring


    EXAMPLES:

    sage: Monoids().Algebras(QQ)
    Category of monoid algebras over Rational Field
    sage: Groups().Algebras(QQ)
    Category of group algebras over Rational Field
    sage: AdditiveMagmas().AdditiveAssociative().Algebras(QQ)
    Category of additive semigroup algebras over Rational Field
    sage: Monoids().Algebras(Rings())
    Category of monoid algebras over Category of rings
See also:

• `algebra_functor.AlgebrasCategory`
• `CovariantFunctorialConstruction`

**CartesianProducts()**

Return the full subcategory of the objects of `self` constructed as Cartesian products.

See also:

• `cartesian_product.CartesianProductFunctor`
• `RegressiveCovariantFunctorialConstruction`

**EXAMPLES:**

```
sage: Sets().CartesianProducts()
Category of Cartesian products of sets
sage: Semigroups().CartesianProducts()
Category of Cartesian products of semigroups
sage: EuclideanDomains().CartesianProducts()
Category of Cartesian products of commutative rings
```

**Enumerated()**

Return the full subcategory of the enumerated objects of `self`.

An enumerated object can be iterated to get its elements.

**EXAMPLES:**

```
sage: Sets().Enumerated()
Category of enumerated sets
sage: Rings().Finite().Enumerated()
Category of finite enumerated rings
sage: Rings().Infinite().Enumerated()
Category of infinite enumerated rings
```

**Facade()**

Return the full subcategory of the facade objects of `self`.

**What is a facade set?**

Recall that, in Sage, *sets are modelled by *parents*, and their elements know which distinguished set they belong to*. For example, the ring of integers \( \mathbb{Z} \) is modelled by the parent \( \mathbb{Z} \), and integers know that they belong to this set:

```
sage: ZZ
Integer Ring
sage: 42.parent()
Integer Ring
```

Sometimes, it is convenient to represent the elements of a parent \( P \) by elements of some other parent. For example, the elements of the set of prime numbers are represented by plain integers:

```
sage: Primes()
Set of all prime numbers: 2, 3, 5, 7, ...
sage: p = Primes().an_element(); p
43
```

(continues on next page)
In this case, \( P \) is called a \textit{facade set}.

This feature is advertised through the category of \( P \):

\[
\text{sage: } \text{Primes()}.\text{category()}
\]

Category of facade infinite enumerated sets

\[
\text{sage: } \text{Sets()}.\text{Facade()}
\]

Category of facade sets

Typical use cases include modeling a subset of an existing parent:

\[
\text{sage: } \text{Set([4, 6, 9])} \quad \# \text{ random}
\]

\[
\text{sage: } \text{Sets().Facade().example()}
\]

An example of facade set: the monoid of positive integers

or the union of several parents:

\[
\text{sage: } \text{Sets().Facade().example("union")}
\]

An example of a facade set: the integers completed by +--infinity

or endowing an existing parent with more (or less!) structure:

\[
\text{sage: } \text{Posets().example("facade")}
\]

An example of a facade poset: the positive integers ordered by \( \rightarrow \)-divisibility

Let us investigate in detail a close variant of this last example: let \( P \) be set of divisors of 12 partially ordered by divisibility. There are two options for representing its elements:

1. as plain integers:

\[
\text{sage: } P = \text{Poset([divisors(12)], attrcall("divides")), facade=True)} \quad \ldots
\]

\[
\text{# needs sage.graphs}
\]

2. as integers, modified to be aware that their parent is \( P \):

\[
\text{sage: } Q = \text{Poset([divisors(12)], attrcall("divides")), facade=False)} \quad \ldots
\]

\[
\text{# needs sage.graphs}
\]

The advantage of option 1. is that one needs not do conversions back and forth between \( P \) and \( \mathbb{Z} \). The disadvantage is that this introduces an ambiguity when writing \( 2 < 3 \): does this compare 2 and 3 w.r.t. the natural order on integers or w.r.t. divisibility?

\[
\text{sage: } 2 < 3
\]

True

To raise this ambiguity, one needs to explicitly specify the underlying poset as in \( 2 <_P 3 \):

\[
\text{sage: } P = \text{Posets().example("facade")}
\]

\[
\text{sage: } P.\text{lt}(2, 3)
\]

False

On the other hand, with option 2. and once constructed, the elements know unambiguously how to compare themselves:
Beware that \( P(2) \) is still the integer 2. Therefore \( P(2) < P(3) \) still compares 2 and 3 as integers:

\[
\text{sage: } P(2) < P(3) \\
\text{True}
\]

In short \( P \) being a facade parent is one of the programmatic counterparts (with e.g. coercions) of the usual mathematical idiom: “for ease of notation, we identify an element of \( P \) with the corresponding integer”. Too many identifications lead to confusion; the lack thereof leads to heavy, if not obfuscated, notations. Finding the right balance is an art, and even though there are common guidelines, it is ultimately up to the writer to choose which identifications to do. This is no different in code.

**See also:**

The following examples illustrate various ways to implement subsets like the set of prime numbers; look at their code for details:

\[
\begin{align*}
\text{sage: } & \text{Sets().example("facade")} \\
& \text{Set of prime numbers (facade implementation)} \\
\text{sage: } & \text{Sets().example("inherits")} \\
& \text{Set of prime numbers} \\
\text{sage: } & \text{Sets().example("wrapper")} \\
& \text{Set of prime numbers (wrapper implementation)}
\end{align*}
\]

**Specifications**

A parent which is a facade must either:

- call `Parent.__init__()` using the `facade` parameter to specify a parent, or tuple thereof.
- overload the method `facade_for()`.

**Note:** The concept of facade parents was originally introduced in the computer algebra system MuPAD.

**Finite()**

Return the full subcategory of the finite objects of `self`.

**EXAMPLES:**

\[
\begin{align*}
\text{sage: } & \text{Sets().Finite()} \\
& \text{Category of finite sets} \\
\text{sage: } & \text{Rings().Finite()} \\
& \text{Category of finite rings}
\end{align*}
\]

**Infinite()**

Return the full subcategory of the infinite objects of `self`.

**EXAMPLES:**
IsomorphicObjects()
Return the full subcategory of the objects of self constructed by isomorphism.

Given a concrete category As() (i.e. a subcategory of Sets()), As().IsomorphicObjects() returns the category of objects of As() endowed with a distinguished description as the image of some other object of As() by an isomorphism in this category.

See Subquotients() for background.

EXAMPLES:
In the following example, $A$ is defined as the image by $x \mapsto x^2$ of the finite set $B = \{1, 2, 3\}$:

```python
sage: A = FiniteEnumeratedSets().IsomorphicObjects().example(); A
The image by some isomorphism of An example of a finite enumerated set: $\mapsto \{1, 2, 3\}$
```

Since $B$ is a finite enumerated set, so is $A$:

```python
sage: A in FiniteEnumeratedSets()
True
sage: A.cardinality()
3
sage: A.list()
[1, 4, 9]
```

The isomorphism from $B$ to $A$ is available as:

```python
sage: A.retract(3)
9
```
and its inverse as:

```python
sage: A.lift(9)
3
```

It often is natural to declare those morphisms as coercions so that one can do $A(b)$ and $B(a)$ to go back and forth between $A$ and $B$ (TODO: refer to a category example where the maps are declared as a coercion). This is not done by default. Indeed, in many cases one only wants to transport part of the structure of $B$ to $A$. Assume for example, that one wants to construct the set of integers $B = \mathbb{Z}$, endowed with max as addition, and + as multiplication instead of the usual + and *. One can construct $A$ as isomorphic to $B$ as an infinite enumerated set. However $A$ is not isomorphic to $B$ as a ring; for example, for $a \in A$ and $a \in B$, the expressions $a + A(b)$ and $B(a) + b$ give completely different results; hence we would not want the expression $a + b$ to be implicitly resolved to any one of above two, as the coercion mechanism would do.

Coercions also cannot be used with facade parents (see Sets.Facade) like in the example above.

We now look at a category of isomorphic objects:

```python
sage: C = Sets().IsomorphicObjects(); C
Category of isomorphic objects of sets
```
Unless something specific about isomorphic objects is implemented for this category, one actually get an optimized super category:

```python
sage: C = Semigroups().IsomorphicObjects(); C
Join of Category of quotients of semigroups
and Category of isomorphic objects of sets
```

See also:
- `Subquotients()` for background
- `isomorphic_objects.IsomorphicObjectsCategory`
- `RegressiveCovariantFunctorialConstruction`

**Metric()**

Return the subcategory of the metric objects of self.

**Quotients()**

Return the full subcategory of the objects of self constructed as quotients.

Given a concrete category `As()` (i.e. a subcategory of `Sets()`), `As().Quotients()` returns the category of objects of `As()` endowed with a distinguished description as quotient (in fact homomorphic image) of some other object of `As()`.

Implementing an object of `As().Quotients()` is done in the same way as for `As().Subquotients()`, namely by providing an ambient space and a lift and a retract map. See `Subquotients()` for detailed instructions.

See also:
- `Subquotients()` for background
- `quotients.QuotientsCategory`
- `RegressiveCovariantFunctorialConstruction`

**EXAMPLES:**

```python
sage: C = Semigroups().Quotients(); C
Category of quotients of semigroups
sage: C.super_categories()
[Category of subquotients of semigroups, Category of quotients of sets]
sage: C.all_super_categories()
[Category of quotients of semigroups,
 Category of subquotients of semigroups,
 Category of semigroups,
 Category of magmas,
 Category of quotients of sets,
```

(continues on next page)
The caller is responsible for checking that the given category admits a well defined category of quotients:

```
sage: EuclideanDomains().Quotients()
Join of Category of euclidean domains
    and Category of subquotients of monoids
    and Category of quotients of semigroups
```

**Subobjects()**
Return the full subcategory of the objects of self constructed as subobjects.

Given a concrete category `As()` (i.e. a subcategory of `Sets()`), `As().Subobjects()` returns the category of objects of `As()` endowed with a distinguished embedding into some other object of `As()`.

Implementing an object of `As().Subobjects()` is done in the same way as for `As().Subquotients()`, namely by providing an ambient space and a lift and a retract map. In the case of a trivial embedding, the two maps will typically be identity maps that just change the parent of their argument. See `Subquotients()` for detailed instructions.

See also:
- `Subquotients()` for background
- `subobjects.SubobjectsCategory`
- RegressiveCovariantFunctorialConstruction

**EXAMPLES:**

```
sage: C = Sets().Subobjects(); C
Category of subobjects of sets
sage: C.super_categories()
[Category of subquotients of sets]
sage: C.all_super_categories()
[Category of subobjects of sets,
     Category of subquotients of sets,
     Category of sets,
     Category of sets with partial maps,
     Category of objects]
```

Unless something specific about subobjects is implemented for this category, one actually gets an optimized super category:

```
sage: C = Semigroups().Subobjects(); C
Join of Category of subquotients of semigroups
    and Category of subobjects of sets
```

The caller is responsible for checking that the given category admits a well defined category of subobjects.

**Subquotients()**
Return the full subcategory of the objects of self constructed as subquotients.

Given a concrete category `self == As()` (i.e. a subcategory of `Sets()`), `As().Subquotients()` returns the category of objects of `As()` endowed with a distinguished description as subquotient of some other object of `As()`.
EXAMPLES:

```
sage: Monoids().Subquotients()
Category of subquotients of monoids
```

A parent \(A\) in \(\text{As}()\) is further in \(\text{As}().\text{Subquotients}()\) if there is a distinguished parent \(B\) in \(\text{As}()\), called the ambient set, a subobject \(B'\) of \(B\), and a pair of maps:

\[
l : A \rightarrow B' \quad \text{and} \quad r : B' \rightarrow A
\]

called respectively the lifting map and retract map such that \(r \circ l\) is the identity of \(A\) and \(r\) is a morphism in \(\text{As}()\).

**Todo:** Draw the typical commutative diagram.

It follows that, for each operation \(op\) of the category, we have some property like:

\[
op_A(e) = r(op_B(l(e))), \quad \text{for all } e \in A
\]

This allows for implementing the operations on \(A\) from those on \(B\).

The two most common use cases are:

- **homomorphic images (or quotients),** when \(B' = B\), \(r\) is an homomorphism from \(B\) to \(A\) (typically a canonical quotient map), and \(l\) a section of it (not necessarily a homomorphism); see \text{Quotients}();
- **subobjects** (up to an isomorphism), when \(l\) is an embedding from \(A\) into \(B\); in this case, \(B'\) is typically isomorphic to \(A\) through the inverse isomorphisms \(r\) and \(l\); see \text{Subobjects}();

**Note:**

- The usual definition of “subquotient” (Wikipedia article Subquotient) does not involve the lifting map \(l\). This map is required in Sage’s context to make the definition constructive. It is only used in computations and does not affect their results. This is relatively harmless since the category is a concrete category (i.e., its objects are sets and its morphisms are set maps).
- In mathematics, especially in the context of quotients, the retract map \(r\) is often referred to as a projection map instead.
- Since \(B'\) is not specified explicitly, it is possible to abuse the framework with situations where \(B'\) is not quite a subobject and \(r\) not quite a morphism, as long as the lifting and retract maps can be used as above to compute all the operations in \(A\). Use at your own risk!

**Assumptions:**

- For any category \(\text{As}(),\text{As}().\text{Subquotients}()\) is a subcategory of \(\text{As}()\).

  Example: a subquotient of a group is a group (e.g., a left or right quotient of a group by a non-normal subgroup is not in this category).

- This construction is covariant: if \(\text{As}()\) is a subcategory of \(\text{Bs}()\), then \(\text{As}().\text{Subquotients}()\) is a subcategory of \(\text{Bs}().\text{Subquotients}()\).

Example: if \(A\) is a subquotient of \(B\) in the category of groups, then it is also a subquotient of \(B\) in the category of monoids.

- If the user (or a program) calls \(\text{As}().\text{Subquotients}()\), then it is assumed that subquotients are well defined in this category. This is not checked, and probably never will be. Note that, if a category \(\text{As}()\) does not specify anything about its subquotients, then its subquotient category looks like this:
Interface: the ambient set $B$ of $A$ is given by $A.ambient()$. The subset $B'$ needs not be specified, so the retract map is handled as a partial map from $B$ to $A$.

The lifting and retract map are implemented respectively as methods $A.lift(a)$ and $A.retract(b)$. As a shorthand for the former, one can use alternatively $a.lift()$:

```sage
sage: S = Semigroups().Subquotients().example(); S
An example of a (sub)quotient semigroup: a quotient of the left zero
→semigroup
sage: S.ambient()
An example of a semigroup: the left zero semigroup
sage: S(3).lift().parent()
An example of a semigroup: the left zero semigroup
sage: S(3) * S(1) == S.retract( S(3).lift() * S(1).lift() )
True
```

See $S$? for more.

Todo: use a more interesting example, like $\mathbb{Z}/n\mathbb{Z}$.

See also:

- `Quotients()`, `Subobjects()`, `IsomorphicObjects()`
- `subquotients.SubquotientsCategory`
- `RegressiveCovariantFunctorialConstruction`

**Topological()**

Return the subcategory of the topological objects of self.

```python
class Subobjects(category, *args)
    Bases: SubobjectsCategory
    A category for subobjects of sets.
    See also:
    Sets().Subobjects()

    EXAMPLES:
    ```
```sage
sage: Sets().Subobjects()
Category of subobjects of sets
sage: Sets().Subobjects().all_super_categories()
[Category of subobjects of sets,
 Category of subquotients of sets,
 Category of sets,
 Category of sets with partial maps,
 Category of objects]
```

class ParentMethods
    Bases: object
class Subquotients(category, *args)
    Bases: SubquotientsCategory
A category for subquotients of sets.

See also:

Sets().Subquotients()

EXAMPLES:

```
sage: Sets().Subquotients()
Category of subquotients of sets
sage: Sets().Subquotients().all_super_categories()
[Category of subquotients of sets, Category of sets, Category of sets with partial maps, Category of objects]
```

class ElementMethods

Bases: object

```
lift()

Lift self to the ambient space for its parent.

EXAMPLES:

```
sage: S = Semigroups().Subquotients().example()
sage: s = S.an_element()
sage: s, s.parent()
(42, An example of a (sub)quotient semigroup: a quotient of the left zero semigroup)
sage: S.lift(s), S.lift(s).parent()
(42, An example of a semigroup: the left zero semigroup)
sage: s.lift(), s.lift().parent()
(42, An example of a semigroup: the left zero semigroup)
```

class ParentMethods

Bases: object

```
ambient()

Return the ambient space for self.

EXAMPLES:

```
sage: Semigroups().Subquotients().example().ambient()
An example of a semigroup: the left zero semigroup
```

See also:

Sets.SubcategoryMethods.Subquotients() for the specifications and lift() and retract().

```
lift(x)

Lift x to the ambient space for self.

INPUT:
• x – an element of self

EXAMPLES:

```
sage: S = Semigroups().Subquotients().example()
sage: s = S.an_element()
sage: s, s.parent()
```
```
(42, An example of a (sub)quotient semigroup:
    a quotient of the left zero semigroup)
sage: S.lift(s), S.lift(s).parent()
(42, An example of a semigroup: the left zero semigroup)
sage: s.lift(), s.lift().parent()
(42, An example of a semigroup: the left zero semigroup)

See also:

retract (x)
Retract x to self.

INPUT:
• x – an element of the ambient space for self

See also:

EXAMPLES:

sage: S = Semigroups().Subquotients().example()
sage: s = S.ambient().an_element()
sage: s, s.parent()
(42, An example of a semigroup: the left zero semigroup)
sage: S.retract(s), S.retract(s).parent()
(42, An example of a (sub)quotient semigroup:
    a quotient of the left zero semigroup)

Topological
alias of TopologicalSpaces
class WithRealizations (category, *args)
Bases: WithRealizationsCategory
class ParentMethods
Bases: object
class Realizations (parent_with_realization)
Bases: Category_realization_of_parent
super_categories ()

EXAMPLES:

sage: A = Sets().WithRealizations().example(); A
    # needs sage.modules
The subset algebra of {1, 2, 3} over Rational Field
sage: A.Realizations().super_categories()
    # needs sage.modules
[Category of realizations of sets]

a_realization ()
Return a realization of self.

EXAMPLES:
**facade_for()**

Return the parents self is a facade for, that is the realizations of self

**EXAMPLES:**

```python
sage: A = Sets().WithRealizations().example(); A
# needs sage.modules
The subset algebra of \{1, 2, 3\} over Rational Field
sage: A.facade_for()
# needs sage.modules
[Facade for the subset algebra of \{1, 2, 3\} over Rational Field in the Fundamental basis, Facade for the subset algebra of \{1, 2, 3\} over Rational Field in the In basis, Facade for the subset algebra of \{1, 2, 3\} over Rational Field in the Out basis]
```

**inject_shorthands**(shorthands=None, verbose=True)

Import standard shorthands into the global namespace.

**INPUT:**
- **shorthands** – a list (or iterable) of strings (default: self._shorthands) or "all" (for self._shorthands_all)
- **verbose** – boolean (default True); whether to print the defined shorthands

**EXAMPLES:**

When computing with a set with multiple realizations, like SymmetricFunctions or SubsetAlgebra, it is convenient to define shorthands for the various realizations, but cumbersome to do it by hand:

```python
sage: S = SymmetricFunctions(ZZ); S
# needs sage.combinat sage.modules
Symmetric Functions over Integer Ring
sage: s = S.s(); s
# needs sage.combinat sage.modules
Symmetric Functions over Integer Ring in the Schur basis
sage: e = S.e(); e
# needs sage.combinat sage.modules
Symmetric Functions over Integer Ring in the elementary basis
```
This method automates the process:

```
sage: # needs sage.combinat sage.modules
sage: S.inject_shorthands()
Defining e as shorthand for
    Symmetric Functions over Integer Ring in the elementary basis
Defining f as shorthand for
    Symmetric Functions over Integer Ring in the forgotten basis
Defining h as shorthand for
    Symmetric Functions over Integer Ring in the homogeneous basis
Defining m as shorthand for
    Symmetric Functions over Integer Ring in the monomial basis
Defining p as shorthand for
    Symmetric Functions over Integer Ring in the powersum basis
Defining s as shorthand for
    Symmetric Functions over Integer Ring in the Schur basis
sage: s[1] - 2*s[1, 1, 1] + s[1, 1, 1, 1] + s[2, 1]
sage: e
    Symmetric Functions over Integer Ring in the elementary basis
sage: p
    Symmetric Functions over Integer Ring in the powersum basis
sage: s
    Symmetric Functions over Integer Ring in the Schur basis
```

Sometimes, like for symmetric functions, one can request for all shorthands to be defined, including less common ones:

```
sage: S.inject_shorthands("all")
# needs sage.combinat sage.modules
Defining e as shorthand for
    Symmetric Functions over Integer Ring in the elementary basis
Defining f as shorthand for
    Symmetric Functions over Integer Ring in the forgotten basis
Defining h as shorthand for
    Symmetric Functions over Integer Ring in the homogeneous basis
Defining ht as shorthand for
    Symmetric Functions over Integer Ring in the
    induced trivial symmetric group character basis
Defining m as shorthand for
    Symmetric Functions over Integer Ring in the monomial basis
Defining o as shorthand for
    Symmetric Functions over Integer Ring in the orthogonal basis
Defining p as shorthand for
    Symmetric Functions over Integer Ring in the powersum basis
Defining s as shorthand for
    Symmetric Functions over Integer Ring in the Schur basis
Defining sp as shorthand for
    Symmetric Functions over Integer Ring in the symplectic basis
Defining st as shorthand for
    Symmetric Functions over Integer Ring in the
    irreducible symmetric group character basis
Defining w as shorthand for
    Symmetric Functions over Integer Ring in the Witt basis
```

The messages can be silenced by setting `verbose=False:`
One can also just import a subset of the shorthands:

```python
sage: # needs sage.combinat sage.modules
sage: SQ = SymmetricFunctions(QQ)
sage: SQ.inject_shorthands(['p', 's'], verbose=False)
sage: p
Symmetric Functions over Rational Field in the powersum basis
sage: s
Symmetric Functions over Rational Field in the Schur basis
```

Note that e is left unchanged:

```python
sage: e
#˓→ needs sage.combinat sage.modules
Symmetric Functions over Integer Ring in the elementary basis
```

\section*{realizations()}

Return all the realizations of self that self is aware of.

EXAMPLES:

```python
sage: A = Sets().WithRealizations().example(); A
#˓→ needs sage.modules
The subset algebra of \{1, 2, 3\} over Rational Field
sage: A.realizations()
#˓→ needs sage.modules
[The subset algebra of \{1, 2, 3\} over Rational Field in the Fundamental basis,
The subset algebra of \{1, 2, 3\} over Rational Field in the In basis,
The subset algebra of \{1, 2, 3\} over Rational Field in the Out basis]
```

\textbf{Note:} Constructing a parent \texttt{P} in the category \texttt{A.Realizations()} automatically adds \texttt{P} to this list by calling \texttt{A._register_realization(A)}

\section*{example (base\_ring=None, set=None)}

Return an example of set with multiple realizations, as per \texttt{Category.example()}.

EXAMPLES:

```python
sage: Sets().WithRealizations().example()
˓→ needs sage.modules
The subset algebra of \{1, 2, 3\} over Rational Field
```

(continues on next page)
extra_super_categories()

A set with multiple realizations is a facade parent.

EXAMPLES:

```python
sage: Sets().WithRealizations().extra_super_categories()
[Category of facade sets]
```

example(choice=None)

Return examples of objects of `Sets()`, as per `Category.example()`.

EXAMPLES:

```python
sage: Sets().example()  # Set of prime numbers (basic implementation)
sage: Sets().example("inherits")  # Set of prime numbers
sage: Sets().example("facade")  # Set of prime numbers (facade implementation)
sage: Sets().example("wrapper")  # Set of prime numbers (wrapper implementation)
```

super_categories()

We include `SetsWithPartialMaps` between `Sets` and `Objects` so that we can define morphisms between sets that are only partially defined. This is also to have the `Homset` constructor not complain that `SetsWithPartialMaps` is not a supercategory of `Fields`, for example.

EXAMPLES:

```python
sage: Sets().super_categories()  # [Category of sets with partial maps]
```

`sage.categories.sets_cat.print_compare(x, y)`


INPUT:

- `x` – an element
- `y` – an element

EXAMPLES:

```python
sage: from sage.categories.sets_cat import print_compare
sage: print_compare(1, 2)
1 != 2
```
4.144 Sets With a Grading

**class** sage.categories.sets_with_grading.SetsWithGrading

**Bases:** Category

The category of sets with a grading.

A set with a grading is a set $S$ equipped with a grading by some other set $I$ (by default the set $\mathbb{N}$ of the non-negative integers):

$$S = \bigcup_{i \in I} S_i$$

where the graded components $S_i$ are (usually finite) sets. The grading function maps each element $s$ of $S$ to its grade $i$, so that $s \in S_i$.

From implementation point of view, if the graded set is enumerated then each graded component should be enumerated (there is a check in the method \_test_graded_components()). The contrary needs not be true.

To implement this category, a parent must either implement graded_component() or subset(). If only subset() is implemented, the first argument must be the grading for compatibility with graded_component(). Additionally either the parent must implement grading() or its elements must implement a method grade(). See the example sage.categories.examples.sets_with_grading.NonNegativeIntegers.

Finally, if the graded set is enumerated (see EnumeratedSets) then each graded component should be enumerated. The contrary needs not be true.

**EXAMPLES:**

A typical example of a set with a grading is the set of non-negative integers graded by themselves:

```python
sage: N = SetsWithGrading().example(); N
Non negative integers
sage: N.category()
Category of facade infinite sets with grading
sage: N.grading_set()
Non negative integers
```

The grading function is given by $N$.grading:

```python
sage: N.grading(4)
4
```

The graded component $N_i$ is the set with one element $i$:

```python
sage: N.graded_component(grade=5)
{5}
sage: N.graded_component(grade=42)
{42}
```

Here are some information about this category:
sage: SetsWithGrading()
Category of sets with grading
sage: SetsWithGrading().super_categories()
[Category of sets]
sage: SetsWithGrading().all_super_categories()
[Category of sets with grading,
 Category of sets,
 Category of sets with partial maps,
 Category of objects]

Todo:

- This should be moved to Sets().WithGrading().
- Should the grading set be a parameter for this category?
- Does the enumeration need to be compatible with the grading? Be careful that the fact that graded components are allowed to be finite or infinite make the answer complicated.

class ParentMethods
    Bases: object

    generating_series()
        Default implementation for generating series.
        OUTPUT:
        A series, indexed by the grading set.
        EXAMPLES:

        sage: N = SetsWithGrading().example(); N
        Non negative integers
        sage: N.generating_series()
        1/(-z + 1)
        sage: Permutations().generating_series()  # needs sage.combinat
        1 + z + 2*z^2 + 6*z^3 + 24*z^4 + 120*z^5 + 720*z^6 + O(z^7)
        .. TODO::

        - Very likely, this should always return a lazy power series.

    graded_component(grade)
        Return the graded component of self with grade grade.
        The default implementation just calls the method subset() with the first argument grade.
        EXAMPLES:

        sage: N = SetsWithGrading().example(); N
        Non negative integers
        sage: N.graded_component(3)
        {3}
**grading**(*elt*)

Return the grading of the element *elt* of *self*. This default implementation calls *elt*.grade().

**EXAMPLES:**

```python
sage: N = SetsWithGrading().example(); N
Non negative integers
sage: N.grading(4)
4
```

**grading_set()**

Return the set *self* is graded by. By default, this is the set of non-negative integers.

**EXAMPLES:**

```python
sage: SetsWithGrading().example().grading_set()
Non negative integers
```

**subset**(*args, **options*)

Return the subset of *self* described by the given parameters.

**See also:**

- graded_component()

**EXAMPLES:**

```python
sage: W = WeightedIntegerVectors([3,2,1]); W
#-needs sage.combinat
Integer vectors weighted by [3, 2, 1]
sage: W.subset(4)
#-needs sage.combinat
Integer vectors of 4 weighted by [3, 2, 1]
```

**super_categories()**

**EXAMPLES:**

```python
sage: SetsWithGrading().super_categories()
[Category of sets]
```

### 4.145 SetsWithPartialMaps

**class** *sage.categories.sets_with_partial_maps.SetsWithPartialMaps*

**Bases:** *Category_singleton*

The category whose objects are sets and whose morphisms are maps that are allowed to raise a `ValueError` on some inputs.

This category is equivalent to the category of pointed sets, via the equivalence sending an object X to X union {error}, a morphism f to the morphism of pointed sets that sends x to f(x) if f does not raise an error on x, or to error if it does.

**EXAMPLES:**

```python
```
4.146 Shephard Groups

class sage.categories.shephard_groups.ShephardGroups
    Bases: Category_singleton
    The category of Shephard groups.

EXAMPLES:

```
sage: from sage.categories.shephard_groups import ShephardGroups
sage: C = ShephardGroups(); C
Category of shephard groups
```

```
sage: ShephardGroups().super_categories()
[Category of finite generalized Coxeter groups]
```

4.147 Simplicial Complexes

class sage.categories.simplicial_complexes.SimplicialComplexes
    Bases: Category_singleton
    The category of abstract simplicial complexes.

An abstract simplicial complex $A$ is a collection of sets $X$ such that:

- $\emptyset \in A$,
- if $X \subset Y \in A$, then $X \in A$.

Todo: Implement the category of simplicial complexes considered as *CW complexes* and rename this to the category of AbstractSimplicialComplexes with appropriate functors.

EXAMPLES:
sage: from sage.categories.simplicial_complexes import SimplicialComplexes
sage: C = SimplicialComplexes(); C
Category of simplicial complexes

class Connected(base_category)
  Bases: CategoryWithAxiom

  The category of connected simplicial complexes.

  EXAMPLES:

sage: from sage.categories.simplicial_complexes import SimplicialComplexes
sage: C = SimplicialComplexes().Connected()
sage: TestSuite(C).run()

class Finite(base_category)
  Bases: CategoryWithAxiom

  Category of finite simplicial complexes.

class ParentMethods
  Bases: object

  dimension()

  Return the dimension of self.

  EXAMPLES:

sage: S = SimplicialComplex([[1,3,4], [1,2],[2,5],[4,5]])
# needs sage.graphs
sage: S.dimension()  # needs sage.graphs
2

class ParentMethods
  Bases: object

  faces()

  Return the faces of self.

  EXAMPLES:

sage: S = SimplicialComplex([[1,3,4], [1,2],[2,5],[4,5]])
# needs sage.graphs
sage: S.faces()  # needs sage.graphs
{-1: {()},
  0: {(1,), (2,), (3,), (4,), (5,)},
  1: {(1, 2), (1, 3), (1, 4), (2, 5), (3, 4), (4, 5)},
  2: {(1, 3, 4)}}

facets()

  Return the facets of self.

  EXAMPLES:
sage: S = SimplicialComplex([[1,3,4], [1,2], [2,5], [4,5]])  # needs sage.graphs
sage: sorted(S.facets())  # needs sage.graphs
[(1, 2), (1, 3, 4), (2, 5), (4, 5)]

class SubcategoryMethods

    Bases: object

    Connected()

    Return the full subcategory of the connected objects of self.

    EXAMPLES:

    sage: from sage.categories.simplicial_complexes import SimplicialComplexes
    sage: SimplicialComplexes().Connected()
    Category of connected simplicial complexes

    super_categories()

    Return the super categories of self.

    EXAMPLES:

    sage: from sage.categories.simplicial_complexes import SimplicialComplexes
    sage: SimplicialComplexes().super_categories()
    [Category of sets]

4.148 Simplicial Sets

class sage.categories.simplicial_sets.SimplicialSets

    Bases: Category_singleton

    The category of simplicial sets.

    A simplicial set $X$ is a collection of sets $X_i$, indexed by the non-negative integers, together with maps

    $$d_i : X_n \to X_{n-1}, \quad 0 \leq i \leq n \quad \text{(face maps)}$$

    $$s_j : X_n \to X_{n+1}, \quad 0 \leq j \leq n \quad \text{(degeneracy maps)}$$

    satisfying the simplicial identities:

    $$d_id_j = d_{j-1}d_i \quad \text{if } i < j$$

    $$d_is_j = s_{j-1}d_i \quad \text{if } i < j$$

    $$d_is_j = s_{j+1}s_j$$

    $$d_is_j = s_jd_{i-1} \quad \text{if } i > j + 1$$

    $$s_is_j = s_{j+1}s_i \quad \text{if } i \leq j$$

    Morphisms are sequences of maps $f_i : X_i \to Y_i$ which commute with the face and degeneracy maps.

    EXAMPLES:

    sage: from sage.categories.simplicial_sets import SimplicialSets
    sage: C = SimplicialSets(); C
    Category of simplicial sets
class Finite(base_category)
Bases: CategoryWithAxiom

Category of finite simplicial sets.

The objects are simplicial sets with finitely many non-degenerate simplices.

class Homsets(category, *args)
Bases: HomsetsCategory

class Endset(base_category)
Bases: CategoryWithAxiom

class ParentMethods
Bases: object

one()

Return the identity morphism in Hom(S, S).

EXAMPLES:

```python
sage: T = simplicial_sets.Torus()
# needs sage.graphs
sage: Hom(T, T).identity()
# needs sage.graphs
Simplicial set endomorphism of Torus
Defn: Identity map
```

class ParentMethods
Bases: object

is_finite()

Return True if this simplicial set is finite, i.e., has a finite number of nondegenerate simplices.

EXAMPLES:

```python
sage: simplicial_sets.Torus().is_finite()  # needs sage.graphs
True
sage: C5 = groups.misc.MultiplicativeAbelian([5])  # needs sage.graphs sage.groups
sage: simplicial_sets.ClassifyingSpace(C5).is_finite()  # needs sage.graphs sage.groups
False
```

is_pointed()

Return True if this simplicial set is pointed, i.e., has a base point.

EXAMPLES:

```python
sage: # needs sage.graphs
sage: from sage.topology.simplicial_set import AbstractSimplex,
# SimplicialSet
sage: v = AbstractSimplex(0)
sage: w = AbstractSimplex(0)
sage: e = AbstractSimplex(1)
sage: X = SimplicialSet({e: (v, w)})
sage: Y = SimplicialSet({e: (v, w)}, base_point=w)
sage: X.is_pointed()
```

(continues on next page)
set_base_point (point)

Return a copy of this simplicial set in which the base point is set to point.

INPUT:

• point – a 0-simplex in this simplicial set

EXAMPLES:

```python
sage: # needs sage.graphs
sage: from sage.topology.simplicial_set import AbstractSimplex,
    SimplicialSet
sage: v = AbstractSimplex(0, name='v_0')
sage: w = AbstractSimplex(0, name='w_0')
sage: e = AbstractSimplex(1)
sage: X = SimplicialSet({e: (v, w)})
sage: Y = SimplicialSet({e: (v, w)}, base_point=w)
sage: Y.base_point()
    w_0
sage: X_star = X.set_base_point(w)
sage: X_star.base_point()
    w_0
sage: Y_star = Y.set_base_point(v)
sage: Y_star.base_point()
    v_0
```

class Pointed (base_category)

Bases: CategoryWithAxiom

class Finite (base_category)

Bases: CategoryWithAxiom

class ParentMethods

Bases: object

fat_wedge (n)

Return the \(n\)-th fat wedge of this pointed simplicial set.

This is the subcomplex of the \(n\)-fold product \(X^n\) consisting of those points in which at least one factor is the base point. Thus when \(n = 2\), this is the wedge of the simplicial set with itself, but when \(n\) is larger, the fat wedge is larger than the \(n\)-fold wedge.

EXAMPLES:

```python
sage: # needs sage.graphs
sage: S1 = simplicial_sets.Sphere(1)
sage: S1.fat_wedge(0)
    Point
sage: S1.fat_wedge(1)
    S^1
sage: S1.fat_wedge(2).fundamental_group()  # needs sage.groups
    Finitely presented group < e0, e1 | >
sage: S1.fat_wedge(4).homology()  # needs sage.groups
```

(continues on next page)
### Smash Product \( \ast \text{others} \)

Return the smash product of this simplicial set with \text{others}.

**INPUT:**

- \text{others} – one or several simplicial sets

**EXAMPLES:**

```sage
definition

sage: # needs sage.graphs sage.groups
sage: S1 = simplicial_sets.Sphere(1)
sage: RP2 = simplicial_sets.RealProjectiveSpace(2)
sage: X = S1.smash_product(RP2)
sage: X.homology(base_ring=GF(2))  
#...
\needs\ sage.modules
\{0: Vector space of dimension 0 over Finite Field of size 2,
1: Vector space of dimension 0 over Finite Field of size 2,
2: Vector space of dimension 1 over Finite Field of size 2,
3: Vector space of dimension 1 over Finite Field of size 2\}
```

### Unset Base Point

Return a copy of this simplicial set in which the base point has been forgotten.

**EXAMPLES:**

```sage
definition

sage: # needs sage.graphs
sage: from sage.topology.simplicial_set import AbstractSimplex,
\trait\ SimplicialSet
sage: v = AbstractSimplex(0, name='v_0')
sage: w = AbstractSimplex(0, name='w_0')
sage: e = AbstractSimplex(1)
sage: Y = SimplicialSet({e: (v, w)}, base_point=w)
sage: Y.is_pointed()
True
sage: Y.base_point()
w_0
sage: Z = Y.unset_base_point()
sage: Z.is_pointed()
False
```

### Class ParentMethods

**Bases:** object

- **base_point()**
  
  Return this simplicial set's base point

**EXAMPLES:**
base_point_map (domain=None)

Return a map from a one-point space to this one, with image the base point.

This raises an error if this simplicial set does not have a base point.

INPUT:

- domain – optional, default None. Use this to specify a particular one-point space as the domain.

  The default behavior is to use the sage.topology.simplicial_set.Point() function to use a standard one-point space.

EXAMPLES:

```sage
# needs sage.graphs
t = simplicial_sets.Torus()
f = t.base_point_map(); f
Simplicial set morphism:
  From: Point
  To: Torus
  Defn: Constant map at (v_0, v_0)
```

```sage
# needs sage.graphs
t = simplicial_sets.Simplex(0)
pt = t.set_base_point(t.n_cells(0)[0])
h = RP3.base_point_map(domain=pt)
```

```sage
# needs sage.groups
t = groups.misc.MultiplicativeAbelian([5])
BC5 = simplicial_sets.ClassifyingSpace(t)
```

connectivity (max_dim=None)

Return the connectivity of this pointed simplicial set.
INPUT:
• \texttt{max_dim} – specify a maximum dimension through which to check. This is required if this
simplicial set is simply connected and not finite.
The dimension of the first nonzero homotopy group. If simply connected, this is the same as the
dimension of the first nonzero homology group.

\textbf{Warning:} See the warning for the \texttt{is_simply_connected()} method.

The connectivity of a contractible space is $+\infty$.

\textbf{EXAMPLES:}

```
sage: # needs sage.graphs sage.groups
sage: simplicial_sets.Sphere(3).connectivity()
2
sage: simplicial_sets.Sphere(0).connectivity()
-1
sage: K = simplicial_sets.Simplex(4)
sage: K = K.set_base_point(K.n_cells(0)[0])
sage: K.connectivity()
+\infty
sage: X = simplicial_sets.Torus().suspension(2)
sage: X.connectivity()
2
```

\texttt{cover(character)}

Return the cover of the simplicial set associated to a character of the fundamental group.
The character is represented by a dictionary, that assigns an element of a finite group to each non-
degenerate 1-dimensional cell. It should correspond to an epimorphism from the fundamental group.

\textbf{INPUT:}
• \texttt{character} – a dictionary

\textbf{EXAMPLES:}

```
sage: # needs sage.graphs sage.groups
sage: C2 = groups.misc.MultiplicativeAbelian([2])
# needs sage.graphs sage.groups
sage: BC2 = simplicial_sets.ClassifyingSpace(C2)
# needs sage.graphs sage.groups
sage: BC2.connectivity()
0
```

(continues on next page)
categoryframework, release 10.3

(continued from previous page)

\[(\sigma_1, (1,2,3)): ((*, ()), (*, (1,2,3))),
(\sigma_1, (1,3,2)): ((*, ()), (*, (1,3,2))),
(\sigma_1, (1,3,2)): ((*, (1,2,3)), (*, (1,3,2)))\}

sage: C.homology(1)  # needs sage.modules
\[\mathbb{Z} \times \mathbb{Z} \times \mathbb{Z} \times \mathbb{Z}\]
sage: C.fundamental_group()
Finitely presented group < e0, e1, e2, e3 | >

covering_map (character)

Return the covering map associated to a character.

The character is represented by a dictionary that assigns an element of a finite group to each non-degenerate 1-dimensional cell. It should correspond to an epimorphism from the fundamental group.

INPUT:
• character – a dictionary

EXAMPLES:

sage: # needs sage.graphs sage.groups
sage: S1 = simplicial_sets.Sphere(1)
sage: W = S1.wedge(S1)
sage: G = CyclicPermutationGroup(3)
sage: a, b = W.n_cells(1)
sage: C = W.covering_map({a : G.gen(0), b : G.one()}); C
Simplicial set morphism:
From: Simplicial set with 9 non-degenerate simplices
To: Wedge: (S^1 v S^1)
Defn: [(*, ()), (*, (1,2,3)), (*, (1,3,2)), (sigma_1, ()),
(\sigma_1, ()), (sigma_1, (1,2,3)), (sigma_1, (1,2,3)),
(\sigma_1, (1,3,2)), (sigma_1, (1,2,3))]
--> [*; *, *, sigma_1, sigma_1, sigma_1, sigma_1, sigma_1, ...

sage: C.domain()
Simplicial set with 9 non-degenerate simplices

sage: C.domain().face_data()
\{(*, ()): None,
(*, (1,2,3)): None,
(*, (1,3,2)): None,
(\sigma_1, ()): ((*, (1,2,3)), (*, ())),
(\sigma_1, ()): ((*, ()), (*, ())),
(\sigma_1, (1,2,3)): ((*, (1,3,2)), (*, (1,2,3))),
(\sigma_1, (1,2,3)): ((*, (1,2,3)), (*, (1,2,3))),
(\sigma_1, (1,3,2)): ((*, ()), (*, (1,3,2))),
(\sigma_1, (1,3,2)): ((*, (1,3,2)), (*, (1,3,2)))\}

fundamental_group (simplify=True)

Return the fundamental group of this pointed simplicial set.

INPUT:
• simplify (bool, optional True) – if False, then return a presentation of the group in terms of generators and relations. If True, the default, simplify as much as GAP is able to.

Algorithm: we compute the edge-path group – see Section 19 of [Kan1958] and Wikipedia article Fundamental_group. Choose a spanning tree for the connected component of the 1-skeleton containing the base point, and then the group’s generators are given by the non-degenerate edges. There are two types of relations: \(e = 1\) if \(e\) is in the spanning tree, and for every 2-simplex, if its faces
are $e_0$, $e_1$, and $e_2$, then we impose the relation $e_0e_1^{-1}e_2 = 1$, where we first set $e_i = 1$ if $e_i$ is degenerate.

**EXAMPLES:**

```python
sage: S1 = simplicial_sets.Sphere(1)
# needs sage.graphs
sage: eight = S1.wedge(S1)
# needs sage.graphs
sage: eight.fundamental_group() # free group on 2 generators
Finitely presented group < e0, e1 | >
```

The fundamental group of a disjoint union of course depends on the choice of base point:

```python
sage: T = simplicial_sets.Torus()
# needs sage.graphs
sage: K = simplicial_sets.KleinBottle()
# needs sage.graphs
sage: X = T.disjoint_union(K)
# needs sage.graphs
sage: X_0 = X.set_base_point(X.n_cells(0)[0])
# needs sage.groups
sage: X_0.fundamental_group().is_abelian()  # needs sage.groups
True
sage: X_1 = X.set_base_point(X.n_cells(0)[1])
# needs sage.groups
sage: X_1.fundamental_group().is_abelian()  # needs sage.groups
False
sage: RP3 = simplicial_sets.RealProjectiveSpace(3)
# needs sage.graphs sage.groups
sage: RP3.fundamental_group()
Finitely presented group < e | e^2 >
```

Compute the fundamental group of some classifying spaces:

```python
sage: C5 = groups.misc.MultiplicativeAbelian([5])
# needs sage.graphs sage.groups
sage: BC5 = C5.nerve()
# needs sage.graphs sage.groups
sage: BC5.fundamental_group()
Finitely presented group < e0 | e0^5 >
```

```python
sage: Sigma3 = groups.permutation.Symmetric(3)
# needs sage.graphs sage.groups
sage: BSigma3 = Sigma3.nerve()
# needs sage.graphs sage.groups
sage: pi = BSigma3.fundamental_group(); pi
Finitely presented group < e1, e2 | e2^2, e1^3, (e2*e1)^2 >
```

```python
sage: pi.order()
6
sage: pi.is_abelian()
False
```

The sphere has a trivial fundamental group:
is_simply_connected()

Return True if this pointed simplicial set is simply connected.

**Warning:** Determining simple connectivity is not always possible, because it requires determining when a group, as given by generators and relations, is trivial. So this conceivably may give a false negative in some cases.

EXAMPLES:

```python
sage: # needs sage.graphs sage.groups
t = simplicial_sets.Torus()
sage: t.is_simply_connected()
False
sage: t.suspension().is_simply_connected()
True
sage: simplicial_sets.KleinBottle().is_simply_connected()
False
sage: # needs sage.graphs
sage: S2 = simplicial_sets.Sphere(2)
sage: S3 = simplicial_sets.Sphere(3)
sage: (S2.wedge(S3)).is_simply_connected()
# needs sage.groups
True
sage: X = S2.disjoint_union(S3)
sage: X = X.set_base_point(X.n_cells(0)[0])
sage: X.is_simply_connected()
False
```

twisted_chain_complex (twisting_operator=None, dimensions=None, augmented=False, cochain=False, verbose=False, subcomplex=None, check=False)

Return the normalized chain complex twisted by some operator.

A twisting operator is a map from the set of simplices to some algebra. The differentials are then twisted by this operator.

**INPUT:**

- `twisting_operator` – a dictionary, associating the twist of each simplex. If it is not given, the canonical one (associated to the laurent polynomial ring abelianization of the fundamental group, ignoring torsion) is used.
- `dimensions` – if None, compute the chain complex in all dimensions. If a list or tuple of
integers, compute the chain complex in those dimensions, setting the chain groups in all other dimensions to zero.

- augmented (optional, default False) – if True, return the augmented chain complex (that is, include a class in dimension $-1$ corresponding to the empty cell).
- cochain (optional, default False) – if True, return the cochain complex (that is, the dual of the chain complex).
- verbose (optional, default False) – ignored.
- subcomplex (optional, default None) – if present, compute the chain complex relative to this subcomplex.
- check (optional, default False) – If True, make sure that the chain complex is actually a chain complex: the differentials are composable and their product is zero.

The normalized chain complex of a simplicial set is isomorphic to the chain complex obtained by modding out by degenerate simplices, and the latter is what is actually constructed here.

**EXAMPLES:**

```python
sage: W = simplicial_sets.Sphere(1).wedge(simplicial_sets.Sphere(2))
sage: W.nondegenerate_simplices()
[*, sigma_1, sigma_2]
sage: s1 = W.nondegenerate_simplices()[1]
sage: L.<t> = LaurentPolynomialRing(QQ)
sage: tw = {s1:t}
sage: ChC = W.twisted_chain_complex(tw)
sage: ChC.differential(1)
[-1 + t]
sage: ChC.differential(2)
[0]
sage: X = simplicial_sets.Torus()
sage: C = X.twisted_chain_complex()
sage: C.differential(1)
[ f3 - 1 f2*f3^-1 - 1 f2 - 1]
sage: C.differential(2)
[ 1 f2*f3^-1]
[ f3 1]
[ -1 -1]
sage: C.differential(3)
[]
sage: Y = simplicial_sets.RealProjectiveSpace(2)
sage: C = Y.twisted_chain_complex()
sage: C.differential(1)
[-1 + F1]
sage: C.differential(2)
[1 + F1]
sage: C.differential(3)
[]
```

**twisted_homology** ($n$, **reduced**=False)

The $n$-th twisted homology module of the simplicial set with respect to the abelianization of the fundamental group.

It is a module over a polynomial ring, including relations to make some variables the multiplicative inverses of others.

**INPUT:**

- $n$ - a positive integer.
• `reduced` - (default: False) if set to True, the presentation matrix will be reduced.

**EXAMPLES:**

```python
sage: X = simplicial_sets.Sphere(1).wedge(simplicial_sets.Sphere(2))
sage: X.twisted_homology(1)
Quotient module by Submodule of Ambient free module of rank 0 over the...
 → integral domain Multivariate Polynomial Ring in f1, f1inv over...
 → Integer Ring
Generated by the rows of the matrix:
[]
sage: X.twisted_homology(2)
Quotient module by Submodule of Ambient free module of rank 1 over the...
 → integral domain Multivariate Polynomial Ring in f1, f1inv over...
 → Integer Ring
Generated by the rows of the matrix:
[f1*f1inv - 1]
```

```python
sage: Y = simplicial_sets.Torus()
sage: Y.twisted_homology(1)
Quotient module by Submodule of Ambient free module of rank 5 over the...
 → integral domain Multivariate Polynomial Ring in f2, f2inv, f3, f3inv...
 → over Integer Ring
Generated by the rows of the matrix:
[ 1  0  0  0  0]
[ 0  1  0  0  0]
[ 0  0  1  0  0]
[ 0  0  0  1  0]
[ 0  0  0  0  1]
[f2*f2inv - 1  0  0  0  0]
[ 0 f2*f2inv - 1  0  0  0]
[ 0  0 f2*f2inv - 1  0  0]
[ 0  0  0 f2*f2inv - 1  0]
[ 0  0  0  0 f2*f2inv - 1]
[f3*f3inv - 1  0  0  0  0]
[ 0 f3*f3inv - 1  0  0  0]
[ 0  0 f3*f3inv - 1  0  0]
[ 0  0  0 f3*f3inv - 1  0]
[ 0  0  0  0 f3*f3inv - 1]
sage: Y.twisted_homology(2)
Quotient module by Submodule of Ambient free module of rank 0 over the...
 → integral domain Multivariate Polynomial Ring in f2, f2inv, f3, f3inv...
 → over Integer Ring
Generated by the rows of the matrix:
[]
sage: Y.twisted_homology(1, reduced=True)
Quotient module by Submodule of Ambient free module of rank 5 over the...
 → integral domain Multivariate Polynomial Ring in f2, f2inv, f3, f3inv...
 → over Integer Ring
Generated by the rows of the matrix:
[1 0 0 0 0]
[0 1 0 0 0]
[0 0 1 0 0]
[0 0 0 1 0]
[0 0 0 0 1]
```

`universal_cover()`

Return the universal cover of the simplicial set. The fundamental group must be finite in order to ensure that the universal cover is a simplicial set of finite type.
EXAMPLES:

```python
sage: # needs sage.groups
sage: RP3 = simplicial_sets.RealProjectiveSpace(3)
sage: C = RP3.universal_cover(); C
Simplicial set with 8 non-degenerate simplices
sage: C.face_data()
{(1, 1): None,
 (1, e): None,
 (f, 1): {(1, e), (1, 1)},
 (f, e): {(1, 1), (1, e)},
 (f * f, 1): {(f, e), s_0 (1, 1), (f, 1)},
 (f * f, e): {(f, 1), s_0 (1, e), (f, e)},
 (f * f * f, 1): ((f, e), s_0 (1, 1), (f, 1)),
 (f * f * f, e): ((f, 1), s_0 (1, e), (f, e)),
 (f * f * f * f, 1): ((f, e), s_0 (1, 1), (f, 1), (f * f, 1)),
 (f * f * f * f, e): ((f, 1), s_0 (1, e), (f, e)),
}
sage: C.fundamental_group()
Finitely presented group < | >
```

class SubcategoryMethods
Bases: object

**Pointed()**

A simplicial set is *pointed* if it has a distinguished base point.

EXAMPLES:

```python
sage: from sage.categories.simplicial_sets import SimplicialSets
sage: SimplicialSets().Pointed().Finite()
Category of finite pointed simplicial sets
```

```python
super_categories()##
```
4.149 Super Algebras

class sage.categories.super_algebras.SuperAlgebras(base_category)
    Bases: SuperModulesCategory

The category of super algebras.

An $R$-super algebra is an $R$-super module $A$ endowed with an $R$-algebra structure satisfying

$$A_0 A_0 \subseteq A_0, \quad A_0 A_1 \subseteq A_1, \quad A_1 A_0 \subseteq A_1, \quad A_1 A_1 \subseteq A_0$$

and $1 \in A_0$.

EXAMPLES:

sage: Algebras(ZZ).Super()
Category of super algebras over Integer Ring

class ParentMethods
    Bases: object

    graded_algebra()

        Return the associated graded algebra to self.

        Warning: Because a super module $M$ is naturally $\mathbb{Z}/2\mathbb{Z}$-graded, and graded modules have a natural filtration induced by the grading, if $M$ has a different filtration, then the associated graded module $\text{gr} M \neq M$. This is most apparent with super algebras, such as the differential Weyl algebra, and the multiplication may not coincide.

tensor(*parents, **kwargs)

        Return the tensor product of the parents.

EXAMPLES:

sage: # needs sage.combinat sage.modules
type: A.<x,y,z> = ExteriorAlgebra(ZZ); A.rename("A")
sage: T = A.tensor(A, A); T
    A # A # A
sage: T in Algebras(ZZ).Graded().SignedTensorProducts()
True
sage: T in Algebras(ZZ).Graded().TensorProducts()
False
sage: A.rename(None)

This also works when the other elements do not have a signed tensor product (github issue #31266):

sage: # needs sage.combinat sage.modules
type: a = SteenrodAlgebra(3).an_element()
sage: M = CombinatorialFreeModule(GF(3), ['s', 't', 'u'])
sage: s = M.basis()['s']
sage: tensor([a, s])

# needs sage.rings.finite_rings

2*Q_1 Q_3 P(2,1) # B['s']

class SignedTensorProducts(category, *args)
Bases: SignedTensorProductsCategory

extra_super_categories()

EXAMPLES:

sage: Coalgebras(QQ).Graded().SignedTensorProducts().extra_super_categories()
[Category of graded coalgebras over Rational Field]
sage: Coalgebras(QQ).Graded().SignedTensorProducts().super_categories()
[Category of graded coalgebras over Rational Field]

Meaning: a signed tensor product of coalgebras is a coalgebra

class SubcategoryMethods
Bases: object

Supercommutative()
Return the full subcategory of the supercommutative objects of self.
A super algebra $M$ is supercommutative if, for all homogeneous $x, y \in M$,

$$x \cdot y = (-1)^{|x||y|} y \cdot x.$$ 

REFERENCES:
Wikipedia article Supercommutative_algebra

EXAMPLES:

sage: Algebras(ZZ).Super().Supercommutative()
Category of supercommutative algebras over Integer Ring
sage: Algebras(ZZ).Super().WithBasis().Supercommutative()
Category of supercommutative algebras with basis over Integer Ring

Supercommutative
alias of SupercommutativeAlgebras

extra_super_categories()

EXAMPLES:

sage: Algebras(ZZ).Super().super_categories() # indirect doctest
[Category of graded algebras over Integer Ring, 
Category of super modules over Integer Ring]
4.150 Super algebras with basis

class sage.categories.super_algebras_with_basis.SuperAlgebrasWithBasis(base_category):

    Bases: SuperModulesCategory

    The category of super algebras with a distinguished basis

    EXAMPLES:

    sage: C = Algebras(ZZ).WithBasis().Super(); C
    Category of super algebras with basis over Integer Ring

    class ElementMethods

        Bases: object

        supercommutator(x)

            Return the supercommutator of self and x.

            Let $A$ be a superalgebra. The supercommutator of homogeneous elements $x, y \in A$ is defined by

            $$[x, y] = xy - (-1)^{|x||y|}yx$$

            and extended to all elements by linearity.

            EXAMPLES:

            sage: # needs sage.modules
            sage: Q = QuadraticForm(ZZ, 3, [1,2,3,4,5,6])
            sage: Cl.<x,y,z> = CliffordAlgebra(Q)
            sage: a = x*y - z
            sage: b = x - y + y*z
            sage: a.supercommutator(b)
            -5*x*y + 8*x*z - 2*y*z - 6*x + 12*y - 5*z
            sage: a.supercommutator(Cl.one())
            0
            sage: Cl.one().supercommutator(a)
            0
            sage: Cl.zero().supercommutator(a)
            0
            sage: a.supercommutator(Cl.zero())
            0
            sage: # needs sage.modules
            sage: Q = QuadraticForm(ZZ, 2, [-1,1,-3])
            sage: Cl.<x,y> = CliffordAlgebra(Q)
            sage: [a*b-b*a for a in Cl.basis() for b in Cl.basis()]
            [0, 0, 0, 0, 0, 0, 2*x*y - 1, -x - 2*y, 0, 0, 6*x + y, 0, 0, x + 2*y, -6*x - y, 0]

        Exterior algebras inherit from Clifford algebras, so supercommutators work as well. We verify the exterior algebra is supercommutative:
sage: E.<x,y,z,w> = ExteriorAlgebra(QQ)  # needs sage.modules
sage: all(b1.supercommutator(b2) == 0  # needs sage.modules
    ....:     for b1 in E.basis() for b2 in E.basis())
True

class ParentMethods
Bases: object

graded_algebra()

Return the associated graded module to self.

See AssociatedGradedAlgebra for the definition and the properties of this.

See also:
graded_algebra()

EXAMPLES:

sage: W.<x,y> = algebras.DifferentialWeyl(QQ)  # needs sage.modules
sage: W.graded_algebra()  # needs sage.combinat sage.modules
Graded Algebra of Differential Weyl algebra of polynomials in x, y over Rational Field

class SignedTensorProducts(category, *args)
Bases: SignedTensorProductsCategory

The category of super algebras with basis constructed by tensor product of super algebras with basis.

extra_super_categories()

EXAMPLES:

sage: Algebras(QQ).Super().SignedTensorProducts().extra_super_categories()
[Category of super algebras over Rational Field]
sage: Algebras(QQ).Super().SignedTensorProducts().super_categories()
[Category of signed tensor products of graded algebras over Rational Field,
 Category of super algebras over Rational Field]

Meaning: a signed tensor product of super algebras is a super algebra

extra_super_categories()

EXAMPLES:

sage: C = Algebras(ZZ).WithBasis().Super()
sage: sorted(C.super_categories(), key=str)  # indirect doctest
[Category of graded algebras with basis over Integer Ring,
 Category of super algebras over Integer Ring,
 Category of super modules with basis over Integer Ring]
4.151 Super Hopf algebras with basis

class sage.categories.super_hopf_algebras_with_basis.SuperHopfAlgebrasWithBasis (base_category)

Bases: SuperModulesCategory

The category of super Hopf algebras with a distinguished basis.

EXAMPLES:

```
sage: C = HopfAlgebras(ZZ).WithBasis().Super(); C
Category of super Hopf algebras with basis over Integer Ring
sage: sorted(C.super_categories(), key=str)
[Category of super Hopf algebras over Integer Ring,
 Category of super algebras with basis over Integer Ring,
 Category of super coalgebras with basis over Integer Ring]
```

class ParentMethods

Bases: object

antipode()

The antipode of this Hopf algebra.

If antipode_basis() is available, this constructs the antipode morphism from self to self by extending it by linearity. Otherwise, self.antipode_by_coercion() is used, if available.

EXAMPLES:

```
sage: A = SteenrodAlgebra(7)  # needs sage.combinat sage.modules
sage: a = A.an_element()      # needs sage.combinat sage.modules
sage: a, A.antipode(a)        # needs sage.combinat sage.modules
(6 Q_1 Q_3 P(2,1), Q_1 Q_3 P(2,1))
```

4.152 Super Lie Conformal Algebras

AUTHORS:


class sage.categories.super_lie_conformal_algebras.SuperLieConformalAlgebras (base_category)

Bases: SuperModulesCategory

The category of super Lie conformal algebras.

EXAMPLES:

```
sage: LieConformalAlgebras(AA).Super()  # needs sage.rings.number_field
Category of super Lie conformal algebras over Algebraic Real Field
```
Notice that we can force to have a purely even super Lie conformal algebra:

```python
sage: bosondict = {('a','a'): {1:{('K',0):1}}}
sage: R = LieConformalAlgebra(QQ, bosondict, names=('a',),
                         central_elements=('K',), super=True)
[0, 0]
```

class `ElementMethods`

Bases: object

```python
    is_even_odd()
    Return 0 if this element is even and 1 if it is odd.
    EXAMPLES:

    sage: R = lie_conformal_algebras.NeveuSchwarz(QQ)
    sage: R.inject_variables()
    Defining L, G, C
    sage: G.is_even_odd()
    1
```

class `Graded`

_bases: GradedModulesCategory

The category of H-graded super Lie conformal algebras.

EXAMPLES:

```python
sage: LieConformalAlgebras(AA).Super().Graded()
Category of H-graded super Lie conformal algebras over Algebraic Real Field
```

class `ParentMethods`

Bases: object

```python
    example()
    An example parent in this category.
    EXAMPLES:

    sage: LieConformalAlgebras(QQ).Super().example()
    The Neveu-Schwarz super Lie conformal algebra over Rational Field
```

extra_super_categories()

The extra super categories of self.

EXAMPLES:

```python
sage: LieConformalAlgebras(QQ).Super().super_categories()
[Category of super modules over Rational Field,
 Category of Lambda bracket algebras over Rational Field]
```
4.153 Super modules

class sage.categories.super_modules.SuperModules(base_category):
    Bases: SuperModulesCategory

    The category of super modules.

    An $R$-super module (where $R$ is a ring) is an $R$-module $M$ equipped with a decomposition $M = M_0 \oplus M_1$ into two $R$-submodules $M_0$ and $M_1$ (called the even part and the odd part of $M$, respectively).

    Thus, an $R$-super module automatically becomes a $\mathbb{Z}/2\mathbb{Z}$-graded $R$-module, with $M_0$ being the degree-0 component and $M_1$ being the degree-1 component.

    EXAMPLES:

    sage: Modules(ZZ).Super()
    Category of super modules over Integer Ring
    sage: Modules(ZZ).Super().super_categories()
    [Category of graded modules over Integer Ring]

    The category of super modules defines the super structure which shall be preserved by morphisms:

    sage: Modules(ZZ).Super().additional_structure()
    Category of super modules over Integer Ring

    class ElementMethods
        Bases: object

        is_even()
            Return if self is an even element.

            EXAMPLES:

            sage: # needs sage.combinat sage.modules
            sage: cat = Algebras(QQ).WithBasis().Super()
            sage: C = CombinatorialFreeModule(QQ, Partitions(), category=cat)
            sage: C.degree_on_basis = sum
            sage: C.basis()[2,2,1].is_even()  # expected False
            False
            sage: C.basis()[2,2].is_even()   # expected True
            True

        is_even_odd()
            Return 0 if self is an even element or 1 if an odd element.

            Note: The default implementation assumes that the even/odd is determined by the parity of degree().
            Overwrite this method if the even/odd behavior is desired to be independent.

            EXAMPLES:

            sage: # needs sage.combinat sage.modules
            sage: cat = Algebras(QQ).WithBasis().Super()
            sage: C = CombinatorialFreeModule(QQ, Partitions(), category=cat)
            sage: C.degree_on_basis = sum
            sage: C.basis()[2,2,1].is_even_odd()  # expected (0)
            (continues on next page)
sage: C.basis()[2,2].is_even_odd()
0

**is_odd()**

Return if *self* is an odd element.

**EXAMPLES:**

```
sage: # needs sage.combinat sage.modules
c sage: cat = Algebras(QQ).WithBasis().Super()
c sage: C = CombinatorialFreeModule(QQ, Partitions(), category=cat)
c sage: C.degree_on_basis = sum
c sage: C.basis()[2,2,1].is_odd()
True
c sage: C.basis()[2,2].is_odd()
False
```

### class ParentMethods

**Bases:** object

**extra_super_categories()**

Adds *VectorSpaces* to the super categories of *self* if the base ring is a field.

**EXAMPLES:**

```
sage: Modules(QQ).Super().extra_super_categories()
[Category of vector spaces over Rational Field]
sage: Modules(ZZ).Super().extra_super_categories()
[]
```

This makes sure that *Modules(QQ).Super()* returns an instance of *SuperModules* and not a join category of an instance of this class and of *VectorSpaces(QQ)*:

```
sage: Modules(QQ).Super()
<...>
sage: type(Modules(QQ).Super())
<class 'sage.categories.super_modules.SuperModules_with_category'>
```

**Todo:** Get rid of this workaround once there is a more systematic approach for the alias *Modules(QQ) -> VectorSpaces(QQ)*. Probably the latter should be a category with axiom, and covariant constructions should play well with axioms.

**super_categories()**

**EXAMPLES:**

```
sage: Modules(ZZ).Super().super_categories()
[Category of graded modules over Integer Ring]
```

**Nota bene:**

```
sage: Modules(QQ).Super()
Category of super modules over Rational Field
sage: Modules(QQ).Super().super_categories()
[Category of graded modules over Rational Field]
```
class sage.categories.super_modules.SuperModulesCategory (base_category)

Bases: CovariantConstructionCategory, Category_over_base_ring

EXAMPLES:

```python
sage: C = Algebras(QQ).Super()
sage: C
Category of super algebras over Rational Field
sage: C.base_category()
Category of algebras over Rational Field
sage: sorted(C.super_categories(), key=str)
[Category of graded algebras over Rational Field,
 Category of super modules over Rational Field]
sage: AlgebrasWithBasis(QQ).Super().base_ring()
Rational Field
sage: HopfAlgebrasWithBasis(QQ).Super().base_ring()
Rational Field
```

classmethod default_super_categories (category, *args)

Return the default super categories of $F_{\text{Cat}}(A, B, ...)$ for $A, B, ...$ parents in $\text{Cat}$.

INPUT:

- cls – the category class for the functor $F$
- category – a category $\text{Cat}$
- *args – further arguments for the functor

OUTPUT:

A join category.

This implements the property that subcategories constructed by the set of whitelisted axioms is a subcategory.

EXAMPLES:

```python
sage: HopfAlgebras(ZZ).WithBasis().FiniteDimensional().Super()  # indirect doctest
Category of finite dimensional super Hopf algebras with basis over Integer
```

4.154 Super modules with basis

class sage.categories.super_modules_with_basis.SuperModulesWithBasis (base_category)

Bases: SuperModulesCategory

The category of super modules with a distinguished basis.

An $R$-super module with a distinguished basis is an $R$-super module equipped with an $R$-module basis whose elements are homogeneous.

EXAMPLES:
class ElementMethods

    Bases: object

    even_component()

    Return the even component of self.

    EXAMPLES:

        sage: # needs sage.modules
        sage: Q = QuadraticForm(QQ, 2, [1,2,3])
        sage: C.<x,y> = CliffordAlgebra(Q)
        sage: a = x*y + x - 3*y + 4
        sage: a.even_component()
        x*y + 4

    is_even_odd()

    Return 0 if self is an even element and 1 if self is an odd element.

    EXAMPLES:

        sage: # needs sage.modules
        sage: Q = QuadraticForm(QQ, 2, [1,2,3])
        sage: C.<x,y> = CliffordAlgebra(Q)
        sage: a = x + y
        sage: a.is_even_odd()
        1
        sage: a = x*y + 4
        sage: a.is_even_odd()
        0
        sage: a = x + 4
        sage: a.is_even_odd()
        Traceback (most recent call last):
        ... ValueError: element is not homogeneous
        sage: E.<x,y> = ExteriorAlgebra(QQ)  # needs sage.modules
        sage: (x*y).is_even_odd()  # needs sage.modules
        0

    is_super_homogeneous()

    Return whether this element is homogeneous, in the sense of a super module (i.e., is even or odd).

    EXAMPLES:

        sage: # needs sage.modules
        sage: Q = QuadraticForm(QQ, 2, [1,2,3])
The exterior algebra has a $\mathbb{Z}$ grading, which induces the $\mathbb{Z}/2\mathbb{Z}$ grading. However the definition of homogeneous elements differs because of the different gradings:

```python
sage: # needs sage.combinat sage.modules
sage: E.<x,y> = ExteriorAlgebra(QQ)
```

```python
tilde{\text{odd}} \text{\_component} ()
Return the odd component of \text{self}.

\text{EXAMPLES:}
```

```python
sage: # needs sage.modules
sage: Q = QuadraticForm(QQ, 2, [1,2,3])
sage: C.<x,y> = CliffordAlgebra(Q)
sage: a = x*y + x - 3*y + 4
```

```python
class ParentMethods
Bases: object
```

4.155 Supercommutative Algebras

The category of supercommutative algebras.

An $R$-supercommutative algebra is an $R$-super algebra $A = A_0 \oplus A_1$ endowed with an $R$-super algebra structure satisfying:

$$x_0x'_0 = x'_0x_0, \quad x_1x'_1 = -x'_1x_1, \quad x_0x_1 = x_1x_0,$$

for all $x_0, x'_0 \in A_0$ and $x_1, x'_1 \in A_1$.

\text{EXAMPLES:}
class SignedTensorProducts (category, *args)

    Bases: SignedTensorProductsCategory

    extra_super_categories()
    
    Return the extra super categories of self.

    A signed tensor product of supercommutative algebras is a supercommutative algebra.

    EXAMPLES:

        sage: C = Algebras(ZZ).Supercommutative().SignedTensorProducts()
        sage: C.extra_super_categories()
        [Category of supercommutative algebras over Integer Ring]

class WithBasis (base_category)

    Bases: CategoryWithAxiom_over_base_ring

    class ParentMethods

        Bases: object

is_genuine_highest_weight (index_set=None)

    Return whether self is a genuine highest weight element.

    INPUT:
    • index_set – (optional) the index set of the (sub)crystal on which to check

    EXAMPLES:

        sage: B = crystals.Tableaux(['A', [1,1]], shape=[3,2,1])
        sage: for b in B.highest_weight_vectors():
        ....:     print("{}").format(b, b.is_genuine_highest_weight())
        [[[-2, -2, -2], [-1, -1], [1]] True
        [[[-2, -2, -2], [-1, 2], [1]] False
        [[-2, -2, 2], [-1, -1], [1]] False
        sage: [b for b in B if b.is_genuine_highest_weight([-1,0])]
        [[[-2, -2, -2], [-1, -1], [1]],
         [[-2, -2, -2], [-1, -1], [2]],
         [[-2, -2, -2], [-1, 2], [2]],
         [[-2, -2, 2], [-1, -1], [2]],
         [[-2, -2, 2], [-1, 2], [2]],
         [[-2, -2, 2], [-1, 2], [1]],
         [[-2, -2, 2], [-1, -1], [1]],
         [[-2, -2, 2], [-1, -1], [1]]]
**is_genuine_lowest_weight** *(index_set=\*None\*)

Return whether *self* is a genuine lowest weight element.

**INPUT:**
- *index_set* – (optional) the index set of the (sub)crystal on which to check

**EXAMPLES:**

```python
sage: B = crystals.Tableaux(['A', [1,1]], shape=[3,2,1])
sage: for b in sorted(B.lowest_weight_vectors()):
    ....:     print("{} {}").format(b, b.is_genuine_lowest_weight())
[[-2, 1, 2], [-1, 2], [1]] False
[[-2, 1, 2], [-1, 2], [2]] False
[[-1, 1, 2], [1, 2], [2]] True
```

**class ParentMethods**

**Bases:** object

**character()**

Return the character of *self*.

**Todo:** Once the *WeylCharacterRing* is implemented, make this consistent with the implementation in *sage.categories.classical_crystals.ClassicalCrystals.ParentMethods.character()*.

**EXAMPLES:**

```python
sage: B = crystals.Letters(['A', [1,2]])
sage: B.character()
B[1, 0, 0, 0, 0] + B[0, 1, 0, 0, 0] + B[0, 0, 1, 0, 0] + B[0, 0, 0, 1, 0] + B[0, 0, 0, 0, 1]
```

**connected_components()**

Return the connected components of *self* as subcrystals.

**EXAMPLES:**

```python
sage: B = crystals.Letters(['A', [1,2]])
sage: B.connected_components()
[Subcrystal of The crystal of letters for type ['A', [1, 2]]]
```

(continues on next page)


connected_components_generators()

Return the tuple of genuine highest weight elements of self.

EXAMPLES:

```python
sage: B = crystals.Letters(['A', [1,2]])
sage: B.genuine_highest_weight_vectors()
(-2,)

sage: T = B.tensor(B)
sage: T.genuine_highest_weight_vectors()
([-2, -1], [-2, -2])
sage: s1, s2 = T.connected_components()
sage: s = s1 + s2
sage: s.genuine_highest_weight_vectors()
([-2, -1], [-2, -2])
```

digraph (index_set=None)

Return the DiGraph associated to self.

EXAMPLES:

```python
sage: B = crystals.Letters(['A', [1,3]])
sage: G = B.digraph(); G
Multi-digraph on 6 vertices

sage: Q = crystals.Letters(['Q', 3])
sage: G = Q.digraph(); G
Multi-digraph on 3 vertices

sage: G.edges(sort=True)
[(-1, 1, 1), (1, 2, 2), (2, 3, -2), (2, 3, 2)]
```

The edges of the crystal graph are by default colored using blue for edge 1, red for edge 2, green for edge 3, and dashed with the corresponding color for barred edges. Edge 0 is dotted black:

```python
sage: view(G)  # optional - dot2tex graphviz, not tested (opens external window)
```

genuine_highest_weight_vectors()

Return the tuple of genuine highest weight elements of self.

EXAMPLES:

```python
sage: B = crystals.Letters(['A', [1,2]])
sage: B.genuine_highest_weight_vectors()
(-2,)

sage: T = B.tensor(B)
sage: T.genuine_highest_weight_vectors()
([-2, -1], [-2, -2])
sage: s1, s2 = T.connected_components()
sage: s = s1 + s2
sage: s.genuine_highest_weight_vectors()
([-2, -1], [-2, -2])
```
**genuine_lowest_weight_vectors()**

Return the tuple of genuine lowest weight elements of self.

**EXAMPLES:**

```python
sage: B = crystals.Letters(['A', [1,2]])
sage: B.genuine_lowest_weight_vectors()
(3,)
sage: T = B.tensor(B)
sage: T.genuine_lowest_weight_vectors()
([3, 3], [3, 2])
```

**highest_weight_vectors()**

Return the highest weight vectors of self.

**EXAMPLES:**

```python
sage: B = crystals.Letters(['A', [1,2]])
sage: B.highest_weight_vectors()
(-2,)
sage: T = B.tensor(B)
sage: T.highest_weight_vectors()
([-2, -2], [-2, -1])
```

We give an example from [BKK2000] that has fake highest weight vectors:

```python
sage: B = crystals.Tableaux(['A', [1,1]], shape=[3,2,1])
sage: sorted(B.highest_weight_vectors())

([[-2, 1, 2], [-1, 2], [1]],
 [[-2, -2, -2], [-1, -1], [1]],
 [[-2, -2, -2], [-1, -1], [1]]),
```

**lowest_weight_vectors()**

Return the lowest weight vectors of self.

**EXAMPLES:**

```python
sage: B = crystals.Letters(['A', [1,2]])
sage: B.lowest_weight_vectors()
(3,)
sage: T = B.tensor(B)
sage: s1, s2 = T.connected_components()
sage: s = s1 + s2
sage: s.genuine_lowest_weight_vectors()
([3, 3], [3, 2])
```

We give an example from [BKK2000] that has fake lowest weight vectors:

```python
sage: B = crystals.Tableaux(['A', [1,1]], shape=[3,2,1])
sage: sorted(B.lowest_weight_vectors())

([[-2, 1, 2], [-1, 2], [1]],
 [[-2, -2, -2], [-1, -1], [1]],
 [790 Chapter 4. Individual Categories
(continues on next page)```
class ParentMethods

Bases: object

tensor(*crystals, **options)

Return the tensor product of self with the crystals B.

EXAMPLES:

```python
sage: B = crystals.Letters(['A',[1,2]])
sage: C = crystals.Tableaux(['A',[1,2]], shape = [2,1])
sage: T = C.tensor(B); T
Full tensor product of the crystals
Crystal of BKK tableaux of shape [2, 1] of gl(2|3),
The crystal of letters for type ['A', [1, 2]])
sage: S = B.tensor(C); S
Full tensor product of the crystals
[The crystal of letters for type ['A', [1, 2]],
Crystal of BKK tableaux of shape [2, 1] of gl(2|3)]
sage: G = T.digraph()
sage: H = S.digraph()
sage: G.is_isomorphic(H, edge_labels= True)
True
```

class TensorProducts(category, *args)

Bases: TensorProductsCategory

The category of regular crystals constructed by tensor product of regular crystals.

extra_super_categories()

EXAMPLES:

```python
sage: from sage.categories.supercrystals import SuperCrystals
sage: SuperCrystals().TensorProducts().extra_super_categories()
[Category of super crystals]
```

super_categories()

EXAMPLES:

```python
sage: from sage.categories.supercrystals import SuperCrystals
sage: C = SuperCrystals()
sage: C.super_categories()
[Category of crystals]```
4.157 Topological Spaces

class sage.categories.topological_spaces.TopologicalSpaces(category, *args)
    Bases: TopologicalSpacesCategory
    The category of topological spaces.

EXAMPLES:

    sage: Sets().Topological()
    Category of topological spaces
    sage: Sets().Topological().super_categories()
    [Category of sets]

The category of topological spaces defines the topological structure, which shall be preserved by morphisms:

    sage: Sets().Topological().additional_structure()
    Category of topological spaces

class CartesianProducts(category, *args)
    Bases: CartesianProductsCategory
    extra_super_categories()
        Implement the fact that a (finite) Cartesian product of topological spaces is a topological space.

EXAMPLES:

    sage: from sage.categories.topological_spaces import TopologicalSpaces
    sage: C = TopologicalSpaces().CartesianProducts()
    sage: C.extra_super_categories()
    [Category of topological spaces]
    sage: C.super_categories()
    [Category of Cartesian products of sets, Category of topological spaces]
    sage: C.axioms()
    frozenset()

class Compact(base_category)
    Bases: CategoryWithAxiom
    The category of compact topological spaces.

class CartesianProducts(category, *args)
    Bases: CartesianProductsCategory
    extra_super_categories()
        Implement the fact that a (finite) Cartesian product of compact topological spaces is compact.

EXAMPLES:

    sage: from sage.categories.topological_spaces import TopologicalSpaces
    sage: C = TopologicalSpaces().Compact().CartesianProducts()
    sage: C.extra_super_categories()
    [Category of compact topological spaces]
    sage: C.super_categories()
    [Category of Cartesian products of topological spaces, Category of compact topological spaces]
    sage: C.axioms()
    frozenset({'Compact'})
class Connected(base_category)
    Bases: CategoryWithAxiom

    The category of connected topological spaces.

class CartesianProducts(category, *args)
    Bases: CartesianProductsCategory

    extra_super_categories()
        Implement the fact that a (finite) Cartesian product of connected topological spaces is connected.

    EXAMPLES:
        sage: from sage.categories.topological_spaces import TopologicalSpaces
        sage: C = TopologicalSpaces().Connected().CartesianProducts()
        sage: C.extra_super_categories()
        [Category of connected topological spaces]
        sage: C.super_categories()
        [Category of Cartesian products of topological spaces,  
         Category of connected topological spaces]
        sage: C.axioms()
        frozenset({'Connected'})

class SubcategoryMethods
    Bases: object

    Compact()
        Return the subcategory of the compact objects of self.

    EXAMPLES:
        sage: Sets().Topological().Compact()
        Category of compact topological spaces

    Connected()
        Return the full subcategory of the connected objects of self.

    EXAMPLES:
        sage: Sets().Topological().Connected()
        Category of connected topological spaces

class sage.categories.topological_spaces.TopologicalSpacesCategory(category, *args)
    Bases: RegressiveCovariantConstructionCategory

4.158 Kac-Moody Algebras With Triangular Decomposition Basis

AUTHORS:
• Travis Scrimshaw (07-15-2017): Initial implementation

class sage.categories.triangular_kac_moody_algebras.TriangularKacMoodyAlgebras(base,  
                             name=None)
    Bases: Category_over_base_ring

    Category of Kac-Moody algebras with a distinguished basis that respects the triangular decomposition.

    We require that the grading group is the root lattice of the appropriate Cartan type.
class ElementMethods

Bases: object

part()

Return whether the element \( v \) is in the lower, zero, or upper part of self.

OUTPUT:

\(-1\) if \( v \) is in the lower part, \( 0 \) if in the zero part, or \( 1 \) if in the upper part

EXAMPLES:

```
sage: # needs sage.combinat sage.modules
sage: L = LieAlgebra(QQ, cartan_type="F4")
sage: L.inject_variables()
Defining e1, e2, e3, e4, f1, f2, f3, f4, h1, h2, h3, h4
sage: e1.part()
1
sage: f4.part()
-1
sage: (h2 + h3).part()
0
sage: (f1.bracket(f2) + 4*f4).part()
-1
sage: (e1 + f1).part()
Traceback (most recent call last):
  ... ValueError: element is not in one part
```

class ParentMethods

Bases: object

e(i=None)

Return the generators \( e \) of self.

INPUT:

\( i \) – (optional) if specified, return just the generator \( e_i \)

EXAMPLES:

```
sage: L = lie_algebras.so(QQ, 5)  # needs sage.combinat sage.modules
sage: L.e()
#...
```

f(i=None)

Return the generators \( f \) of self.

INPUT:

\( i \) – (optional) if specified, return just the generator \( f_i \)

EXAMPLES:

```
sage: L = lie_algebras.so(QQ, 5)  # needs sage.combinat sage.modules
sage: L.f()
#...
```

(continues on next page)
\textbf{verma\_module}(\textit{la}, \textit{basis\_key}=None, **\textit{kwds})

Return the Verma module with highest weight \textit{la} over \textit{self}.

\textbf{INPUT:}

\begin{itemize}
  \item \textit{basis\_key} – (optional) a key function for the indexing set of the basis elements of \textit{self}
\end{itemize}

\textbf{EXAMPLES:}

\begin{verbatim}
sage: # needs sage.combinat sage.modules
sage: L = lie_algebras.sl(QQ, 3)
sage: P = L.cartan_type().root_system().weight_lattice()
sage: La = P.fundamental_weights()
sage: M = L.verma_module(La[1] + La[2])
sage: M
of Lie algebra of ['A', 2] in the Chevalley basis
\end{verbatim}

\textbf{super\_categories}()

\textbf{EXAMPLES:}

\begin{verbatim}
sage: from sage.categories.triangular_kac_moody_algebras import
    TriangularKacMoodyAlgebras
sage: TriangularKacMoodyAlgebras(QQ).super_categories()
[Join of Category of graded Lie algebras with basis over Rational Field
  and Category of kac moody algebras over Rational Field]
\end{verbatim}

\section{4.159 Unique factorization domains}

\textbf{class} \texttt{sage.categories.unique\_factorization\_domains.\_\_\_UniqueFactorizationDomains}

\textbf{Bases:} \texttt{Category\_singleton}

The category of (constructive) unique factorization domains.

In a constructive unique factorization domain we can constructively factor members into a product of a finite number of irreducible elements.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: UniqueFactorizationDomains()
Category of unique factorization domains
sage: UniqueFactorizationDomains().super_categories()
[Category of gcd domains]
\end{verbatim}

\textbf{class} \texttt{ElementMethods}

\textbf{Bases:} \texttt{object}

\textbf{radical}(\textit{*\texttt{args}, **\texttt{kwds}})

Return the radical of this element, i.e. the product of its irreducible factors.
This default implementation calls `squarefree_decomposition` if available, and `factor` otherwise.

See also:

`squarefree_part()`

EXAMPLES:

```python
sage: Pol.<x> = QQ[]
```

```python
sage: (x^2*(x-1)^3).radical()
```

```python
x^2 - x
```

```python
sage: pol = 37 * (x-1)^3 * (x-2)^2 * (x-1/3)^7 * (x-3/7)
```

```python
sage: pol.radical()
```

```python
37*x^4 - 2923/21*x^3 + 1147/7*x^2 - 1517/21*x + 74/7
```

```python
sage: Integer(10).radical()
```

```python
10
```

```python
sage: Integer(-100).radical()
```

```python
10
```

```python
sage: Integer(0).radical()
```

```python
Traceback (most recent call last):
  ...
ArithmeticError: radical of 0 is not defined
```

The next example shows how to compute the radical of a number, assuming no prime > 100000 has exponent > 1 in the factorization:

```python
sage: n = 2^1000-1; n / radical(n, limit=100000)
```

```python
125
```

`squarefree_part()`

Return the square-free part of this element, i.e. the product of its irreducible factors appearing with odd multiplicity.

This default implementation calls `squarefree_decomposition`.

See also:

`radical()`

EXAMPLES:

```python
sage: Pol.<x> = QQ[]
```

```python
sage: (x^2*(x-1)^3).squarefree_part()
```

```python
x - 1
```

```python
sage: pol = 37 * (x-1)^3 * (x-2)^2 * (x-1/3)^7 * (x-3/7)
```

```python
sage: pol.squarefree_part()
```

```python
37*x^3 - 1369/21*x^2 + 703/21*x - 37/7
```

class ParentMethods

Bases: object

`is_unique_factorization_domain` *(proof=True)*

Return True, since this in an object of the category of unique factorization domains.

EXAMPLES:
additional_structure()

Return whether self is a structure category.

See also:

Category.additional_structure()

The category of unique factorization domains does not define additional structure: a ring morphism between unique factorization domains is a unique factorization domain morphism.

EXAMPLES:

sage: UniqueFactorizationDomains().additional_structure()

super_categories()

EXAMPLES:

sage: UniqueFactorizationDomains().super_categories()

[Category of gcd domains]

4.160 Unital algebras

class sage.categories.unital_algebras.UnitalAlgebras(base_category)

Bases: CategoryWithAxiom_over_base_ring

The category of non-associative algebras over a given base ring.

A non-associative algebra over a ring $R$ is a module over $R$ which is also a unital magma.

Warning: Until github issue #15043 is implemented, Algebras is the category of associative unital algebras; thus, unlike the name suggests, UnitalAlgebras is not a subcategory of Algebras but of MagmaticAlgebras.

EXAMPLES:

sage: from sage.categories.unital_algebras import UnitalAlgebras
sage: C = UnitalAlgebras(ZZ); C
Category of unital algebras over Integer Ring

class CartesianProducts(category, *args)

Bases: CartesianProductsCategory

The category of unital algebras constructed as Cartesian products of unital algebras.

This construction gives the direct product of algebras. See discussion on:

- http://groups.google.fr/group/sage-devel/browse_thread/thread/35a72b1d0a2f77a348f42ae77a66d16#348f42ac77a66d16
- Wikipedia article Direct_product

4.160. Unital algebras
class ParentMethods
    Bases: object

    one()
    
    Return the multiplicative unit element.

    EXAMPLES:

    sage: S2 = simplicial_complexes.Sphere(2)
sage: H = S2.cohomology_ring(QQ)
sage: C = cartesian_product([H, H])
sage: one = C.one()
sage: one
B[(0, (0, 0))] + B[(1, (0, 0))]
    True
    sage: all(b == b * one for b in C.basis())
    True

eextra_super_categories()
A Cartesian product of algebras is endowed with a natural unital algebra structure.

    EXAMPLES:

    sage: from sage.categories.unital_algebras import UnitalAlgebras
sage: C = UnitalAlgebras(QQ).CartesianProducts()
sage: C.extra_super_categories()
[Category of unital algebras over Rational Field]
sage: sorted(C.super_categories(), key=str)
[Category of Cartesian products of distributive magmas and additive...
    Category of Cartesian products of unital magmas,
    Category of Cartesian products of vector spaces over Rational Field,
    Category of unital algebras over Rational Field]

class ParentMethods
    Bases: object

    from_base_ring(r)
    
    Return the canonical embedding of r into self.

    INPUT:
    • r — an element of self.base_ring()

    EXAMPLES:

    sage: A = AlgebrasWithBasis(QQ).example(); A
    # needs sage.combinat sage.modules
    An example of an algebra with basis:
    the free algebra on the generators ('a', 'b', 'c') over Rational Field
sage: A.from_base_ring(1)
# needs sage.combinat sage.modules
B[word: ]

class WithBasis(base_category)
    Bases: CategoryWithAxiom_over_base_ring
class ParentMethods
    Bases: object
from_base_ring()

from_base_ring_from_one_basis(r)

Implement the canonical embedding from the ground ring.

INPUT:
• r – an element of the coefficient ring

EXAMPLES:

```
sage: # needs sage.combinat sage.modules
sage: A = AlgebrasWithBasis(QQ).example()
sage: A.from_base_ring_from_one_basis(3)
3*B
sage: A.from_base_ring(3)
3*B
sage: A(3)
3*B
```

one()

Return the multiplicative unit element.

EXAMPLES:

```
sage: A = AlgebrasWithBasis(QQ).example()  # needs sage.combinat sage.modules
sage: A.one()  # needs sage.combinat sage.modules
B
```

one_basis()

When the one of an algebra with basis is an element of this basis, this optional method can return the index of this element. This is used to provide a default implementation of one(), and an optimized default implementation of from_base_ring().

EXAMPLES:

```
sage: # needs sage.combinat sage.modules
sage: A = AlgebrasWithBasis(QQ).example()  # needs sage.combinat sage.modules
sage: A.one_basis()
word:
sage: A.one()  # needs sage.combinat sage.modules
B
sage: A.from_base_ring(4)
4*B
```

one_from_one_basis()

Return the one of the algebra, as per Monoids.ParentMethods.one()

By default, this is implemented from one_basis(), if available.

EXAMPLES:

```
sage: # needs sage.combinat sage.modules
sage: A = AlgebrasWithBasis(QQ).example()
sage: A.one_basis()  # needs sage.combinat sage.modules
```

(continues on next page)
4.161 Vector Bundles

class sage.categories.vector_bundles.VectorBundles(base_space, base_field, name=None)

   Bases: Category_over_base_ring

   The category of vector bundles over any base space and base field.

   See also:

   TopologicalVectorBundle

   EXAMPLES:

   sage: M = Manifold(2, 'M', structure='top')
sage: from sage.categories.vector_bundles import VectorBundles
sage: C = VectorBundles(M, RR); C
Category of vector bundles over Real Field with 53 bits of precision
   with base space 2-dimensional topological manifold M
sage: C.super_categories()
[Category of topological spaces]

class Differentiable(base_category)

   Bases: CategoryWithAxiom_over_base_ring

   The category of differentiable vector bundles.

   A differentiable vector bundle is a differentiable manifold with differentiable surjective projection on a differentiable base space.

class Smooth(base_category)

   Bases: CategoryWithAxiom_over_base_ring

   The category of smooth vector bundles.

   A smooth vector bundle is a smooth manifold with smooth surjective projection on a smooth base space.

class SubcategoryMethods

   Bases: object

   Differentiable()

       Return the subcategory of the differentiable objects of self.

   EXAMPLES:

       sage: M = Manifold(2, 'M')
sage: from sage.categories.vector_bundles import VectorBundles
sage: VectorBundles(M, RR).Differentiable()
Category of differentiable vector bundles over Real Field with 53 bits of precision with base space 2-dimensional differentiable manifold M
**Smooth()**

Return the subcategory of the smooth objects of *self*.

**EXAMPLES:**

```
sage: M = Manifold(2, 'M')
sage: from sage.categories.vector_bundles import VectorBundles
sage: VectorBundles(M, RR).Smooth()
Category of smooth vector bundles over Real Field with 53 bits of precision with base space 2-dimensional differentiable manifold M
```

**base_space()**

Return the base space of this category.

**EXAMPLES:**

```
sage: M = Manifold(2, 'M', structure='top')
sage: from sage.categories.vector_bundles import VectorBundles
sage: VectorBundles(M, RR).base_space()
2-dimensional topological manifold M
```

**super_categories()**

**EXAMPLES:**

```
sage: M = Manifold(2, 'M')
sage: from sage.categories.vector_bundles import VectorBundles
sage: VectorBundles(M, RR).super_categories()
[Category of topological spaces]
```

### 4.162 Vector Spaces

**class** `sage.categories.vector_spaces.VectorSpaces(K)`

**Bases:** `Category_module`

The category of (abstract) vector spaces over a given field `K` with an embedding in an ambient vector space.

**EXAMPLES:**

```
sage: VectorSpaces(QQ)
Category of vector spaces over Rational Field
sage: VectorSpaces(QQ).super_categories()
[Category of modules over Rational Field]
```

**class CartesianProducts(category, *args)**

**Bases:** `CartesianProductsCategory`

**extra_super_categories()**

The category of vector spaces is closed under Cartesian products:

```
sage: C = VectorSpaces(QQ)
sage: C.CartesianProducts()
Category of Cartesian products of vector spaces over Rational Field
```

(continues on next page)
class DualObjects(category, *args)
    Bases: DualObjectsCategory

    extra_super_categories()
    Returns the dual category

    EXAMPLES:
    The category of algebras over the Rational Field is dual to the category of coalgebras over the same field:

        sage: C = VectorSpaces(QQ)
        sage: C.dual()
        Category of duals of vector spaces over Rational Field
        sage: C.dual().super_categories()  # indirect doctest
        [Category of vector spaces over Rational Field]

class ElementMethods
    Bases: object

class Filtered(base_category)
    Bases: FilteredModulesCategory
    Category of filtered vector spaces.

class FiniteDimensional(base_category)
    Bases: CategoryWithAxiom_over_base_ring

class TensorProducts(category, *args)
    Bases: TensorProductsCategory

    extra_super_categories()
    Implement the fact that a (finite) tensor product of finite dimensional vector spaces is a finite dimensional vector space.

    EXAMPLES:

        sage: VectorSpaces(QQ).FiniteDimensional().TensorProducts().extra_super_categories()
        [Category of finite dimensional vector spaces over Rational Field]
        sage: VectorSpaces(QQ).FiniteDimensional().TensorProducts().FiniteDimensional()  # indirect doctest
        Category of tensor products of finite dimensional vector spaces over Rational Field

class Graded(base_category)
    Bases: GradedModulesCategory
    Category of graded vector spaces.

class ParentMethods
    Bases: object

    dimension()
    Return the dimension of this vector space.

    EXAMPLES:
```
sage: M = FreeModule(FiniteField(19), 100)  # needs sage.modules
sage: W = M.submodule([M.gen(50)])  # needs sage.modules
sage: W.dimension()  # needs sage.modules
1
sage: M = FiniteRankFreeModule(QQ, 3)  # needs sage.modules
sage: M.dimension()  # needs sage.modules
3
sage: M.tensor_module(1, 2).dimension()  # needs sage.modules
27
```

class TensorProducts(category, *args)

Bases: TensorProductsCategory

extra_super_categories()

The category of vector spaces is closed under tensor products:

```
sage: C = VectorSpaces(QQ)
sage: C.TensorProducts()
Category of tensor products of vector spaces over Rational Field
sage: C in C.TensorProducts().super_categories()
True
```

class WithBasis(base_category)

Bases: CategoryWithAxiom_over_base_ring

class CartesianProducts(category, *args)

Bases: CartesianProductsCategory

extra_super_categories()

The category of vector spaces with basis is closed under Cartesian products:

```
sage: C = VectorSpaces(QQ).WithBasis()
sage: C.CartesianProducts()
Category of Cartesian products of vector spaces with basis over Rational Field
sage: C in C.CartesianProducts().super_categories()
True
```

class Filtered(base_category)

Bases: FilteredModulesCategory

Category of filtered vector spaces with basis.

documented

```
example(base_ring=None)

Return an example of a graded vector space with basis, as per Category.example().

EXAMPLES:
```
```
sage: Modules(QQ).WithBasis().Graded().example()  # needs sage.combinat sage.modules
```
```
An example of a graded module with basis:
the free module on partitions over Rational Field

```
class FiniteDimensional(base_category):
    Bases: CategoryWithAxiom_over_base_ring

class TensorProducts(category, *args):
    Bases: TensorProductsCategory
    extra_super_categories()
    Implement the fact that a (finite) tensor product of finite dimensional vector spaces is a finite dimensional vector space.

    EXAMPLES:
    sage: VectorSpaces(QQ).WithBasis().FiniteDimensional().
    ← TensorProducts().extra_super_categories()
    [Category of finite dimensional vector spaces with basis over _
    ← Rational Field]
    sage: VectorSpaces(QQ).WithBasis().FiniteDimensional().
    ← TensorProducts().FiniteDimensional()
    Category of tensor products of finite dimensional vector spaces with...
    ← basis over Rational Field

class Graded(base_category):
    Bases: GradedModulesCategory

    Category of graded vector spaces with basis.

    example(base_ring=None)
    Return an example of a graded vector space with basis, as per Category.example().

    EXAMPLES:
    sage: Modules(QQ).WithBasis().Graded().example()    #...
    ← needs sage.combinat sage.modules
    An example of a graded module with basis:
    the free module on partitions over Rational Field

class TensorProducts(category, *args):
    Bases: TensorProductsCategory
    extra_super_categories()
    The category of vector spaces with basis is closed under tensor products:

    sage: C = VectorSpaces(QQ).WithBasis()
    sage: C.TensorProducts()
    Category of tensor products of vector spaces with basis over Rational...
    ← Field
    sage: C in C.TensorProducts().super_categories()
    True

    is_abelian()
    Return whether this category is abelian.
    This is always True since the base ring is a field.

    EXAMPLES:
additional_structure()
    Return None.
    Indeed, the category of vector spaces defines no additional structure: a bimodule morphism between two
    vector spaces is a vector space morphism.

See also:
Category.additional_structure()

Todo: Should this category be a CategoryWithAxiom?

EXAMPLES:

sage: VectorSpaces(QQ).additional_structure()

base_field()
    Returns the base field over which the vector spaces of this category are all defined.

EXAMPLES:

sage: VectorSpaces(QQ).base_field()
Rational Field

super_categories()
    EXAMPLES:

sage: VectorSpaces(QQ).super_categories()
[Category of modules over Rational Field]

4.163 Weyl Groups

class sage.categories.weyl_groups.WeylGroups
    Bases: Category_singleton

    The category of Weyl groups

    See the Wikipedia page of Weyl Groups.

    EXAMPLES:

sage: WeylGroups()
Category of Weyl groups
sage: WeylGroups().super_categories()
[Category of Coxeter groups]

Here are some examples:

sage: WeylGroups().example() # todo: not implemented
sage: FiniteWeylGroups().example()
The symmetric group on {0, ..., 3}
This one will eventually be also in this category:

```python
sage: SymmetricGroup(4)
Symmetric group of order 4! as a permutation group
```

```python
class ElementMethods
    Bases: object

bruhat_lower_covers_coroots()
    Return all 2-tuples \((v, \alpha)\) where \(v\) is covered by \(\text{self}\) and \(\alpha\) is the positive coroot such that \(\text{self} = v s_\alpha\) where \(s_\alpha\) is the reflection orthogonal to \(\alpha\).

ALGORITHM:
    See bruhat_lower_covers() and bruhat_lower_covers_reflections() for Coxeter groups.

EXAMPLES:
```python
tenure
sage: W = WeylGroup(['A',3], prefix="s")
sage: w = W.from_reduced_word([3,1,2,1])
sage: w.bruhat_lower_covers_coroots()
 (s3*s2*s1, alphacheck[2]), (s3*s1*s2, alphacheck[1])]
```

bruhat_upper_covers_coroots()
    Returns all 2-tuples \((v, \alpha)\) where \(v\) covers \(\text{self}\) and \(\alpha\) is the positive coroot such that \(\text{self} = v s_\alpha\) where \(s_\alpha\) is the reflection orthogonal to \(\alpha\).

ALGORITHM:
    See bruhat_upper_covers() and bruhat_upper_covers_reflections() for Coxeter groups.

EXAMPLES:
```python
tenure
sage: W = WeylGroup(['A',4], prefix="s")
sage: w = W.from_reduced_word([3,1,2,1])
sage: w.bruhat_upper_covers_coroots()
[(s1*s2*s3*s2*s1, alphacheck[3]),
 (s2*s3*s1*s2*s1, alphacheck[2] + alphacheck[3]),
 (s3*s4*s1*s2*s1, alphacheck[4]),
```

inversion_arrangement(side='right')
    Return the inversion hyperplane arrangement of \(\text{self}\).

INPUT:
    • side = 'right' (default) or 'left'

OUTPUT:
    A (central) hyperplane arrangement whose hyperplanes correspond to the inversions of \(\text{self}\) given as roots.
The side parameter determines on which side to compute the inversions.

**EXAMPLES:**

```
sage: W = WeylGroup(['A',3])
sage: w = W.from_reduced_word([1, 2, 3, 1, 2])
sage: A = w.inversion_arrangement(); A
Arrangement of 5 hyperplanes of dimension 3 and rank 3
sage: A.hyperplanes()
(Hyperplane 0*a1 + 0*a2 + a3 + 0,
 Hyperplane 0*a1 + a2 + 0*a3 + 0,
 Hyperplane 0*a1 + a2 + a3 + 0,
 Hyperplane a1 + a2 + 0*a3 + 0,
 Hyperplane a1 + a2 + a3 + 0)
```

The identity element gives the empty arrangement:

```
sage: W = WeylGroup(['A',3])
sage: W.one().inversion_arrangement()
Empty hyperplane arrangement of dimension 3
```

**inversions** (side='right', inversion_type='reflections')

Return the set of inversions of self.

**INPUT:**
- side = 'right' (default) or 'left'
- inversion_type = 'reflections' (default), 'roots', or 'coroots'

**OUTPUT:**
For reflections, the set of reflections r in the Weyl group such that self r < self. For (co)roots, the set of positive (co)roots that are sent by self to negative (co)roots; their associated reflections are described above.

If side is 'left', the inverse Weyl group element is used.

**EXAMPLES:**

```
sage: W = WeylGroup(['C',2], prefix="s")
sage: w = W.from_reduced_word([1,2])
sage: w.inversions()
[s2, s2*s1*s2]
sage: w.inversions(inversion_type = 'reflections')
[s2, s2*s1*s2]
sage: w.inversions(inversion_type = 'roots')
[alpha[2], alpha[1] + alpha[2]]
sage: w.inversions(inversion_type = 'coroots')
[alphacheck[2], alphacheck[1] + 2*alphacheck[2]]
sage: w.inversions(side = 'left')
[s1, s1*s2*s1]
sage: w.inversions(side = 'left', inversion_type = 'roots')
[alpha[1], 2*alpha[1] + alpha[2]]
sage: w.inversions(side = 'left', inversion_type = 'coroots')
[alphacheck[1], alphacheck[1] + alphacheck[2]]
```

**is_pieri_factor**

Returns whether self is a Pieri factor, as used for computing Stanley symmetric functions.

**See also:**
- `stanley_symmetric_function()`
left_pieri_factorizations (max_length=None)

Returns all factorizations of self as $uv$, where $u$ is a Pieri factor and $v$ is an element of the Weyl group.

See also:

- WeylGroups.ParentMethods.pieri_factors()
- sage.combinat.root_system.pieri_factors

EXAMPLES:

If we take $w = w_0$ the maximal element of a strict parabolic subgroup of type $A_{n_1} \times \cdots \times A_{n_k}$, then the Pieri factorizations are in correspondence with all Pieri factors, and there are $\prod 2^{n_i}$ of them:
for \( i \) in \([-1, 0, 1, 2]\)
[0, 1, 2, 2]

sage: W = WeylGroup(['C',4,1])
sage: w = W.from_reduced_word([0,3,2,1,0])
sage: w.left_pieri_factorizations().cardinality()
7
sage: [(u.reduced_word(),v.reduced_word())
    for (u,v) in w.left_pieri_factorizations()]
[(\[]), ([3, 2, 0, 1, 0]),
 ([0], [3, 2, 1, 0]),
 ([3], [2, 0, 1, 0]),
 ([3, 0], [2, 1, 0]),
 ([3, 2], [0, 1, 0]),
 ([3, 2, 0], [1, 0]),
 ([3, 2, 0, 1], [0])]

sage: W = WeylGroup(['B',4,1])
sage: W.from_reduced_word([0,2,1,0]).left_pieri_factorizations().
˓→cardinality()
6

quantum_bruhat_successors (index_set=None, roots=False, quantum_only=False)

Return the successors of \( self \) in the quantum Bruhat graph on the parabolic quotient of the Weyl group determined by the subset of Dynkin nodes \( \text{index\_set} \).

INPUT:

- \( \text{self} \) – a Weyl group element, which is assumed to be of minimum length in its coset with respect to the parabolic subgroup
- \( \text{index\_set} \) – (default: None) indicates the set of simple reflections used to generate the parabolic subgroup; the default value indicates that the subgroup is the identity
- \( \text{roots} \) – (default: False) if True, returns the list of 2-tuples \((w, \alpha)\) where \( w \) is a successor and \( \alpha \) is the positive root associated with the successor relation
- \( \text{quantum\_only} \) – (default: False) if True, returns only the quantum successors

EXAMPLES:

sage: W = WeylGroup(['A',3], prefix="s")
sage: w = W.from_reduced_word([3,1,2])
sage: w.quantum_bruhat_successors([1], roots = True)
[(s3, alpha[2]), (s1*s2*s3*s2, alpha[3]),
 (s2*s3*s1*s2, alpha[1] + alpha[2] + alpha[3])]
sage: w.quantum_bruhat_successors([1,3])
[1, s2*s3*s1*s2]
sage: w.quantum_bruhat_successors(roots = True)
[(s3*s1*s2*s1, alpha[1]),
 (s3*s1, alpha[2]),
 (s1*s2*s3*s2, alpha[3]),
 (s2*s3*s1*s2, alpha[1] + alpha[2] + alpha[3])]
sage: w.quantum_bruhat_successors()
[s3*s1*s2*s1, s3*s1, s1*s2*s3*s2, s2*s3*s1*s2]
sage: w.quantum_bruhat_successors(quantum_only = True)
[s3*s1]
sage: w = W.from_reduced_word([2,3])
sage: w.quantum_bruhat_successors([1,3])
Traceback (most recent call last):
...
ValueError: s2*s3 is not of minimum length in its coset
of the parabolic subgroup generated by the reflections \(1, 3\)

**reflection_to_coroot()**

Return the coroot associated with the reflection `self`.

**EXAMPLES:**

```python
sage: W = WeylGroup(['C',2],prefix="s")
sage: W.from_reduced_word([1,2,1]).reflection_to_coroot()
sage: W.from_reduced_word([1,2]).reflection_to_coroot()
Traceback (most recent call last):
  ...  ValueError: s1*s2 is not a reflection
sage: W.long_element().reflection_to_coroot()
Traceback (most recent call last):
  ...  ValueError: s2*s1*s2*s1 is not a reflection
```

**reflection_to_root()**

Return the root associated with the reflection `self`.

**EXAMPLES:**

```python
sage: W = WeylGroup(['C',2],prefix="s")
sage: W.from_reduced_word([1,2,1]).reflection_to_root()
sage: W.from_reduced_word([1,2]).reflection_to_root()
Traceback (most recent call last):
  ...  ValueError: s1*s2 is not a reflection
sage: W.long_element().reflection_to_root()
Traceback (most recent call last):
  ...  ValueError: s2*s1*s2*s1 is not a reflection
```

**stanley_symmetric_function()**

Return the affine Stanley symmetric function indexed by `self`.

**INPUT:**
- `self` – an element \(w\) of a Weyl group

Returns the affine Stanley symmetric function indexed by \(w\). Stanley symmetric functions are defined as generating series of the factorizations of \(w\) into Pieri factors and weighted by a statistic on Pieri factors.

**See also:**
- `stanley_symmetric_function_as_polynomial()`
- `WeylGroups.ParentMethods.pieri_factors()`
- `sage.combinat.root_system.pieri_factors`

**EXAMPLES:**

```python
sage: W = WeylGroup(['A', 3, 1])
sage: W.from_reduced_word([3,1,2,0,3,1,0]).stanley_symmetric_function()
8*m[1, 1, 1, 1, 1, 1, 1] + 4*m[2, 1, 1, 1, 1]
  + 2*m[2, 2, 1, 1, 1] + m[2, 2, 2, 1]
```

(continues on next page)
sage: A = AffinePermutationGroup(['A', 3, 1])
sage: A.from_reduced_word([3, 1, 2, 0, 3, 1, 0]).stanley_symmetric_function()
8*m[1, 1, 1, 1, 1, 1, 1] + 4*m[2, 1, 1, 1, 1] + 2*m[2, 2, 1, 1, 1] + 2*m[2, 2, 2, 1]

sage: W = WeylGroup(['C', 3, 1])
sage: W.from_reduced_word([0, 2, 1, 0]).stanley_symmetric_function()
32*m[1, 1, 1, 1] + 16*m[2, 1, 1, 1] + 8*m[2, 2] + 4*m[3, 1]

sage: W = WeylGroup(['B', 3, 1])
sage: W.from_reduced_word([3, 2, 1]).stanley_symmetric_function()
2*m[1, 1, 1] + m[2, 1] + 1/2*m[3]

sage: W = WeylGroup(['B', 4])
sage: w = W.from_reduced_word([3, 2, 1, 1])
sage: w.stanley_symmetric_function()  # long time (6s on sage.math, 2011)
48*m[1, 1, 1, 1] + 24*m[2, 1, 1, 1] + 12*m[2, 2] + 8*m[3, 1, 1] + 2*m[4]

sage: A = AffinePermutationGroup(['A', 4, 1])
sage: a = A([-2, 0, 1, 4, 12])
sage: a.stanley_symmetric_function()
6*m[1, 1, 1, 1, 1, 1, 1] + 3*m[2, 1, 1, 1, 1, 1] + 5*m[2, 2, 1, 1, 1] + 4*m[2, 2, 2, 1] + 2*m[3, 1, 1, 1, 1] + 3*m[3, 2, 1, 1] + 3*m[3, 3, 1] + 2*m[4, 1, 1, 1] + 2*m[4, 2, 1] + m[4, 3, 1] + 3*m[5, 1, 1] + 2*m[5, 2] + m[6] + m[7]

Onemoreexample (github issue #14095):

sage: G = SymmetricGroup(4)
sage: w = G.from_reduced_word([3, 2, 3, 1])
sage: w.stanley_symmetric_function()
3*m[1, 1, 1, 1] + 2*m[2, 1, 1] + m[2, 2] + m[3, 1] + m[4, 1] + m[4, 2]

REFERENCES:
- [BH1994]
- [Lam2008]
- [LSS2009]
- [Pon2010]

`stanley_symmetric_function_as_polynomial (max_length=None)`

Returns a multivariate generating function for the number of factorizations of a Weyl group element into Pieri factors of decreasing length, weighted by a statistic on Pieri factors.

See also:
- `stanley_symmetric_function()`
- `WeylGroups.ParentMethods.pieri_factors()`
- `sage.combinat.root_system.pieri_factors`

INPUT:
- `self` – an element `w` of a Weyl group `W`
- `max_length` – a non negative integer or infinity (default: infinity)

Returns the generating series for the Pieri factorizations `w = u_1 \cdots u_k`, where `u_i` is a Pieri factor for all `i`, `l(w) = \sum_{i=1}^{k} l(u_i)` and `max_length \geq l(u_1) \geq \cdots \geq l(u_k)`.

A factorization `u_1 \cdots u_k` contributes a monomial of the form \( \prod_i x_{l(u_i)} \), with coefficient given by
\[ \prod_i 2^{c(u_i)}, \text{ where } c \text{ is a type-dependent statistic on Pieri factors, as returned by the method } u[i]. \]

```
sage: W = WeylGroup(['A', 3, 1])
sage: W.from_reduced_word([[]]).stanley_symmetric_function_as_polynomial()
1
sage: W.from_reduced_word([[]]).stanley_symmetric_function_as_polynomial()
x1
sage: W.from_reduced_word([1]).stanley_symmetric_function_as_polynomial()
x1^2
sage: W.from_reduced_word([2,1]).stanley_symmetric_function_as_polynomial()
x1^2 + x2
sage: W.from_reduced_word([1,2]).stanley_symmetric_function_as_polynomial()
x1^3 + x1*x2
sage: W.from_reduced_word([1,2,1]).stanley_symmetric_function_as_polynomial()
x1^3 + 2*x1^2*x2 + x2^2 + x1*x3
sage: x = W.from_reduced_word([[2,3,1,2,1,0]])
# long time
22*x1^7 + 11*x1^5*x2 + 5*x1^3*x2^2 + 3*x1^4*x3 + 2*x1*x2^3 + x1^2*x2*x3
sage: y = W.from_reduced_word([[3,1,2,0,3,1,0]])
# long time
8*x1^7 + 4*x1^5*x2 + 2*x1^3*x2^2 + x1^2*x2*x3
```

Algorithm: Induction on the left Pieri factors. Note that this induction preserves subsets of \( W \) which are stable by taking right factors, and in particular Grassmanian elements.

Finite

alias of `FiniteWeylGroups`

class ParentMethods

Bases: object

`bruhat_cone(x, y, side='upper', backend='cdd')`

Return the (upper or lower) Bruhat cone associated to the interval \([x, y]\).

To a cover relation \( v \prec w \) in strong Bruhat order you can assign a positive root \( \beta \) given by the unique reflection \( s_\beta \) such that \( s_\beta v = w \).

The upper Bruhat cone of the interval \([x, y]\) is the non-empty, polyhedral cone generated by the roots corresponding to \( x \prec a \) for all atoms \( a \) in the interval. The lower Bruhat cone of the interval \([x, y]\) is the non-empty, polyhedral cone generated by the roots corresponding to \( c \prec y \) for all coatoms \( c \) in the interval.

INPUT:
• x - an element in the group \( W \)
• y - an element in the group \( W \)
• side (default: 'upper') – must be one of the following:
  – 'upper' - return the upper Bruhat cone of the interval \([x, y]\)
  – 'lower' - return the lower Bruhat cone of the interval \([x, y]\)
• backend – string (default: 'cdd'); the backend to use to create the polyhedron

EXAMPLES:

```python
sage: W = WeylGroup(['A',2])
sage: x = W.from_reduced_word([1])
sage: y = W.w0
sage: W.bruhat_cone(x, y)
A 2-dimensional polyhedron in QQ^3
defined as the convex hull of 1 vertex and 2 rays
```

```python
sage: W = WeylGroup(['E',6])
sage: x = W.one()
sage: y = W.w0
sage: W.bruhat_cone(x, y, side='lower')
A 6-dimensional polyhedron in QQ^8
defined as the convex hull of 1 vertex and 6 rays
```

REFERENCES:
• [Dy1994]
• [JS2021]

coxeter_matrix()

Return the Coxeter matrix associated to self.

EXAMPLES:

```python
sage: G = WeylGroup(['A',3])
sage: G.coxeter_matrix()
[1 3 2]
[3 1 3]
[2 3 1]
```

pieri_factors(*args, **keywords)

Returns the set of Pieri factors in this Weyl group.

For any type, the set of Pieri factors forms a lower ideal in Bruhat order, generated by all the conjugates of some special element of the Weyl group. In type \( A_n \), this special element is \( s_n \cdots s_1 \), and the conjugates are obtained by rotating around this reduced word.

These are used to compute Stanley symmetric functions.

See also:
• WeylGroups.ElementMethods.stanley_symmetric_function()
• sage.combinat.root_system.pieri_factors

EXAMPLES:

```python
sage: W = WeylGroup(['A',5,1])
sage: PF = W.pieri_factors()
sage: PF.cardinality()
63
sage: W = WeylGroup(['B',3])
```

(continues on next page)
sage: PF = W.pieri_factors()
sage: sorted([w.reduced_word() for w in PF])

[[],
 [1],
 [1, 2],
 [1, 2, 1],
 [1, 2, 3],
 [1, 2, 3, 1],
 [1, 2, 3, 2],
 [1, 2, 3, 2, 1],
 [2],
 [2, 1],
 [2, 3],
 [2, 3, 1],
 [2, 3, 2],
 [2, 3, 2, 1],
 [3],
 [3, 1],
 [3, 1, 2],
 [3, 1, 2, 1],
 [3, 2],
 [3, 2, 1]]

sage: W = WeylGroup(['C',4,1])
sage: PF = W.pieri_factors()
sage: W.from_reduced_word([3,2,0]) in PF
True

 quantum_bruhat_graph(index_set=())

Return the quantum Bruhat graph of the quotient of the Weyl group by a parabolic subgroup \( W_J \).

INPUT:

• index_set – (default: ()) a tuple \( J \) of nodes of the Dynkin diagram

By default, the value for index_set indicates that the subgroup is trivial and the quotient is the full Weyl group.

EXAMPLES:

sage: W = WeylGroup(['A',3], prefix="s")
sage: g = W.quantum_bruhat_graph((1,3))
sage: g
Parabolic Quantum Bruhat Graph of Weyl Group of type ['A', 3] (as a matrix group acting on the ambient space) for nodes (1, 3): Digraph on 6 vertices
sage: g.vertices(sort=True)
[s2*s3*s1*s2, s3*s1*s2, s1*s2, s3*s2, s2, 1]
sage: g.edges(sort=True)
[(s2*s3*s1*s2, s2, alpha[2]),
 (s3*s1*s2, s2*s3*s1*s2, alpha[1] + alpha[2] + alpha[3]),
 (s3*s1*s2, 1, alpha[2]),
 (s1*s2, s3*s1*s2, alpha[2] + alpha[3]),
 (s3*s2, s3*s1*s2, alpha[1] + alpha[2]),
 (s2, s1*s2, alpha[1] + alpha[2]),
 (s2, s3*s2, alpha[2] + alpha[3]),
 (1, s2, alpha[2])]
additional_structure()

    Return None.

    Indeed, the category of Weyl groups defines no additional structure: Weyl groups are a special class of Coxeter groups.

    See also:

    Category.additional_structure()

Todo: Should this category be a CategoryWithAxiom?

EXAMPLES:

    sage: WeylGroups().additional_structure()

super_categories()

EXAMPLES:

    sage: WeylGroups().super_categories()

[Category of Coxeter groups]

4.164 Technical Categories

4.164.1 Facade Sets

For background, see What is a facade set?.

class sage.categories.facade_sets.FacadeSets(base_category)

    Bases: CategoryWithAxiom_singleton

class ParentMethods

    Bases: object

    facade_for()

        Returns the parents this set is a facade for

        This default implementation assumes that self has an attribute _facade_for, typically initialized by Parent.__init__(). If the attribute is not present, the method raises a NotImplementedError.

        EXAMPLES:

        sage: S = Sets().Facade().example(); S
        An example of facade set: the monoid of positive integers
        sage: S.facade_for()
        (Integer Ring,)

        Check that github issue #13801 is corrected:
\begin{verbatim}
sage: class A(Parent):
    ....:     def __init__(self):
    ....:         Parent.__init__(self, category=Sets(), facade=True)

sage: a = A()
sage: a.facade_for()
Traceback (most recent call last):
  ... NotImplementedException: this parent did not specify which parents it is a facade for

\textbf{is\_parent\_of} (\textit{element})

Returns whether \textit{self} is the parent of \textit{element}

\textbf{INPUT:}

\begin{itemize}
  \item \textit{element} – any object
\end{itemize}

Since \textit{self} is a facade domain, this actually tests whether the parent of \textit{element} is any of the parent \textit{self} is a facade for.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: S = Sets().Facade().example(); S
An example of facade set: the monoid of positive integers

sage: S.is_parent_of(1)
True

sage: S.is_parent_of(1/2)
False
\end{verbatim}

This method differs from \_contains\_() in two ways. First, this does not take into account the fact that \textit{self} may be a strict subset of the parent(s) it is a facade for:

\begin{verbatim}
sage: -1 in S, S.is_parent_of(-1)
(False, True)
\end{verbatim}

Furthermore, there is no coercion attempted:

\begin{verbatim}
sage: int(1) in S, S.is_parent_of(int(1))
(True, False)
\end{verbatim}

\textbf{Warning:} this implementation does not handle facade parents of facade parents. Is this a feature we want generically?

\textbf{example} (\textit{choice='subset'})

Returns an example of facade set, as per \texttt{Category.example()}.

\textbf{INPUT:}

\begin{itemize}
  \item \textit{choice} = 'union' or 'subset' (default: 'subset').
\end{itemize}

\textbf{EXAMPLES:}

\begin{verbatim}
sage: Sets().Facade().example()
An example of facade set: the monoid of positive integers

sage: Sets().Facade().example(choice='union')
An example of a facade set: the integers completed by +-infinity

sage: Sets().Facade().example(choice='subset')
An example of facade set: the monoid of positive integers
\end{verbatim}
\end{verbatim}
5.1 Covariant Functorial Constructions

A functorial construction is a collection of functors $(F_{\text{Cat}})_{\text{Cat}}$ (indexed by a collection of categories) which associate to a sequence of parents $(A, B, ...)$ in a category $\text{Cat}$ a parent $F_{\text{Cat}}(A, B, ...)$. Typical examples of functorial constructions are cartesian_product and tensor_product.

The category of $F_{\text{Cat}}(A, B, ...)$, which only depends on $\text{Cat}$, is called the (functorial) construction category.

A functorial construction is (category)-covariant if for every categories $\text{Cat}$ and $\text{SuperCat}$, the category of $F_{\text{Cat}}(A, B, ...)$ is a subcategory of the category of $F_{\text{SuperCat}}(A, B, ...)$ whenever $\text{Cat}$ is a subcategory of $\text{SuperCat}$. A functorial construction is (category)-regressive if the category of $F_{\text{Cat}}(A, B, ...)$ is a subcategory of $\text{Cat}$.

The goal of this module is to provide generic support for covariant functorial constructions. In particular, given some parents $A, B, ...$ in respective categories $\text{Cat}_A, \text{Cat}_B, ...$, it provides tools for calculating the best known category for the parent $F(A, B, ...)$. For examples, knowing that Cartesian products of semigroups (resp. monoids, groups) have a semigroup (resp. monoid, group) structure, and given a group $B$ and two monoids $A$ and $C$ it can calculate that $A \times B \times C$ is naturally endowed with a monoid structure.

See CovariantFunctorialConstruction, CovariantConstructionCategory and Regressive-CovariantConstructionCategory for more details.

AUTHORS:

- Nicolas M. Thiery (2010): initial revision

```python
class sage.categories.covariant_functorial_construction.CovariantConstructionCategory (cat-

ey, *args)

Bases: FunctorialConstructionCategory

Abstract class for categories $F_{\text{Cat}}$ obtained through a covariant functorial construction

additional_structure ()

Return the additional structure defined by self.

By default, a functorial construction category $A.F()$ defines additional structure if and only if $A$ is the category defining $F$. The rationale is that, for a subcategory $B$ of $A$, the fact that $B.F()$ morphisms shall preserve the $F$-specific structure is already imposed by $A.F()$.

See also:

- Category.additional_structure()
- is_construction_defined_by_base()
EXAMPLES:

```
sage: Modules(ZZ).Graded().additional_structure()
Category of graded modules over Integer Ring
sage: Algebras(ZZ).Graded().additional_structure()
```

classmethod `default_super_categories` (category, *args)
Return the default super categories of \( F_{\text{Cat}}(A, B, ...) \) for \( A, B, ... \) parents in \( \text{Cat} \).

**INPUT:**

- `cls` – the category class for the functor \( F \)
- `category` – a category \( \text{Cat} \)
- `*args` – further arguments for the functor

**OUTPUT:** a (join) category

The default implementation is to return the join of the categories of \( F(A, B, ...) \) for \( A, B, ... \) in turn in each of the super categories of `category`.

This is implemented as a class method, in order to be able to reconstruct the functorial category associated to each of the super categories of `category`.

**EXAMPLES:**

Bialgebras are both algebras and coalgebras:

```
sage: Bialgebras(QQ).super_categories()
[Category of algebras over Rational Field, 
Category of coalgebras over Rational Field]
```

Hence tensor products of bialgebras are tensor products of algebras and tensor products of coalgebras:

```
sage: Bialgebras(QQ).TensorProducts().super_categories()
[Category of tensor products of algebras over Rational Field, 
Category of tensor products of coalgebras over Rational Field]
```

Here is how `default_super_categories()` was called internally:

```
sage: C = sage.categories.tensor.TensorProductsCategory
sage: C.default_super_categories(Bialgebras(QQ))
Join of Category of tensor products of algebras over Rational Field and Category of tensor products of coalgebras over Rational Field
```

We now show a similar example, with the `Algebra` functor which takes a parameter `QQ`:

```
sage: FiniteMonoids().super_categories()
[Category of monoids, Category of finite semigroups]
sage: sorted(FiniteMonoids().Algebras(QQ).super_categories(), key=str)
[Category of finite dimensional algebras with basis over Rational Field, 
Category of finite set algebras over Rational Field, 
Category of monoid algebras over Rational Field]
```

Note that neither the category of `finite` semigroup algebras nor that of monoid algebras appear in the result; this is because there is currently nothing specific implemented about them.

Here is how `default_super_categories()` was called internally:
sage: C = sage.categories.algebra_functor.AlgebrasCategory
sage: C.default_super_categories(FiniteMonoids(), QQ)
Join of Category of finite dimensional algebras with basis over Rational Field
and Category of monoid algebras over Rational Field
and Category of finite set algebras over Rational Field

is_construction_defined_by_base()
Return whether the construction is defined by the base of self.

EXAMPLES:
The graded functorial construction is defined by the modules category. Hence this method returns True for
graded modules and False for other graded xxx categories:
sage: Modules(ZZ).Graded().is_construction_defined_by_base()
True
sage: Algebras(QQ).Graded().is_construction_defined_by_base()
False
sage: Modules(ZZ).WithBasis().Graded().is_construction_defined_by_base()
False

This is implemented as follows: given the base category $A$ and the construction $F$ of self, that is self $= A.$ $F()$, check whether no super category of $A$ has $F$ defined.

Note: Recall that, when $A$ does not implement the construction $F$, a join category is returned. Therefore,
in such cases, this method is not available:
sage: Bialgebras(QQ).Graded().is_construction_defined_by_base()
Traceback (most recent call last):
  ... AttributeError: 'JoinCategory_with_category' object has
  no attribute 'is_construction_defined_by_base'

class sage.categories.covariant_functorial_construction.
CovariantFunctorialConstruction
Bases: UniqueRepresentation, SageObject
An abstract class for construction functors $F$ (eg $F = \text{Cartesian product, tensor product, } Q\text{-algebra, …}$) such that:

- Each category $\text{Cat}$ (eg $\text{Cat} = \text{Groups()}$) can provide a category $F_{\text{Cat}}$ for parents constructed via this
  functor (eg $F_{\text{Cat}} = \text{CartesianProductsOf(Groups())}$).

- For every category $\text{Cat}$, $F_{\text{Cat}}$ is a subcategory of $F_{\text{SuperCat}}$ for every super category $\text{SuperCat}$ of $\text{Cat}$ (the
  functorial construction is (category)-covariant).

- For parents $A, B, \ldots$, respectively in the categories $\text{Cat}_A, \text{Cat}_B, \ldots$, the category of $F(A, B, \ldots)$ is $F_{\text{Cat}}$
  where $\text{Cat}$ is the meet of the categories $\text{Cat}_A, \text{Cat}_B, \ldots$.

This covers two slightly different use cases:

- In the first use case, one uses directly the construction functor to create new parents:
sage: tensor()  # todo: not implemented (add an example)
or even new elements, which indirectly constructs the corresponding parent:
• In the second use case, one implements a parent, and then put it in the category $F_{\text{Cat}}$ to specify supplementary mathematical information about that parent.

The main purpose of this class is to handle automatically the trivial part of the category hierarchy. For example, `CartesianProductsOf(Groups())` is set automatically as a subcategory of `CartesianProductsOf(Monoids())`.

In practice, each subclass of this class should provide the following attributes:

• `_functor_category` - a string which should match the name of the nested category class to be used in each category to specify information and generic operations for elements of this category.

• `_functor_name` - a string which specifies the name of the functor, and also (when relevant) of the method on parents and elements used for calling the construction.

TODO: What syntax do we want for $F_{\text{Cat}}$? For example, for the tensor product construction, which one do we want among (see chat on IRC, on 07/12/2009):

• `tensor(Cat)`
• `tensor((Cat, Cat))`
• `tensor.of((Cat, Cat))`
• `tensor.category_from_categories((Cat, Cat, Cat))`
• `Cat.TensorProducts()`

The syntax `Cat.TensorProducts()` does not support well multivariate constructions like `tensor.of([Algebras(), HopfAlgebras(), ...])`. Also it forces every category to be (somehow) aware of all the tensorial construction that could apply to it, even those which are only induced from super categories.

Note: for each functorial construction, there probably is one (or several) largest categories on which it applies. For example, the `CartesianProducts()` construction makes only sense for concrete categories, that is subcategories of `Sets()`.

`category_from_categories(categories)`

Return the category of $F(A, B, ...)$ for $A, B, ...$ parents in the given categories.

INPUT:

• `self`: a functor $F$

• `categories`: a non empty tuple of categories

EXAMPLES:

```sage`
Cat1 = Rings()
Cat2 = Groups()
cartesian_product.category_from_categories((Cat1, Cat1, Cat1))
```

Join of Category of rings and ...

and Category of Cartesian products of monoids

and Category of Cartesian products of commutative additive groups

```sage`
cartesian_product.category_from_categories((Cat1, Cat2))
```

Category of Cartesian products of monoids

`category_from_category(category)`

Return the category of $F(A, B, ...)$ for $A, B, ...$ parents in `category`.

INPUT:
• self: a functor $F$

• category: a category

EXAMPLES:

```python
sage: tensor.category_from_category(ModulesWithBasis(QQ))
Category of tensor products of vector spaces with basis over Rational Field
```

# TODO: add support for parametrized functors

`category_from_parents (parents)`

Return the category of $F(A, B, ...)$ for $A, B, ...$ parents.

INPUT:

• self: a functor $F$

• parents: a list (or iterable) of parents.

EXAMPLES:

```python
sage: E = CombinatorialFreeModule(QQ, ['a', 'b', 'c'])
needs sage.modules
sage: tensor.category_from_parents((E, E, E))
needs sage.modules
```

```python
Category of tensor products of finite dimensional vector spaces with basis over Rational Field
```

class sage.categories.covariant_functorial_construction.FunctorialConstructionCategory (category, *args)

Bases: Category

Abstract class for categories $F_{\text{Cat}}$ obtained through a functorial construction

`base_category ()`

Return the base category of the category self.

For any category $B = F_{\text{Cat}}$ obtained through a functorial construction $F$, the call $B.base_category ()$ returns the category $\text{Cat}$.

EXAMPLES:

```python
sage: Semigroups().Quotients().base_category()
Category of semigroups
```

classmethod `category_of (category, *args)`

Return the image category of the functor $F_{\text{Cat}}$.

This is the main entry point for constructing the category $F_{\text{Cat}}$ of parents $F(A, B, ...)$ constructed from parents $A, B, ...$ in $\text{Cat}$.

INPUT:

• cls – the category class for the functorial construction $F$

• category – a category $\text{Cat}$

• *args – further arguments for the functor

EXAMPLES:
sage: C = sage.categories.tensor.TensorProductsCategory
sage: C.category_of(ModulesWithBasis(QQ))
Category of tensor products of vector spaces with basis over Rational Field

sage: C = sage.categories.algebra_functor.AlgebrasCategory
sage: C.category_of(FiniteMonoids(), QQ)
Join of Category of finite dimensional algebras with basis over Rational Field
    and Category of monoid algebras over Rational Field
    and Category of finite set algebras over Rational Field

extra_super_categories()

Return the extra super categories of a construction category.

Default implementation which returns [].

EXAMPLES:

sage: Sets().Subquotients().extra_super_categories()
[]
sage: Semigroups().Quotients().extra_super_categories()
[]

super_categories()

Return the super categories of a construction category.

EXAMPLES:

sage: Sets().Subquotients().super_categories()
[Category of sets]
sage: Semigroups().Quotients().super_categories()
[Category of subquotients of semigroups, Category of quotients of sets]

class sage.categories.covariant_functorial_construction.RegressiveCovariantConstructionCategory

Bases: CovariantConstructionCategory

Abstract class for categories $F_{Cat}$ obtained through a regressive covariant functorial construction

classmethod default_super_categories(category, *args)

Return the default super categories of $F_{Cat}(A, B, ...)$ for $A, B, ...$ parents in $Cat$.

INPUT:

• cls – the category class for the functor $F$
• category – a category $Cat$
• *args – further arguments for the functor

OUTPUT:

A join category.

This implements the property that an induced subcategory is a subcategory.

EXAMPLES:

A subquotient of a monoid is a monoid, and a subquotient of semigroup:
5.2 Cartesian Product Functorial Construction

AUTHORS:

- Nicolas M. Thiery (2008-2010): initial revision and refactoring

class sage.categories.cartesian_product.CartesianProductFunctor(category=None)

Bases: CovariantFunctorialConstruction, MultivariateConstructionFunctor

The Cartesian product functor.

EXAMPLES:

sage: cartesian_product
The cartesian_product functorial construction

cartesian_product takes a finite collection of sets, and constructs the Cartesian product of those sets:

sage: A = FiniteEnumeratedSet(['a','b','c'])
sage: B = FiniteEnumeratedSet([1,2])
sage: C = cartesian_product([A, B]); C
The Cartesian product of ({'a', 'b', 'c'}, {1, 2})
sage: C.an_element()
('a', 1)
sage: C.list()  # todo: not implemented
[['a', 1], ['a', 2], ['b', 1], ['b', 2], ['c', 1], ['c', 2]]

If those sets are endowed with more structure, say they are monoids (hence in the category Monoids()), then the result is automatically endowed with its natural monoid structure:

sage: M = Monoids().example()
sage: M
An example of a monoid: the free monoid generated by ('a', 'b', 'c', 'd')
sage: M.rename('M')
sage: C = cartesian_product([M, ZZ, QQ])
sage: C
The Cartesian product of (M, Integer Ring, Rational Field)
sage: C.an_element()
('abcd', 1, 1/2)
sage: C.an_element()^2
('abcdabcd', 1, 1/4)
sage: C.category()
Category of Cartesian products of monoids

sage: Monoids().CartesianProducts()
Category of Cartesian products of monoids

The Cartesian product functor is covariant: if A is a subcategory of B, then A.CartesianProducts() is a subcategory of B.CartesianProducts() (see also CovariantFunctorialConstruction):

sage: C.categories()

(continues on next page)
Hence, the role of `Monoids().CartesianProducts()` is solely to provide mathematical information and algorithms which are relevant to Cartesian product of monoids. For example, it specifies that the result is again a monoid, and that its multiplicative unit is the Cartesian product of the units of the underlying sets:

```
sage: C.one()
('1', 1, 1)
```

Those are implemented in the nested class `Monoids.CartesianProducts` of `Monoids(QQ)`. This nested class is itself a subclass of `CartesianProductsCategory`.

```
symbol = '+'

class sage.categories.cartesian_product.CartesianProductsCategory(category, *args)
Bases: CovariantConstructionCategory
An abstract base class for all CartesianProducts categories.

CartesianProducts()
Return the category of (finite) Cartesian products of objects of self.

By associativity of Cartesian products, this is self (a Cartesian product of Cartesian products of A's is a Cartesian product of A's).

EXAMPLES:
```
sage: ModulesWithBasis(QQ).CartesianProducts().CartesianProducts()
Category of Cartesian products of vector spaces with basis over Rational Field
```

```
base_ring()
The base ring of a Cartesian product is the base ring of the underlying category.

EXAMPLES:
```
sage: Algebras(ZZ).CartesianProducts().base_ring()
Integer Ring
```
AUTHORS:

- Nicolas M. Thiéry (2008-2010): initial revision and refactorization

class sage.categories.tensor.TensorProductFunctor

Bases: CovariantFunctorialConstruction

A singleton class for the tensor functor.

This functor takes a collection of vector spaces (or modules with basis), and constructs the tensor product of those vector spaces. If this vector space is in a subcategory, say that of Algebras(QQ), it is automatically endowed with its natural algebra structure, thanks to the category Algebras(QQ).TensorProducts() of tensor products of algebras. For elements, it constructs the natural tensor product element in the corresponding tensor product of their parents.

The tensor functor is covariant: if A is a subcategory of B, then A.TensorProducts() is a subcategory of B.TensorProducts() (see also CovariantFunctorialConstruction). Hence, the role of Algebras(QQ).TensorProducts() is solely to provide mathematical information and algorithms which are relevant to tensor product of algebras.

Those are implemented in the nested class TensorProducts of Algebras(QQ). This nested class is itself a subclass of TensorProductsCategory.

symbol = ' # '

unicode_symbol = ' ⊗ '

class sage.categories.tensor.TensorProductsCategory(category, *args)

Bases: CovariantConstructionCategory

An abstract base class for all TensorProducts's categories

TensorProducts()

Returns the category of tensor products of objects of self

By associativity of tensor products, this is self (a tensor product of tensor products of Cat's is a tensor product of Cat's)

EXAMPLES:

```
sage: ModulesWithBasis(QQ).TensorProducts().TensorProducts()
Category of tensor products of vector spaces with basis over Rational Field
```

base()

The base of a tensor product is the base (usually a ring) of the underlying category.

EXAMPLES:

```
sage: ModulesWithBasis(ZZ).TensorProducts().base()
Integer Ring
```

sage.categories.tensor.tensor = The tensor functorial construction

The tensor product functorial construction

See TensorProductFunctor for more information

EXAMPLES:
5.4 Signed Tensor Product Functorial Construction

AUTHORS:

- Travis Scrimshaw (2019-07): initial version

class sage.categories.signed_tensor.SignedTensorProductFunctor

    Bases: CovariantFunctorialConstruction

    A singleton class for the signed tensor functor.

    This functor takes a collection of graded algebras (possibly with basis) and constructs the signed tensor product of those algebras. If this algebra is in a subcategory, say that of $\text{Algebras}(\mathbb{Q}).\text{Graded}()$, it is automatically endowed with its natural algebra structure, thanks to the category $\text{Algebras}(\mathbb{Q}).\text{Graded}()$. $\text{SignedTensorProducts}()$ of signed tensor products of graded algebras. For elements, it constructs the natural tensor product element in the corresponding tensor product of their parents.

    The signed tensor functor is covariant: if $A$ is a subcategory of $B$, then $A.\text{SignedTensorProducts}()$ is a subcategory of $B.\text{SignedTensorProducts}()$ (see also $\text{CovariantFunctorialConstruction}$). Hence, the role of $\text{Algebras}(\mathbb{Q}).\text{Graded}()\text{SignedTensorProducts}()$ is solely to provide mathematical information and algorithms which are relevant to signed tensor product of graded algebras.

    Those are implemented in the nested class $\text{SignedTensorProducts}$ of $\text{Algebras}(\mathbb{Q}).\text{Graded}()$. This nested class is itself a subclass of $\text{SignedTensorProductsCategory}$.

EXAMPLES:

class sage.categories.signed_tensor.SignedTensorProductsCategory(category, *args)

    Bases: CovariantConstructionCategory

    An abstract base class for all $\text{SignedTensorProducts}$'s categories.

    $\text{SignedTensorProducts}()$

    Return the category of signed tensor products of objects of $\text{self}$.

    By associativity of signed tensor products, this is $\text{self}$ (a tensor product of signed tensor products of $\text{Cat}$'s is a tensor product of $\text{Cat}$'s with the same twisting morphism)

    EXAMPLES:
The base of a signed tensor product is the base (usually a ring) of the underlying category.

EXAMPLES:

```sage
sage: AlgebrasWithBasis(ZZ).Graded().SignedTensorProducts().base()
Integer Ring
```

# 5.5 Dual functorial construction

AUTHORS:

- Nicolas M. Thiery (2009-2010): initial revision

```python
class sage.categories.dual.DualFunctor
    Bases: CovariantFunctorialConstruction
    A singleton class for the dual functor
    symbol = '^*'```

```python
class sage.categories.dual.DualObjectsCategory(category, *args)
    Bases: CovariantConstructionCategory```

# 5.6 Group algebras and beyond: the Algebra functorial construction

## 5.6.1 Introduction: group algebras

Let $G$ be a group and $R$ be a ring. For example:

```sage
sage: G = DihedralGroup(3)
sage: R = QQ
```

The *group algebra* $A = RG$ of $G$ over $R$ is the space of formal linear combinations of elements of $group$ with coefficients in $R$:

```sage
sage: A = G.algebra(R); A
Algebra of Dihedral group of order 6 as a permutation group
    over Rational Field
sage: a = A.an_element(); a
() + (1,2) + 3*(1,2,3) + 2*(1,3,2)
```

This space is endowed with an algebra structure, obtained by extending by bilinearity the multiplication of $G$ to a multiplication on $RG$:

```sage
sage: A in Algebras
True
sage: a * a
14*() + 5*(2,3) + 2*(1,2) + 10*(1,2,3) + 13*(1,3,2) + 5*(1,3)
```

In particular, the product of two basis elements is induced by the product of the corresponding elements of the group, and the unit of the group algebra is indexed by the unit of the group:
For the user convenience and backward compatibility, the group algebra can also be constructed with:

```python
sage: GroupAlgebra(G, R)
Algebra of Dihedral group of order 6 as a permutation group
   over Rational Field
```

Since [github issue #18700](https://github.com/sagemath/sage/issues/18700), both constructions are strictly equivalent:

```python
sage: GroupAlgebra(G, R) is G.algebra(R)
True
```

Group algebras are further endowed with a Hopf algebra structure; see below.

### 5.6.2 Generalizations

The above construction extends to weaker multiplicative structures than groups: magmas, semigroups, monoids. For a monoid $S$, we obtain the monoid algebra $RS$, which is defined exactly as above:

```python
sage: S = Monoids().example(); S
An example of a monoid: the free monoid generated by ('a', 'b', 'c', 'd')
sage: A = S.algebra(QQ); A
Algebra of An example of a monoid: the free monoid generated by ('a', 'b', 'c', 'd')
   over Rational Field
sage: A.category()
Category of monoid algebras over Rational Field
```

This construction also extends to additive structures: magmas, semigroups, monoids, or groups:

```python
sage: S = CommutativeAdditiveMonoids().example(); S
An example of a commutative monoid: the free commutative monoid generated by ('a', 'b', 'c', 'd')
sage: U = S.algebra(QQ); U
Algebra of An example of a commutative monoid: the free commutative monoid generated by ('a', 'b', 'c', 'd')
   over Rational Field
sage: U in Algebras(QQ)
True
sage: (a,b,c,d) = S.additive_semigroup_generators()
sage: U(a) * U(b)
B[a + b]
```

Despite saying “free module”, this is really an algebra, whose multiplication is induced by the addition of elements of $S$:

```python
sage: U in Algebras(QQ)
True
sage: (a,b,c,d) = S.additive_semigroup_generators()
sage: U(a) * U(b)
B[a + b]
```

To cater uniformly for the use cases above and some others, for $S$ a set and $K$ a ring, we define in Sage the algebra of $S$ as the $K$-free module with basis indexed by $S$, endowed with whatever algebraic structure can be induced from that of $S$. 

---

828 Chapter 5. Functorial constructions
**Warning:** In most use cases, the result is actually an algebra, hence the name of this construction. In other cases this name is misleading:

```sage
A = Sets().example().algebra(QQ); A
Algebra of Set of prime numbers (basic implementation)
over Rational Field
```

```sage
A.category()
Category of set algebras over Rational Field
```

```sage
A
in
Algebras(QQ)
False
```

Suggestions for a uniform, meaningful, and non misleading name are welcome!

To achieve this flexibility, the features are implemented as a *Covariant Functorial Constructions* that is essentially a hierarchy of categories each providing the relevant additional features:

```sage
A = DihedralGroup(3).algebra(QQ)
A.categories()
[Category of finite group algebras over Rational Field,
...
Category of group algebras over Rational Field,
...
Category of monoid algebras over Rational Field,
...
Category of semigroup algebras over Rational Field,
...
Category of unital magma algebras over Rational Field,
...
Category of magma algebras over Rational Field,
...
Category of set algebras over Rational Field,
...]```

### 5.6.3 Specifying the algebraic structure

Constructing the algebra of a set endowed with both an additive and a multiplicative structure is ambiguous:

```sage
Z3 = IntegerModRing(3)
A = Z3.algebra(QQ)
Traceback (most recent call last):
...
TypeError: `Z = Ring of integers modulo 3` is both
an additive and a multiplicative semigroup.
Constructing its algebra is ambiguous.
Please use, e.g., S.algebra(QQ, category=Semigroups())
```

This ambiguity can be resolved using the `category` argument of the construction:

```sage
A = Z3.algebra(QQ, category=Monoids()); A
Algebra of Ring of integers modulo 3 over Rational Field
```

```sage
A.category()
Category of finite dimensional monoid algebras over Rational Field
```

```sage
A = Z3.algebra(QQ, category=CommutativeAdditiveGroups()); A
Algebra of Ring of integers modulo 3 over Rational Field
```

(continues on next page)
In general, the `category` argument can be used to specify which structure of $S$ shall be extended to $KS$.

### 5.6.4 Group algebras, continued

Let us come back to the case of a group algebra $A = RG$. It is endowed with more structure and in particular that of a Hopf algebra:

```python
sage: G = DihedralGroup(3)
sage: A = G.algebra(R); A
Algebra of Dihedral group of order 6 as a permutation group over Rational Field
sage: A in HopfAlgebras(R).FiniteDimensional().WithBasis()
True
```

The basis elements are *group-like* for the coproduct: $\Delta(g) = g \otimes g$:

```python
sage: s
(1,2,3)
sage: s.coproduct()
(1,2,3) # (1,2,3)
```

The counit is the constant function 1 on the basis elements:

```python
sage: A = GroupAlgebra(DihedralGroup(6), QQ)
sage: [A.counit(g) for g in A.basis()]
[1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1]
```

The antipode is given on basis elements by $\chi(g) = g^{-1}$:

```python
sage: A = GroupAlgebra(DihedralGroup(3), QQ)
sage: s
(1,2,3)
sage: s.antipode()
(1,3,2)
```

By Maschke’s theorem, for a finite group whose cardinality does not divide the characteristic of the base field, the algebra is semisimple:

```python
sage: SymmetricGroup(5).algebra(QQ) in Algebras(QQ).Semisimple()
True
sage: CyclicPermutationGroup(10).algebra(FiniteField(7)) in Algebras.Semisimple
True
sage: CyclicPermutationGroup(10).algebra(FiniteField(5)) in Algebras.Semisimple
False
```
5.6.5 Coercions

Let $RS$ be the algebra of some structure $S$. Then $RS$ admits the natural coercion from any other algebra $R'S'$ of some structure $S'$, as long as $R'$ coerces into $R$ and $S'$ coerces into $S$.

For example, since there is a natural inclusion from the dihedral group $D_2$ of order 4 into the symmetric group $S_4$ of order $4!$, and since there is a natural map from the integers to the rationals, there is a natural map from $\mathbb{Z}[D_2]$ to $\mathbb{Q}[S_4]$:

```sage
sage: A = DihedralGroup(2).algebra(ZZ)
sage: B = SymmetricGroup(4).algebra(QQ)
sage: a = A.an_element(); a
() + 2*(3,4) + 3*(1,2) + (1,2)(3,4)
sage: b = B.an_element(); b
() + (2,3,4) + 2*(1,3)(2,4) + 3*(1,4)(2,3)
sage: B(a)
() + 2*(3,4) + 3*(1,2) + (1,2)(3,4)
sage: B(a) * b  # a is automatically converted to an element of B
() + 2*(3,4) + 2*(2,3) + (2,3,4) + 3*(1,2) + (1,2)(3,4) + (1,3,2)
+ 3*(1,3,4,2) + 5*(1,3)(2,4) + 13*(1,3,2,4) + 12*(1,4,2,3) + 5*(1,4)(2,3)
sage: parent(a * b)
Symmetric group algebra of order 4 over Rational Field
```

There is no obvious map in the other direction, though:

```sage
sage: B(a)
Traceback (most recent call last):
  ...
TypeError: do not know how to make x (= () + (2,3,4) + 2*(1,3)(2,4) + 3*(1,4)(2,3))
an element of self
(=Algebra of Dihedral group of order 4 as a permutation group over Integer Ring)
```

If $S$ is a unital (additive) magma, then $RS$ is a unital algebra, and thus admits a coercion from its base ring $R$ and any ring that coerces into $R$.

```sage
sage: G = DihedralGroup(2)
sage: A = G.algebra(ZZ)
sage: A(2)
2*
```

If $S$ is a multiplicative group, then $RS$ admits a coercion from $S$ and from any group which coerce into $S$:

```sage
sage: g = DihedralGroup(2).gen(0); g
(3,4)
sage: A(g)
(3,4)
sage: A(2) * g
2*(3,4)
```

Note that there is an ambiguity if $S'$ is a group which coerces into both $R$ and $S$. For example) if $S$ is the additive group $(\mathbb{Z}, +)$, and $A = RS$ is its group algebra, then the integer 2 can be coerced into $A$ in two ways – via $S$, or via the base ring $R$ – and the answers are different. It that case the coercion to $R$ takes precedence. In particular, if $\mathbb{Z}$ is the ring (or group) of integers, then $\mathbb{Z}$ will coerce to any $RS$, by sending $\mathbb{Z}$ to $R$. In generic code, it is therefore recommended to always explicitly use $A.monomial(g)$ to convert an element of the group into $A$.

AUTHORS:

- David Loeffler (2008-08-24): initial version
- Martin Raum (2009-08): update to use new coercion model – see github issue #6670.
• John Palmieri (2011-07): more updates to coercion, categories, etc., group algebras constructed using CombinatorialFreeModule – see github issue #6670.

• Nicolas M. Thiéry (2010-2017), Travis Scrimshaw (2017): generalization to a covariant functorial construction for monoid algebras, and beyond – see e.g. github issue #18700.

**class** [sage.categories.algebra_functor.AlgebraFunctor](base_ring)

**Bases:** CovariantFunctorialConstruction

For a fixed ring, a functor sending a group/… to the corresponding group/… algebra.

**EXAMPLES:**

```python
sage: from sage.categories.algebra_functor import AlgebraFunctor
sage: F = AlgebraFunctor(QQ); F
The algebra functorial construction
sage: F(DihedralGroup(3))
Algebra of Dihedral group of order 6 as a permutation group over Rational Field
```

**base_ring()**

Return the base ring for this functor.

**EXAMPLES:**

```python
sage: from sage.categories.algebra_functor import AlgebraFunctor
sage: AlgebraFunctor(QQ).base_ring()
Rational Field
```

**class** [sage.categories.algebra_functor.AlgebrasCategory](category, *args)

**Bases:** CovariantConstructionCategory, Category_over_base_ring

An abstract base class for categories of monoidal algebras, groups algebras, and the like.

**See also:**

• [Sets.ParentMethods.algebra()](#)

• [Sets.SubcategoryMethods.Algebras()](#)

• [CovariantFunctorialConstruction](#)

**INPUT:**

• `base_ring` – a ring

**EXAMPLES:**

```python
sage: C = Groups().Algebras(QQ); C
Category of group algebras over Rational Field
sage: C = Monoids().Algebras(QQ); C
Category of monoid algebras over Rational Field
sage: C._short_name()
'Algebras'
```

```latex
\textbf{Algebras}(\textbf{Monoids})
```

**class** ParentMethods

**Bases:** object
coproduct_on_basis\( (g) \)

Return the coproduct of the element \( g \) of the basis.

Each basis element \( g \) is group-like. This method is used to compute the coproduct of any element.

EXAMPLES:

```python
sage: PF = NonDecreasingParkingFunctions(4)
sage: A = PF.algebra(ZZ); A
Algebra of Non-decreasing parking functions of size 4 over Integer Ring
sage: g = PF.an_element(); g
[1, 1, 1, 1]
sage: A.coproduct_on_basis(g)
B[[1, 1, 1, 1]] # B[[1, 1, 1, 1]]
sage: a = A.an_element(); a
2*B[[1, 1, 1, 1]] + 2*B[[1, 1, 1, 2]] + 3*B[[1, 1, 1, 3]]
sage: a.coproduct()
2*B[[1, 1, 1, 1]] # B[[1, 1, 1, 1]] +
2*B[[1, 1, 1, 2]] # B[[1, 1, 1, 2]] +
3*B[[1, 1, 1, 3]] # B[[1, 1, 1, 3]]
```

5.6. Group algebras and beyond: the Algebra functorial construction 833
5.7 Subquotient Functorial Construction

AUTHORS:
- Nicolas M. Thiery (2010): initial revision

```python
class sage.categories.subquotients.SubquotientsCategory(category, *args)
    Bases: RegressiveCovariantConstructionCategory
```

5.8 Quotients Functorial Construction

AUTHORS:
- Nicolas M. Thiery (2010): initial revision

```python
class sage.categories.quotients.QuotientsCategory(category, *args)
    Bases: RegressiveCovariantConstructionCategory
```

```python
classmethod default_super_categories(category)
    Returns the default super categories of category.Quotients()
```

Mathematical meaning: if $A$ is a quotient of $B$ in the category $C$, then $A$ is also a subquotient of $B$ in the category $C$.

INPUT:
- `cls` – the class QuotientsCategory
- `category` – a category $Cat$

OUTPUT: a (join) category

In practice, this returns `category.Subquotients()`, joined together with the result of the method `RegressiveCovariantConstructionCategory.default_super_categories()` (that is the join of `category` and `cat.Quotients()` for each `cat` in the super categories of `category`).

EXAMPLES:
Consider `category=Groups()`, which has `cat=Monoids()` as super category. Then, a subgroup of a group $G$ is simultaneously a subquotient of $G$, a group by itself, and a quotient monoid of $G$:

```python
sage: Groups().Quotients().super_categories()
[Category of groups, Category of subquotients of monoids, Category of...
→quotients of semigroups]
```

Mind the last item above: there is indeed currently nothing implemented about quotient monoids.

This resulted from the following call:

```python
sage: sage.categories.quotients.QuotientsCategory.default_super_categories(Groups())
Join of Category of groups and Category of subquotients of monoids and...
→Category of quotients of semigroups
```
5.9 Subobjects Functorial Construction

AUTHORS:

• Nicolas M. Thiery (2010): initial revision

class sage.categories.subobjects.SubobjectsCategory(category, *args)
    Bases: RegressiveCovariantConstructionCategory

classmethod default_super_categories(category)
    Returns the default super categories of category.Subobjects()

Mathematical meaning: if A is a subobject of B in the category C, then A is also a subquotient of B in the category C.

INPUT:

• cls – the class SubobjectsCategory

• category – a category Cat

OUTPUT: a (join) category

In practice, this returns category.Subquotients(), joined together with the result of the method RegressiveCovariantConstructionCategory.default_super_categories() (that is the join of category and cat.Subobjects() for each cat in the super categories of category).

EXAMPLES:

Consider category=Groups(), which has cat=Monoids() as super category. Then, a subgroup of a group G is simultaneously a subquotient of G, a group by itself, and a submonoid of G:

```
sage: Groups().Subobjects().super_categories()
[Category of groups, Category of subquotients of monoids, Category of...
 → subobjects of sets]
```

Mind the last item above: there is indeed currently nothing implemented about submonoids.

This resulted from the following call:

```
sage: sage.categories.subobjects.SubobjectsCategory.default_super_categories(Groups())
Join of Category of groups and Category of subquotients of monoids and...
 → Category of subobjects of sets
```

5.10 Isomorphic Objects Functorial Construction

AUTHORS:

• Nicolas M. Thiery (2010): initial revision

class sage.categories.isomorphic_objects.IsomorphicObjectsCategory(category, *args)
    Bases: RegressiveCovariantConstructionCategory

classmethod default_super_categories(category)
    Returns the default super categories of category.IsomorphicObjects()

Mathematical meaning: if A is the image of B by an isomorphism in the category C, then A is both a subobject of B and a quotient of B in the category C.
INPUT:

- cls – the class IsomorphicObjectsCategory
- category – a category \textit{Cat}

OUTPUT: a (join) category

In practice, this returns \texttt{category.Subobjects()} and \texttt{category.Quotients()}, joined together with the result of the method \texttt{RegressiveCovariantConstructionCategory.default_super_categories()} (that is the join of \texttt{category} and \texttt{cat.IsomorphicObjects()} for each \texttt{cat} in the super categories of \texttt{category}).

EXAMPLES:

Consider \texttt{category=Groups()}, which has \texttt{cat=Monoids()} as super category. Then, the image of a group $G'$ by a group isomorphism is simultaneously a subgroup of $G$, a subquotient of $G$, a group by itself, and the image of $G$ by a monoid isomorphism:

```
sage: Groups().IsomorphicObjects().super_categories()
[Category of groups,
 Category of subquotients of monoids,
 Category of quotients of semigroups,
 Category of isomorphic objects of sets]
```

Mind the last item above: there is indeed currently nothing implemented about isomorphic objects of monoids. This resulted from the following call:

```
sage: sage.categories.isomorphic_objects.IsomorphicObjectsCategory.default_super_categories(Groups())
Join of Category of groups and
Category of subquotients of monoids and
Category of quotients of semigroups and
Category of isomorphic objects of sets
```

5.11 Homset categories

\texttt{class sage.categories.homsets.Homsets}

Bases: \texttt{Category_singleton}

The category of all homsets.

EXAMPLES:

```
sage: from sage.categories.homsets import Homsets
sage: Homsets()
Category of homsets
```

This is a subcategory of \texttt{Sets()}:  

```
sage: Homsets().super_categories()
[Category of sets]
```

By this, we assume that all homsets implemented in Sage are sets, or equivalently that we only implement locally small categories. See \texttt{Wikipedia article Category\_\textunderscore\_\text{mathematics}}.

\texttt{github issue \#17364}: every homset category shall be a subcategory of the category of all homsets:
This is tested in `HomsetsCategory._test_homsets_category()`.

```python
sage: from sage.categories.homsets import Homsets
gsage: Homsets().Endset()
Category of endsets
```

class `ParentMethods`:
    Bases: object

    `is_endomorphism_set()`
    Return `True` as `self` is in the category of `Endsets`.

    EXAMPLES:

```python
sage: P.<t> = ZZ[]
sage: E = End(P)
sage: E.is_endomorphism_set()
True
```

`extra_super_categories()`
Implement the fact that endsets are monoids.

See also:

`CategoryWithAxiom.extra_super_categories()`

    EXAMPLES:

```python
sage: from sage.categories.homsets import Homsets
gsage: Homsets().Endset().extra_super_categories()
[Category of monoids]
```

5.11. Homset categories
class SubcategoryMethods

    Bases: object

    Endset()

    Return the subcategory of the homsets of self that are endomorphism sets.

    EXAMPLES:

    sage: Sets().Homsets().Endset()
    Category of endsets of sets

    sage: Posets().Homsets().Endset()
    Category of endsets of posets

super_categories()

    Return the super categories of self.

    EXAMPLES:

    sage: from sage.categories.homsets import Homsets
    sage: Homsets()
    Category of homsets

class sage.categories.homsets.HomsetsCategory(category, *args)

    Bases: FunctorialConstructionCategory

    base()

    If this homsets category is subcategory of a category with a base, return that base.

    Todo: Is this really useful?

    EXAMPLES:

    sage: ModulesWithBasis(ZZ).Homsets().base()
    Integer Ring

classmethod default_super_categories(category)

    Return the default super categories of category.Homsets().

    INPUT:

    • cls -- the category class for the functor \( F \)
    • category -- a category \( \text{Cat} \)

    OUTPUT: a category

    As for the other functorial constructions, if category implements a nested Homsets class, this method is used in combination with category.Homsets().extra_super_categories() to compute the super categories of category.Homsets().
EXAMPLES:

If `category` has one or more full super categories, then the join of their respective homsets category is returned. In this example, this join consists of a single category:

```python
from sage.categories.homsets import HomsetsCategory
from sage.categories.additive_groups import AdditiveGroups

C = AdditiveGroups()
C.full_super_categories()

H = HomsetsCategory.default_super_categories(C); H

H = HomsetsCategory.default_super_categories(AdditiveGroups()); H
```

and, given that nothing specific is currently implemented for homsets of additive groups, `H` is directly the category thereof:

```python
C.Homsets()
```

Similarly for rings: a ring homset is just a homset of unital magmas and additive magmas:

```python
Rings().Homsets()
```

Otherwise, if `category` implements a nested class `Homsets`, this method returns the category of all homsets:

```python
AdditiveMagmas().Homsets()
```

which gives one of the super categories of `category.Homsets()`:

```python
AdditiveMagmas().Homsets().super_categories()
```

the other coming from `category.Homsets().extra_super_categories()`:

```python
AdditiveMagmas().Homsets().extra_super_categories()
```

Finally, as a last resort, this method returns a stub category modelling the homsets of this category:

```python
hasattr(Posets, "Homsets")
H = HomsetsCategory.default_super_categories(Posets()); H
```

(continues on next page)
```python
sage: Posets().Homsets()
Category of homsets of posets
```

```python
class sage.categories.homsets.HomsetsOf(category, *args)
    Bases: HomsetsCategory

Default class for homsets of a category.

This is used when a category $C$ defines some additional structure but not a homset category of its own. Indeed, unlike for covariant functorial constructions, we cannot represent the homset category of $C$ by just the join of the homset categories of its super categories.

EXAMPLES:
```python
sage: C = (Magmas() & Posets()).Homsets(); C
Category of homsets of magmas and posets
sage: type(C)
<class 'sage.categories.homsets.HomsetsOf_with_category'>
```

```python
super_categories()
```

Return the super categories of self.

A stub homset category admits a single super category, namely the category of all homsets.

EXAMPLES:
```python
sage: C = (Magmas() & Posets()).Homsets(); C
Category of homsets of magmas and posets
sage: type(C)
<class 'sage.categories.homsets.HomsetsOf_with_category'>
sage: C.super_categories()
[Category of homsets]
```

5.12 Realizations Covariant Functorial Construction

See also:

- `Sets().WithRealizations` for an introduction to realizations and with realizations.
- `sage.categories.covariant_functorial_construction` for an introduction to covariant functorial constructions.
- `sage.categories.examples.with_realizations` for an example.

```python
class sage.categories.realizations.Category_realization_of_parent(parent_with_realization)
    Bases: Category_over_base, BindableClass

An abstract base class for categories of all realizations of a given parent

INPUT:

- `parent_with_realization` – a parent

See also:

`Sets().WithRealizations`

EXAMPLES:
The role of this base class is to implement some technical goodies, like the binding `A.Realizations()` when a subclass `Realizations` is implemented as a nested class in `A` (see the code of the example):

```
sage: C = A.Realizations(); C
    Category of realizations of The subset algebra of {1, 2, 3} over Rational Field
```

as well as the name for that category.

```
sage.categories.realizations.Realizations(self)
Return the category of realizations of the parent self or of objects of the category self
INPUT:
  • self – a parent or a concrete category
```

Note: this function is actually inserted as a method in the class `Category` (see `Realizations()`). It is defined here for code locality reasons.

EXAMPLES:

The category of realizations of some algebra:

```
sage: Algebras(QQ).Realizations()
Join of Category of algebras over Rational Field
    and Category of realizations of unital magmas
```

The category of realizations of a given algebra:

```
sage: A = Sets().WithRealizations().example(); A
    The subset algebra of (1, 2, 3) over Rational Field
sage: A.Realizations()
    Category of realizations of The subset algebra of (1, 2, 3) over Rational Field
```

```
sage: C = GradedHopfAlgebrasWithBasis(QQ).Realizations(); C
Join of Category of graded Hopf algebras with basis over Rational Field
    and Category of realizations of Hopf algebras over Rational Field
sage: C.super_categories()
[Category of graded Hopf algebras with basis over Rational Field,
  Category of realizations of Hopf algebras over Rational Field]
sage: TestSuite(C).run()
```

See also:
  • `Sets().WithRealizations`
  • `ClasscallMetaclass`
Todo: Add an optional argument to allow for:

```
sage: Realizations(A, category=Blahs()) # todo: not implemented
```

class sage.categories.realizations.RealizationsCategory(category, *args)

    Bases: RegressiveCovariantConstructionCategory

An abstract base class for all categories of realizations category
Relization are implemented as RegressiveCovariantConstructionCategory. See there for the docu-
mentation of how the various bindings such as Sets().Realizations() and P.Realizations(), where
P is a parent, work.

See also:
Sets().WithRealizations

5.13 With Realizations Covariant Functorial Construction

See also:

- Sets().WithRealizations for an introduction to realizations and with realizations.
- sage.categories.covariant_functorial_construction for an introduction to covariant func-
torial constructions.

sage.categories.with_realizations.WithRealizations(self)

    Return the category of parents in self endowed with multiple realizations.

    INPUT:

    - self -- a category

See also:

- The documentation and code (sage.categories.examples.with_realizations) of
  Sets().WithRealizations().example() for more on how to use and implement a parent
with several realizations.
- Various use cases:
  - SymmetricFunctions
  - QuasiSymmetricFunctions
  - NonCommutativeSymmetricFunctions
  - SymmetricFunctionsNonCommutingVariables
  - DescentAlgebra
  - algebras.Moebius
  - IwahoriHeckeAlgebra
  - ExtendedAffineWeylGroup
- The Implementing Algebraic Structures thematic tutorial.
- sage.categories.realizations
**Note:** this function is actually inserted as a method in the class `Category` (see `WithRealizations()`). It is defined here for code locality reasons.

**EXAMPLES:**

```sage
sage: Sets().WithRealizations()
Category of sets with realizations
```

### Parent with realizations

Let us now explain the concept of realizations. A parent with realizations is a facade parent (see `Sets.Facade`) admitting multiple concrete realizations where its elements are represented. Consider for example an algebra $A$ which admits several natural bases:

```sage
A = Sets().WithRealizations().example(); A
```

For each such basis $B$ one implements a parent $P_B$ which realizes $A$ with its elements represented by expanding them on the basis $B$:

```sage
sage: # needs sage.modules
sage: A.F()
The subset algebra of {1, 2, 3} over Rational Field in the Fundamental basis
sage: A.Out()
The subset algebra of {1, 2, 3} over Rational Field in the Out basis
sage: A.In()
The subset algebra of {1, 2, 3} over Rational Field in the In basis
sage: A.an_element()
F[{}] + 2*F[{1}] + 3*F[{2}] + F[{1, 2}]
```

If $B$ and $B'$ are two bases, then the change of basis from $B$ to $B'$ is implemented by a canonical coercion between $P_B$ and $P_{B'}$:

```sage
sage: # needs sage.combinat sage.modules
sage: F = A.F(); In = A.In(); Out = A.Out()
sage: i = In.an_element(); i
In[{}] + 2*In[{1}] + 3*In[{2}] + In[{1, 2}]
sage: F(i)
7*F[{}] + 3*F[{1}] + 4*F[{2}] + F[{1, 2}]
sage: F.coerce_map_from(Out)
Generic morphism:
  From: The subset algebra of {1, 2, 3} over Rational Field in the Out basis
  To:   The subset algebra of {1, 2, 3} over Rational Field in the Fundamental

allowing for mixed arithmetic:

```sage
sage: (1 + Out.from_set({1})) * In.from_set({2, 3})
```

In our example, there are three realizations:
Rationale

Besides some goodies described below, the role of $A$ is threefold:

• To provide, as illustrated above, a single entry point for the algebra as a whole: documentation, access to its properties and different realizations, etc.

• To provide a natural location for the initialization of the bases and the coercions between, and other methods that are common to all bases.

• To let other objects refer to $A$ while allowing elements to be represented in any of the realizations.

We now illustrate this second point by defining the polynomial ring with coefficients in $A$:

```python
sage: A.realizations()  #...
→needs sage.modules
[The subset algebra of {1, 2, 3} over Rational Field in the Fundamental basis,
The subset algebra of {1, 2, 3} over Rational Field in the In basis,
The subset algebra of {1, 2, 3} over Rational Field in the Out basis]
```

Instead of manually defining the shorthands $F$, $In$, and $Out$, as above one can just do:

```python
sage: A.inject_shorthands()  #...
→needs sage.combinat sage.modules
Defining $F$ as shorthand for
The subset algebra of {1, 2, 3} over Rational Field in the Fundamental basis
Defining $In$ as shorthand for
The subset algebra of {1, 2, 3} over Rational Field in the In basis
Defining $Out$ as shorthand for
The subset algebra of {1, 2, 3} over Rational Field in the Out basis
```

In the following examples, the coefficients turn out to be all represented in the $F$ basis:

```python
sage: A.realizations()  #...
→needs sage.modules
[The subset algebra of {1, 2, 3} over Rational Field in the Fundamental basis,
The subset algebra of {1, 2, 3} over Rational Field in the In basis,
The subset algebra of {1, 2, 3} over Rational Field in the Out basis]
```

```python
sage: P = A['x']; P  #...
→needs sage.modules
Univariate Polynomial Ring in $x$ over
The subset algebra of {1, 2, 3} over Rational Field
sage: x = P.gen()  #...
→needs sage.modules
```

```python
sage: P.one()  #...
→needs sage.modules
$F[\{\}]
```

```python
sage: (P.an_element() + 1)^2  #...
→needs sage.modules
$F[\{\}]*x^2 + 2*F[\{\}]*x + F[\{\}]
```

However we can create a polynomial with mixed coefficients, and compute with it:

```python
sage: p = P([1, In[\{1\}], Out[\{2\}]]); p  #...
→needs sage.combinat sage.modules
Out[\{2\}]*x^2 + In[\{1\}]*x + F[\{\}]
```

```python
sage: p^2  #...
→needs sage.combinat sage.modules
Out[\{2\}]*x^4
+ (-8*In[\{\}] + 4*In[\{1\}] + 8*In[\{2\}] + 4*In[\{3\}]
    - 4*In[\{1, 2\}] - 2*In[\{1, 3\}] - 4*In[\{2, 3\}] + 2*In[\{1, 2, 3\}])*x^3
```
Note how each coefficient involves a single basis which need not be that of the other coefficients. Which basis is used depends on how coercion happened during mixed arithmetic and needs not be deterministic.

One can easily coerce all coefficient to a given basis with:

```sage
p.map_coefficients(In)
```

Alas, the natural notation for constructing such polynomials does not yet work:

```sage
In[{1}] * x
```

```
Traceback (most recent call last):
...
TypeError: unsupported operand parent(s) for *:
The subset algebra of {1, 2, 3} over Rational Field in the In basis
and 'Univariate Polynomial Ring in x over The subset algebra of {1, 2, 3} over Rational Field'
```

### The category of realizations of $A$

The set of all realizations of $A$, together with the coercion morphisms is a category (whose class inherits from `Category_realization_of_parent`):

```sage
A.Realizations()
```

The various parent realizing $A$ belong to this category:

```sage
A.F() in A.Realizations()
```

`A` itself is in the category of algebras with realizations:

```sage
A in Algebras(QQ).WithRealizations()
```

The (mostly technical) `WithRealizations` categories are the analogs of the `*WithSeveralBases` categories in MuPAD-Combinat. They provide support tools for handling the different realizations and the morphisms between them.

Typically, `VectorSpaces(QQ).FiniteDimensional().WithRealizations()` will eventually be in charge, whenever a coercion $\phi : A \rightarrow B$ is registered, to register $\phi^{-1}$ as coercion $B \rightarrow A$ if there is none defined yet. To achieve this, `FiniteDimensionalVectorSpaces` would provide a nested class `WithRealizations` implementing the appropriate logic.
WithRealizations is a **recessive covariant functorial construction**. On our example, this simply means that \( A \) is automatically in the category of rings with realizations (covariance):

```plaintext
sage: A in Rings().WithRealizations()  #...
  → needs sage.modules
  True
```

and in the category of algebras (regressiveness):

```plaintext
sage: A in Algebras(QQ)  #...
  → needs sage.modules
  True
```

**Note:** For \( C \) a category, \( C.WithRealizations() \) in fact calls `sage.categories.with_realizations.WithRealizations(C)`. The later is responsible for building the hierarchy of the categories with realizations in parallel to that of their base categories, optimizing away those categories that do not provide a WithRealizations nested class. See `sage.categories.covariant_functorial_construction` for the technical details.

**Note:** Design question: currently WithRealizations is a recessive construction. That is self. WithRealizations() is a subcategory of self by default:

```plaintext
sage: Algebras(QQ).WithRealizations().super_categories()
[Category of algebras over Rational Field,
  Category of monoids with realizations,
  Category of additive unital additive magmas with realizations]
```

Is this always desirable? For example, \( \text{AlgebrasWithBasis}(\mathbb{Q})\).WithRealizations() should certainly be a subcategory of \( \text{Algebras}(\mathbb{Q}) \), but not of \( \text{AlgebrasWithBasis}(\mathbb{Q}) \). This is because AlgebrasWithBasis(\mathbb{Q}) is specifying something about the concrete realization.

```plaintext
class sage.categories.with_realizations.WithRealizationsCategory(category, *args)
Bases: RegressiveCovariantConstructionCategory

An abstract base class for all categories of parents with multiple realizations.

See also:

Sets().WithRealizations
```

The role of this base class is to implement some technical goodies, such as the name for that category.
EXAMPLES OF PARENTS USING CATEGORIES

6.1 Examples of algebras with basis

An example of an algebra with basis: the free algebra

\[ A = \text{AlgebrasWithBasis}(\mathbb{Q}).\text{example}() \]

Return the generators of this algebra, as per \texttt{algebra_generators()}.

\[ w1, w2 \]

Product of basis elements, as per \texttt{AlgebrasWithBasis.ParentMethods.product_on_basis()}. 

(continues on next page)
6.2 Examples of commutative additive monoids

```
sage: A.product_on_basis(Words("acb"), Words("cba"))
B[word: acbcba]
sage: (a,b,c) = A.algebra_generators()
sage: a * (1-b)^2 * c
```

An example of a commutative additive monoid: the free commutative monoid

This class illustrates a minimal implementation of a commutative monoid.

EXAMPLES:

```
sage: S = CommutativeAdditiveMonoids().example(); S
An example of a commutative monoid: the free commutative monoid generated by ('a', 'b', 'c', 'd')
sage: S.category()
Category of commutative additive monoids
```

This is the free semigroup generated by:

```
sage: S.additive_semigroup_generators()
Family (a, b, c, d)
```

with product rule given by \(a \times b = a\) for all \(a, b\):

```
sage: (a,b,c,d) = S.additive_semigroup_generators()
```

We conclude by running systematic tests on this commutative monoid:

```
sage: TestSuite(S).run(verbosity = True)
running ._test_additive_associativity() . . . pass
running ._test_additive_associativity() . . . pass
running ._test_additive_associativity() . . . pass
running ._test_additive_associativity() . . . pass
running ._test_additive_associativity() . . . pass
```

(continues on next page)
class Element (parent, iterable)
       Bases: Element

   zero ()
     Returns the zero of this additive monoid, as per CommutativeAdditiveMonoids.
       ParentMethods.zero().

       EXAMPLES:

       sage: M = CommutativeAdditiveMonoids().example(); M
       An example of a commutative monoid: the free commutative monoid generated by ('a', 'b', 'c', 'd')
       sage: M.zero()
       0

6.3 Examples of commutative additive semigroups

sage.categories.examples.commutative_additive_semigroups.Example
   alias of FreeCommutativeAdditiveSemigroup

class sage.categories.examples.commutative_additive_semigroups.FreeCommutativeAdditiveSemigroup
   Bases: UniqueRepresentation, Parent

   An example of a commutative additive monoid: the free commutative monoid

   This class illustrates a minimal implementation of a commutative additive monoid.

   EXAMPLES:

   sage: S = CommutativeAdditiveSemigroups().example(); S
   An example of a commutative semigroup: the free commutative semigroup generated by ('a', 'b', 'c', 'd')
   sage: S.category()
   Category of commutative additive semigroups
This is the free semigroup generated by:

```
sage: S.additive_semigroup_generators()
Family (a, b, c, d)
```

with product rule given by \( a \times b = a \) for all \( a, b \):

```
sage: (a,b,c,d) = S.additive_semigroup_generators()
```

We conclude by running systematic tests on this commutative monoid:

```
sage: TestSuite(S).run( verbose = True )
running ._test_additive_associativity() . . . pass
running ._test_an_element() . . . pass
running ._test_cardinality() . . . pass
running ._test_category() . . . pass
running ._test_construction() . . . pass
running ._test_elements() . . .
   Running the test suite of self.an_element()
running ._test_category() . . . pass
running ._test_eq() . . . pass
running ._test_new() . . . pass
running ._test_not_implemented_methods() . . . pass
running ._test_pickling() . . . pass
pass
running ._test_elements_eq_reflexive() . . . pass
running ._test_elements_eq_symmetric() . . . pass
running ._test_elements_eq_transitive() . . . pass
running ._test_elements_neq() . . . pass
running ._test_eq() . . . pass
running ._test_new() . . . pass
running ._test_not_implemented_methods() . . . pass
running ._test_pickling() . . . pass
running ._test_some_elements() . . . pass
```

```class Element (parent, iterable)
Bases: ElementWrapper

EXAMPLES:
```
```
sage: F = CommutativeAdditiveSemigroups().example()
sage: x = F.element_class(F, (('a',4), ('b', 0), ('a', 2), ('c', 1), ('d',-5)))
sage: x
2*a + c + 5*d
sage: x.value
{'a': 2, 'b': 0, 'c': 1, 'd': 5}
sage: x.parent()
An example of a commutative semigroup: the free commutative semigroup_-
   generated by ('a', 'b', 'c', 'd')
```

Internally, elements are represented as dense dictionaries which associate to each generator of the monoid its multiplicity. In order to get an element, we wrap the dictionary into an element via `ElementWrapper`:

```
sage: x.value
{'a': 2, 'b': 0, 'c': 1, 'd': 5}
```

`additive_semigroup_generators()`
Returns the generators of the semigroup.

**EXAMPLES:**

```python
sage: F = CommutativeAdditiveSemigroups().example()
sage: F.additive_semigroup_generators()
Family (a, b, c, d)
```

**an_element()**

Returns an element of the semigroup.

**EXAMPLES:**

```python
sage: F = CommutativeAdditiveSemigroups().example()
sage: F.an_element()
a + 2*b + 3*c + 4*d
```

**summation**(x, y)

Returns the product of x and y in the semigroup, as per `CommutativeAdditiveSemigroups.ParentMethods.summation()`.

**EXAMPLES:**

```python
sage: F = CommutativeAdditiveSemigroups().example()
(sage, (a,b,c,d) = F.additive_semigroup_generators()
sage: F.summation(a,b)
a + b
sage: (a+b) + (a+c)
2*a + b + c
```

### 6.4 Examples of Coxeter groups

### 6.5 Example of a crystal

```python
class sage.categories/examples/crystals.HighestWeightCrystalOfTypeA(n=3)
Bases: UniqueRepresentation, Parent

An example of a crystal: the highest weight crystal of type $A_n$ of highest weight $\omega_1$.

The purpose of this class is to provide a minimal template for implementing crystals. See `CrystalOfLetters` for a full featured and optimized implementation.

**EXAMPLES:**

```python
sage: C = Crystals().example()
sage: C
Highest weight crystal of type $A_3$ of highest weight $\omega_1$
sage: C.category()
Category of classical crystals
```

The elements of this crystal are in the set $\{1, \ldots, n + 1\}$.
The crystal operators themselves correspond to the elementary transpositions:

```
sage: b = C.module_generators[0]
sage: b.f(1)
2
sage: b.f(1).e(1) == b
True
```

Only the following basic operations are implemented:

- `cartan_type()` or an attribute `_cartan_type`
- an attribute `module_generators`
- `Element.e()`
- `Element.f()`

All the other usual crystal operations are inherited from the categories; for example:

```
sage: C.cardinality()
4
```

```python
class Element
    Bases: ElementWrapper

    e(i)
    Returns the action of $e_i$ on self.

    EXAMPLES:
    sage: C = Crystals().example(4)
    sage: [[c,i,c.e(i)] for i in C.index_set() for c in C if c.e(i) is not None]
    [[2, 1, 1], [3, 2, 2], [4, 3, 3], [5, 4, 4]]

    f(i)
    Returns the action of $f_i$ on self.

    EXAMPLES:
    sage: C = Crystals().example(4)
    sage: [[c,i,c.f(i)] for i in C.index_set() for c in C if c.f(i) is not None]
    [[1, 1, 2], [2, 2, 3], [3, 3, 4], [4, 4, 5]]
```

```python
class sage.categories.examples.crystals.NaiveCrystal
    Bases: UniqueRepresentation, Parent

    This is an example of a “crystal” which does not come from any kind of representation, designed primarily to test the Stembridge local rules with. The crystal has vertices labeled 0 through 5, with 0 the highest weight.

    The code here could also possibly be generalized to create a class that automatically builds a crystal from an edge-colored digraph, if someone feels adventurous.
```
Currently, only the methods `highest_weight_vector()`, `e()`, and `f()` are guaranteed to work.

**EXAMPLES:**

```python
sage: C = Crystals().example(choice='naive')
sage: C.highest_weight_vector()
0
```

**class Element**

**Bases:** `ElementWrapper`

`e(i)`

Returns the action of $e_i$ on `self`.

**EXAMPLES:**

```python
sage: C = Crystals().example(choice='naive')
sage: [[c,i,c.e(i)] for i in C.index_set() for c in [C(j) for j in [0..5]] if c.e(i) is not None]
[[[1, 1, 0], [2, 1, 1], [3, 1, 2], [5, 1, 3], [4, 2, 0], [5, 2, 4]]
```

`f(i)`

Returns the action of $f_i$ on `self`.

**EXAMPLES:**

```python
sage: C = Crystals().example(choice='naive')
sage: [[c,i,c.f(i)] for i in C.index_set() for c in [C(j) for j in [0..5]] if c.f(i) is not None]
[[[0, 1, 1], [1, 1, 2], [2, 1, 3], [3, 1, 5], [0, 2, 4], [4, 2, 5]]
```

### 6.6 Examples of CW complexes

```python
sage.categories.examples.cw_complexes.Example
alias of Surface
```

**class** `sage.categories.examples.cw_complexes.Surface(bdy=(1, 2, 1, 2))`

**Bases:** `UniqueRepresentation`, `Parent`

An example of a CW complex: a (2-dimensional) surface.

This class illustrates a minimal implementation of a CW complex.

**EXAMPLES:**

```python
sage: from sage.categories.cw_complexes import CWComplexes
sage: X = CWComplexes().example(); X
An example of a CW complex: the surface given by the boundary map (1, 2, 1, 2)
sage: X.category()
Category of finite finite dimensional CW complexes
```

We conclude by running systematic tests on this manifold:

```python
sage: TestSuite(X).run()
```
class Element (parent, dim, name)
Bases: Element
A cell in a CW complex.
dimension()
    Return the dimension of self.
EXAMPLES:

    sage: from sage.categories.cw_complexes import CWComplexes
    sage: X = CWComplexes().example()
    sage: f = X.an_element()
    sage: f.dimension()
    2

an_element()
    Return an element of the CW complex, as per Sets.ParentMethods.an_element().
EXAMPLES:

    sage: from sage.categories.cw_complexes import CWComplexes
    sage: X = CWComplexes().example()
    sage: X.an_element()
    2-cell f
cells()
    Return the cells of self.
EXAMPLES:

    sage: from sage.categories.cw_complexes import CWComplexes
    sage: X = CWComplexes().example()
    sage: C = X.cells()
    sage: sorted((d, C[d]) for d in C.keys())
    [(0, (0-cell v,)),
     (1, (0-cell e1, 0-cell e2)),
     (2, (2-cell f,))]

6.7 Example of facade set

class sage.categories.examples.facade_sets.IntegersCompletion
    Bases: UniqueRepresentation, Parent
    An example of a facade parent: the set of integers completed with + - ∞
    This class illustrates a minimal implementation of a facade parent that models the union of several other parents.
    EXAMPLES:

    sage: S = Sets().Facade().example("union"); S
    An example of a facade set: the integers completed by +∞-infinity

class sage.categories.examples.facade_sets.PositiveIntegerMonoid
    Bases: UniqueRepresentation, Parent
    An example of a facade parent: the positive integers viewed as a multiplicative monoid
This class illustrates a minimal implementation of a facade parent which models a subset of a set.

EXAMPLES:

```python
sage: S = Sets().Facade().example(); S
An example of facade set: the monoid of positive integers
```

### 6.8 Examples of finite Coxeter groups

```python
class sage.categories.examples.finite_coxeter_groups.DihedralGroup(n=5)
Bases: UniqueRepresentation, Parent

An example of finite Coxeter group: the $n$-th dihedral group of order $2n$.

The purpose of this class is to provide a minimal template for implementing finite Coxeter groups. See `DihedralGroup` for a full featured and optimized implementation.

EXAMPLES:

```python
sage: G = FiniteCoxeterGroups().example()
```

This group is generated by two simple reflections $s_1$ and $s_2$ subject to the relation $(s_1s_2)^n = 1$:

```python
sage: G.simple_reflections()
Finite family {1: (1,), 2: (2,)}

sage: s1, s2 = G.simple_reflections()
sage: (s1*s2)^5 == G.one()
True
```

An element is represented by its reduced word (a tuple of elements of `self.index_set()`):

```python
sage: G.an_element()
(1, 2)

sage: list(G)
[((),
 (1,),
 (2,),
 (1, 2),
 (2, 1),
 (1, 2, 1),
 (2, 1, 2),
 (1, 2, 1, 2),
 (2, 1, 2, 1),
 (1, 2, 1, 2, 1)]
```

This reduced word is unique, except for the longest element where the chosen reduced word is $(1, 2, 1, 2\ldots)$:

```python
sage: G.long_element()
(1, 2, 1, 2, 1)
```

```python
class Element
    Bases: ElementWrapper
```
**apply_simple_reflection_right** ($i$)


**EXAMPLES:**

```python
sage: D5 = FiniteCoxeterGroups().example(5)
sage: [i^2 for i in D5]  # indirect doctest
[(), (), (), (1, 2, 1, 2), (2, 1, 2, 1), (), (), (2, 1), (1, 2), ()]
sage: [i^5 for i in D5]  # indirect doctest
[(), (1,), (2,), (), (), (1, 2, 1), (2, 1, 2), (), (), (1, 2, 1, 2, 1)]
```

**has_right_descent** ($i$, `positive=False`, `side='right'`)

Implements `SemiGroups.ElementMethods.has_right_descent()`.

**EXAMPLES:**

```python
sage: D6 = FiniteCoxeterGroups().example(6)
sage: s = D6.simple_reflections()
sage: s[1].has_descent(1)  # indirect doctest
True
sage: s[1].has_descent(1)  # indirect doctest
True
sage: s[1].has_descent(2)  # indirect doctest
False
sage: D6.one().has_descent(1)  # indirect doctest
False
sage: D6.one().has_descent(2)  # indirect doctest
False
sage: D6.long_element().has_descent(1)  # indirect doctest
True
sage: D6.long_element().has_descent(2)  # indirect doctest
True
```

**wrapped_class**

alias of `tuple`

**coxeter_matrix**()

Return the Coxeter matrix of `self`.

**EXAMPLES:**

```python
sage: FiniteCoxeterGroups().example(6).coxeter_matrix()
[1 6]
[6 1]
```

**degrees**()

Return the degrees of `self`.

**EXAMPLES:**

```python
sage: FiniteCoxeterGroups().example(6).degrees()
(2, 6)
```

**index_set**()


**EXAMPLES:**

```python
6.9 Example of a finite dimensional algebra with basis

sage.categories.examples.finite_dimensional_algebras_with_basis.Example
alias of KroneckerQuiverPathAlgebra

class sage.categories.examples.finite_dimensional_algebras_with_basis.KroneckerQuiverPathAlgebra

Bases: CombinatorialFreeModule

An example of a finite dimensional algebra with basis: the path algebra of the Kronecker quiver.

This class illustrates a minimal implementation of a finite dimensional algebra with basis. See sage.quivers.algebra.PathAlgebra for a full-featured implementation of path algebras.

algebra_generators()  
Return algebra generators for this algebra.

See also:
Algebras.ParentMethods.algebra_generators().

EXAMPLES:

sage: A = FiniteDimensionalAlgebrasWithBasis(QQ).example(); A
An example of a finite dimensional algebra with basis: the path algebra of the Kronecker quiver (containing the arrows a:x→y and b:x→y) over Rational Field
sage: A.algebra_generators()
Finite family {'x': x, 'y': y, 'a': a, 'b': b}

one()  
Return the unit of this algebra.

See also:
AlgebrasWithBasis.ParentMethods.one_basis()  

EXAMPLES:

sage: A = FiniteDimensionalAlgebrasWithBasis(QQ).example()  
sage: A.one()
A coercion map from the Rational Field to an algebra

6.9. Example of a finite dimensional algebra with basis 857
**product_on_basis** \((w_1, w_2)\)

Return the product of the two basis elements indexed by \(w_1\) and \(w_2\).

See also:

AlgebrasWithBasis.ParentMethods.product_on_basis().

**EXAMPLES:**

```sage
A = FiniteDimensionalAlgebrasWithBasis(QQ).example()
```

Here is the multiplication table for the algebra:

```sage
matrix([[p*q for q in A.basis()] for p in A.basis()])
```

Here we take some products of linear combinations of basis elements:

```sage
x, y, a, b = A.basis()
sage: a * (1-b)^2 * x
0
sage: x*a + b*y
a + b
sage: x*x
x
sage: x*y
0
sage: x*a*y
a
```

## 6.10 Examples of a finite dimensional Lie algebra with basis

**class** `sage.categories.examples.finite_dimensional_lie_algebras_with_basis.AbelianLieAlgebra`

**Bases:** `Parent, UniqueRepresentation`

An example of a finite dimensional Lie algebra with basis: the abelian Lie algebra.

Let \(R\) be a commutative ring, and \(M\) an \(R\)-module. The **abelian Lie algebra** on \(M\) is the \(R\)-Lie algebra obtained by endowing \(M\) with the trivial Lie bracket \([a, b] = 0\) for all \(a, b \in M\).

This class illustrates a minimal implementation of a finite dimensional Lie algebra with basis.

**INPUT:**

- \(R\) – base ring
- \(n\) – (optional) a nonnegative integer (default: `None`)
- \(M\) – an \(R\)-module (default: the free \(R\)-module of rank \(n\)) to serve as the ground space for the Lie algebra
ambient – (optional) a Lie algebra; if this is set, then the resulting Lie algebra is declared a Lie subalgebra of ambient

OUTPUT:
The abelian Lie algebra on $M$.

class Element
Bases: Element

lift()
Return the lift of self to the universal enveloping algebra.

EXAMPLES:

```python
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()
sage: a, b, c = L.lie_algebra_generators()
sage: elt = 2*a + 2*b + 3*c
sage: elt.lift()  # needs sage.combinat
2*b0 + 2*b1 + 3*b2
```

monomial_coefficients (copy=True)
Return the monomial coefficients of self.

EXAMPLES:

```python
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()
sage: a, b, c = L.lie_algebra_generators()
sage: elt = 2*a + 2*b + 3*c
sage: elt.monomial_coefficients()
{0: 2, 1: 2, 2: 3}
```

to_vector (order=None, sparse=False)
Return self as a vector in self.parent().module().

See the docstring of the latter method for the meaning of this.

EXAMPLES:

```python
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()
sage: a, b, c = L.lie_algebra_generators()
sage: elt = 2*a + 2*b + 3*c
sage: elt.to_vector()
(2, 2, 3)
```

ambient()
Return the ambient Lie algebra of self.

EXAMPLES:

```python
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()
sage: a, b, c = L.lie_algebra_generators()
sage: S = L.subalgebra([2*a+b, b + c])
sage: S.ambient() == L
True
```

basis()
Return the basis of self.

EXAMPLES:
\begin{verbatim}
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()
sage: L.basis()
Finite family {0: (1, 0, 0), 1: (0, 1, 0), 2: (0, 0, 1)}
\end{verbatim}

**basis_matrix()**

Return the basis matrix of self.

**EXAMPLES:**

\begin{verbatim}
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()
sage: L.basis_matrix()
[1 0 0]
[0 1 0]
[0 0 1]
\end{verbatim}

**from_vector (v, order=None)**

Return the element of self corresponding to the vector \( v \) in self.module().

Implement this if you implement \texttt{module()); see the documentation of \texttt{sage.categories.lie_algebras.LieAlgebras.module()} for how this is to be done.

**EXAMPLES:**

\begin{verbatim}
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()
sage: u = L.from_vector(vector(QQ, (1, 0, 0))); u
(1, 0, 0)
sage: parent(u) is L
True
\end{verbatim}

**gens ()**

Return the generators of self.

**EXAMPLES:**

\begin{verbatim}
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()
sage: L.gens()
((1, 0, 0), (0, 1, 0), (0, 0, 1))
\end{verbatim}

**ideal (gens)**

Return the Lie subalgebra of self generated by the elements of the iterable \( \texttt{gens} \).

This currently requires the ground ring \( R \) to be a field.

**EXAMPLES:**

\begin{verbatim}
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()
sage: a, b, c = L.lie_algebra_generators()
sage: L.subalgebra([2*a+b, b + c])
An example of a finite dimensional Lie algebra with basis:
  the 2-dimensional abelian Lie algebra over Rational Field with
  basis matrix:
  [ 1 0 -1/2]
  [ 0 1  1]
\end{verbatim}

**is_ideal (A)**

Return if self is an ideal of the ambient space A.

**EXAMPLES:**
```
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()
sage: a, b, c = L.lie_algebra_generators()
sage: L.is_ideal(L)
True
sage: S1 = L.subalgebra([2*a+b, b + c])
sage: S1.is_ideal(L)
True
sage: S2 = L.subalgebra([2*a+b])
sage: S2.is_ideal(S1)
True
sage: S1.is_ideal(S2)
False
```

**lie_algebra_generators()**

Return the basis of `self`.

**EXAMPLES:**

```
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()
sage: L.basis()
Finite family {0: (1, 0, 0), 1: (0, 1, 0), 2: (0, 0, 1)}
```

**module()**

Return an \( R \)-module which is isomorphic to the underlying \( R \)-module of `self`.

See `sage.categories.lie_algebras.LieAlgebras.module()` for an explanation.

In this particular example, this returns the module \( M \) that was used to construct `self`.

**EXAMPLES:**

```
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()
sage: L.module()
Vector space of dimension 3 over Rational Field
sage: a, b, c = L.lie_algebra_generators()
sage: S = L.subalgebra([2*a+b, b + c])
sage: S.module()
Vector space of degree 3 and dimension 2 over Rational Field
Basis matrix:
[ 1 0 -1/2]
[ 0 1 1]
```

**subalgebra(gens)**

Return the Lie subalgebra of `self` generated by the elements of the iterable `gens`.

This currently requires the ground ring \( R \) to be a field.

**EXAMPLES:**

```
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()
sage: a, b, c = L.lie_algebra_generators()
sage: L.subalgebra([2*a+b, b + c])
An example of a finite dimensional Lie algebra with basis: the 2-dimensional abelian Lie algebra over Rational Field with basis matrix:
[ 1 0 -1/2]
[ 0 1 1]
```
zero()

Return the zero element.

EXAMPLES:

```
sage: L = LieAlgebras(QQ).FiniteDimensional().WithBasis().example()
sage: L.zero()
(0, 0, 0)
```

sage.categories.examples.finite_dimensional_lie_algebras_with_basis.Example

alias of AbelianLieAlgebra

### 6.11 Examples of finite enumerated sets

```python
class sage.categories.examples.finite_enumerated_sets.Example
    Bases: UniqueRepresentation, Parent

An example of a finite enumerated set: \{1, 2, 3\}

This class provides a minimal implementation of a finite enumerated set.

See FiniteEnumeratedSet for a full featured implementation.
```

EXAMPLES:

```
sage: C = FiniteEnumeratedSets().example()
sage: C.cardinality()
3
sage: C.list()
[1, 2, 3]
sage: C.an_element()
1
```

This checks that the different methods of the enumerated set \(C\) return consistent results:

```
sage: TestSuite(C).run(verbosxe = True)
running ._test_an_element() . . . pass
running ._test_cardinality() . . . pass
running ._test_category() . . . pass
running ._test_category() . . . pass
running ._test_construction() . . . pass
running ._test_elements() . . .
    Running the test suite of self.an_element()
    running ._test_category() . . . pass
    running ._test_eq() . . . pass
    running ._test_new() . . . pass
    running ._test_nonzero_equal() . . . pass
    running ._test_not_implemented_methods() . . . pass
    running ._test_pickling() . . . pass
    pass
running ._test_elements_eq_reflexive() . . . pass
running ._test_elements_eq_symmetric() . . . pass
running ._test_elements_eq_transitive() . . . pass
running ._test_elements_neq() . . . pass
running ._test_enumerated_set_contains() . . . pass
running ._test_enumerated_set_iter_cardinality() . . . pass
running ._test_enumerated_set_iter_list() . . . pass
(continues on next page)
```
class sage.categories.examples.finiteEnumeratedSets.IsomorphicObjectOfFiniteEnumeratedSet:

Bases: UniqueRepresentation, Parent

ambient()

Returns the ambient space for self, as per Sets.Subquotients.ParentMethods.ambient().

EXAMPLES:

```
sage: C = FiniteEnumeratedSets().IsomorphicObjects().example(); C
The image by some isomorphism of An example of a finite enumerated set: {1,2,3}
sage: C.ambient()
An example of a finite enumerated set: {1,2,3}
```

lift(x)

INPUT:
- x – an element of self

Lifts x to the ambient space for self, as per Sets.Subquotients.ParentMethods.lift().

EXAMPLES:

```
sage: C = FiniteEnumeratedSets().IsomorphicObjects().example(); C
The image by some isomorphism of An example of a finite enumerated set: {1,2,3}
sage: C.lift(9)
3
```

retract(x)

INPUT:
- x – an element of the ambient space for self
Retracts \( x \) from the ambient space to \( \text{self} \), as per \texttt{Sets.Subquotients.ParentMethods.retract()}.

**EXAMPLES:**

```
sage: C = FiniteEnumeratedSets().IsomorphicObjects().example(); C
The image by some isomorphism of An example of a finite enumerated set: \{1,2, \rightarrow 3\}
sage: C.retract(3) 9
```

### 6.12 Examples of finite monoids

**sage.categories.examples.finite_monoids**

**Example**

alias of \texttt{IntegerModMonoid}

```
class sage.categories.examples.finite_monoids.IntegerModMonoid(n=12)
    Bases: UniqueRepresentation, Parent

An example of a finite monoid: the integers mod \( n \)

This class illustrates a minimal implementation of a finite monoid.

**EXAMPLES:**

```
sage: S = FiniteMonoids().example(); S
An example of a finite multiplicative monoid: the integers modulo 12
sage: S.category()
Category of finitely generated finite enumerated monoids
```

We conclude by running systematic tests on this monoid:

```
sage: TestSuite(S).run(vertose = True)
running ._test_an_element() . . . pass
running ._test_associativity() . . . pass
running ._test_cardinality() . . . pass
running ._test_category() . . . pass
running ._test_construction() . . . pass
running ._test_elements() . . .
    Running the test suite of self.an_element()
    running .test_category() . . . pass
    running .test_eq() . . . pass
    running .test_new() . . . pass
    running .test_not_implemented_methods() . . . pass
    running .test_pickling() . . . pass
    pass
running ._test_elements_eq_reflexive() . . . pass
running ._test_elements_eq_symmetric() . . . pass
running ._test_elements_eq_transitive() . . . pass
running ._test_elements_neq() . . . pass
running ._test_enumerated_set_contains() . . . pass
running ._test_enumerated_set_iter_cardinality() . . . pass
running ._test_enumerated_set_iter_list() . . . pass
running ._test_eq() . . . pass
running ._test_new() . . . pass
```

(continues on next page)
class Element
    Bases: ElementWrapper

    wrapped_class
        alias of Integer

an_element()
    Returns an element of the monoid, as per Sets.ParentMethods.an_element().

    EXAMPLES:

    sage: M = FiniteMonoids().example()
sage: M.an_element()
6

one()
    Return the one of the monoid, as per Monoids.ParentMethods.one().

    EXAMPLES:

    sage: M = FiniteMonoids().example()
sage: M.one()
1

product(x, y)
    Return the product of two elements x and y of the monoid, as per Semigroups.ParentMethods.product().

    EXAMPLES:

    sage: M = FiniteMonoids().example()
sage: M.product(M(3), M(5))
3

semigroup_generators()
    Returns a set of generators for self, as per Semigroups.ParentMethods.semigroup_generators(). Currently this returns all integers mod n, which is of course far from optimal!

    EXAMPLES:

    sage: M = FiniteMonoids().example()
sage: M.semigroup_generators()
Family (0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11)
6.13 Examples of finite semigroups

sage.categories.examples.finite_semigroups.Example
    alias of LeftRegularBand

class sage.categories.examples.finite_semigroups.LeftRegularBand(alphabet=('a', 'b', 'c', 'd'))

    Bases: UniqueRepresentation, Parent

An example of a finite semigroup

This class provides a minimal implementation of a finite semigroup.

EXAMPLES:

```
sage: S = FiniteSemigroups().example(); S
An example of a finite semigroup:
    the left regular band generated by ('a', 'b', 'c', 'd')

this is the semigroup generated by:

    sage: S = FiniteSemigroups().example(); S
    sage: S.semigroup_generators()
    Family ('a', 'b', 'c', 'd')

such that \(x^2 = x\) and \(xyx = xy\) for any \(x\) and \(y\) in \(S\):

    sage: S('dab')
    'dab'
    sage: S('dab') * S('acb')
    'dabc'

It follows that the elements of \(S\) are strings without repetitions over the alphabet \(a, b, c, d\):

    sage: sorted(S.list())
    ['a', 'ab', 'abc', 'abcd', 'abd', 'abdc', 'ac', 'acb', 'acbd', 'acd',
     'acdb', 'ad', 'adb', 'adbc', 'adc', 'adcb', 'b', 'ba', 'bac',
     'bacd', 'bad', 'badc', 'bc', 'bca', 'bcad', 'bcd', 'bcda', 'bd',
     'bdac', 'bdc', 'bdca', 'c', 'ca', 'cab', 'cabd', 'cad',
     'cadb', 'cb', 'cba', 'cbad', 'cbda', 'cd', 'cda', 'cdab',
     'cdb', 'cdba', 'd', 'da', 'dab', 'dac', 'dacb', 'db',
     'dbac', 'dbca', 'dc', 'dca', 'dcab', 'dcba', 'dcb', 'dcba']

It also follows that there are finitely many of them:

    sage: S.cardinality()
    64

Indeed:

    sage: 4 * (1 + 3 * (1 + 2 * (1 + 1)))
    64

As expected, all the elements of \(S\) are idempotents:

    sage: all(x.is_idempotent() for x in S)
    True

Now, let us look at the structure of the semigroup:
We conclude by running systematic tests on this semigroup:

```python
sage: TestSuite(S).run(verbose = True)
running ._test_an_element() ... pass
running ._test_associativity() ... pass
running ._test_cardinality() ... pass
running ._test_category() ... pass
running ._test_construction() ... pass
running ._test_elements() ... 
  Running the test suite of self.an_element()
running ._test_category() ... pass
running ._test_eq() ... pass
running ._test_new() ... pass
running ._test_not_implemented_methods() ... pass
running ._test_pickling() ... pass
pass
running ._test_elements_eq_reflexive() ... pass
running ._test_elements_eq_symmetric() ... pass
running ._test_elements_eq_transitive() ... pass
running ._test_elements_neq() ... pass
running ._test_enumerated_set_contains() ... pass
running ._test_enumerated_set_iter_cardinality() ... pass
running ._test_enumerated_set_iter_list() ... pass
running ._test_eq() ... pass
running ._test_new() ... pass
running ._test_not_implemented_methods() ... pass
running ._test_pickling() ... pass
running ._test_some_elements() ... pass
```

```python
class Element
    Bases: ElementWrapper

    wrapped_class
        alias of str

    an_element()

        Returns an element of the semigroup.

        EXAMPLES:

        sage: S = FiniteSemigroups().example()
        sage: S.an_element()
        'cdab'
        sage: S = FiniteSemigroups().example("b")
        sage: S.an_element()
        'b'

    product(x, y)

        Returns the product of two elements of the semigroup.
```
EXAMPLES:

```
sage: S = FiniteSemigroups().example()
sage: S('a') * S('b')
'ab'
sage: S('a') * S('b') * S('a')
'ab'
sage: S('a') * S('a')
'a'
```

`semigroup_generators()`

Returns the generators of the semigroup.

EXAMPLES:

```
sage: S = FiniteSemigroups().example(alphabet=('x', 'y'))
sage: S.semigroup_generators()
Family ('x', 'y')
```

### 6.14 Examples of finite Weyl groups

```
sage.categories.examples.finite_weyl_groups.Example
   alias of SymmetricGroup
class sage.categories.examples.finite_weyl_groups.SymmetricGroup(n=4)
   Bases: UniqueRepresentation, Parent
   An example of finite Weyl group: the symmetric group, with elements in list notation.

   The purpose of this class is to provide a minimal template for implementing finite Weyl groups. See SymmetricGroup for a full featured and optimized implementation.

   EXAMPLES:

```
sage: S = FiniteWeylGroups().example()
sage: S
The symmetric group on {0, ..., 3}
sage: S.category()
Category of finite irreducible Weyl groups
```

The elements of this group are permutations of the set \{0, ..., 3\}:

```
sage: S.one()
(0, 1, 2, 3)
sage: S.an_element()
(1, 2, 3, 0)
```

The group itself is generated by the elementary transpositions:

```
sage: S.simple_reflections()
Finite family {0: (1, 0, 2, 3), 1: (0, 2, 1, 3), 2: (0, 1, 3, 2)}
```

Only the following basic operations are implemented:

- `one()`
- `product()`
• `simple_reflection()`
• `cartan_type()`
• `Element.has_right_descent()`.

All the other usual Weyl group operations are inherited from the categories:

```python
sage: S.cardinality()
24
sage: S.long_element()
(3, 2, 1, 0)

sage: S.cayley_graph(side="left").plot()  # needs sage.graphs sage.plot
Graphics object consisting of 120 graphics primitives
```

Alternatively, one could have implemented `sage.categories.coxeter_groups.CoxeterGroups.ElementMethods.apply_simple_reflection()` instead of `simple_reflection()` and `product()`. See `CoxeterGroups().example()`.

class Element
Bases: `ElementWrapper`

`has_right_descent(i)`

Implements `CoxeterGroups.ElementMethods.has_right_descent()`.

EXAMPLES:

```python
sage: S = FiniteWeylGroups().example()
sage: s = S.simple_reflections()
sage: (s[1] * s[2]).has_descent(2)
True
```

cartan_type()

Return the Cartan type of `self`.

EXAMPLES:

```python
sage: FiniteWeylGroups().example().cartan_type()  # needs sage.modules
['A', 3] relabelled by {1: 0, 2: 1, 3: 2}
```

degrees()

Return the degrees of `self`.

EXAMPLES:

```python
sage: W = FiniteWeylGroups().example()
sage: W.degrees()
(2, 3, 4)
```

index_set()


EXAMPLES:

```python
sage: FiniteWeylGroups().example().index_set()
[0, 1, 2]
```
one()
Implements Monoids.ParentMethods.one().
EXAMPLES:

```
sage: FiniteWeylGroups().example().one()
(0, 1, 2, 3)
```

product(x, y)
Implements Semigroups.ParentMethods.product().
EXAMPLES:

```
sage: s = FiniteWeylGroups().example().simple_reflections()
(0, 2, 3, 1)
```

simple_reflection(i)
Implement CoxeterGroups.ParentMethods.simple_reflection() by returning the transposition \((i, i + 1)\).
EXAMPLES:

```
sage: FiniteWeylGroups().example().simple_reflection(2)
(0, 1, 3, 2)
```

6.15 Examples of graded connected Hopf algebras with basis

sage.categories.examples.graded_connected_hopf_algebras_with_basis.Example
alias of GradedConnectedCombinatorialHopfAlgebraWithPrimitiveGenerator
class sage.categories.examples.graded_connected_hopf_algebras_with_basis.GradedConnectedCombinatorialHopfAlgebraWithPrimitiveGenerator

Bases: CombinatorialFreeModule

This class illustrates an implementation of a graded Hopf algebra with basis that has one primitive generator of degree 1 and basis elements indexed by non-negative integers.

This Hopf algebra example differs from what topologists refer to as a graded Hopf algebra because the twist operation in the tensor rule satisfies

\[
(\mu \otimes \mu) \circ (id \otimes \tau \otimes id) \circ (\Delta \otimes \Delta) = \Delta \circ \mu
\]

where \(\tau(x \otimes y) = y \otimes x\).

coproduct_on_basis(i)
The coproduct of a basis element.

\[
\Delta(P_i) = \sum_{j=0}^{i} P_{i-j} \otimes P_j
\]

INPUT:

• \(i\) – a non-negative integer

OUTPUT:

• an element of the tensor square of self
**degree_on_basis** \((i)\)

The degree of a non-negative integer is itself

**INPUT:**
- \(i\) – a non-negative integer

**OUTPUT:**
- a non-negative integer

**one_basis**

Returns 0, which index the unit of the Hopf algebra.

**OUTPUT:**
- the non-negative integer 0

**product_on_basis** \((i, j)\)

The product of two basis elements.

The product of elements of degree \(i\) and \(j\) is an element of degree \(i+j\).

**INPUT:**
- \(i, j\) – non-negative integers

**OUTPUT:**
- a basis element indexed by \(i+j\)

### 6.16 Examples of graded modules with basis

```python
sage: H = GradedHopfAlgebrasWithBasis(QQ).Connected().example()
sage: H.one_basis()
0
sage: H.one()
P0
```

**product_on_basis** \((i, j)\)

The product of two basis elements.

The product of elements of degree \(i\) and \(j\) is an element of degree \(i+j\).

**INPUT:**
- \(i, j\) – non-negative integers

**OUTPUT:**
- a basis element indexed by \(i+j\)

**class** `sage.categories.examples.graded_modules_with_basis.GradedPartitionModule` *(base_ring)*

**Bases:** *CombinatorialFreeModule*

This class illustrates an implementation of a graded module with basis: the free module over partitions.

**INPUT:**
- \(R\) – base ring

The implementation involves the following:

- A choice of how to represent elements. In this case, the basis elements are partitions. The algebra is constructed as a `CombinatorialFreeModule` on the set of partitions, so it inherits all of the methods for such objects, and has operations like addition already defined.

```python
sage: A = GradedModulesWithBasis(QQ).example()
```

**Note:** `sage.modules`
• A basis function - this module is graded by the non-negative integers, so there is a function defined in this module, creatively called \texttt{basis()}, which takes an integer \(d\) as input and returns a family of partitions representing a basis for the algebra in degree \(d\).

```sage
sage: A.basis(2)
˓→ # needs sage.modules
Lazy family (Term map from Partitions to An example of a graded module with
˓→ basis: the free module on partitions over Rational Field(i)_{i in...
˓→ Parts of the integer 2}
sage: A.basis(6)[Partition([3,2,1])]
˓→ # needs sage.modules
P[3, 2, 1]
```

• If the algebra is called \(A\), then its basis function is stored as \texttt{A.basis}. Thus the function can be used to find a basis for the degree \(d\) piece: essentially, just call \texttt{A.basis(d)}. More precisely, call \(x\) for each \(x\) in \texttt{A.basis(d)}.

```sage
sage: [m for m in A.basis(4)]
˓→ # needs sage.modules
[P[4], P[3, 1], P[2, 2], P[2, 1, 1], P[1, 1, 1, 1]]
```

• For dealing with basis elements: \texttt{degree_on_basis()}, and \texttt{_repr_term()}. The first of these defines the degree of any monomial, and then the degree method for elements – see the next item – uses it to compute the degree for a linear combination of monomials. The last of these determines the print representation for monomials, which automatically produces the print representation for general elements.

```sage
sage: A.degree_on_basis(Partition([4,3]))
˓→ # needs sage.modules
7
sage: A._repr_term(Partition([4,3]))
˓→ # needs sage.modules
'P[4, 3]'
```

• There is a class for elements, which inherits from \texttt{IndexedFreeModuleElement}. An element is determined by a dictionary whose keys are partitions and whose corresponding values are the coefficients. The class implements two things: an \texttt{is_homogeneous} method and a \texttt{degree} method.

```sage
sage: p = A.monomial(Partition([3,2,1])); p
˓→ # needs sage.modules
P[3, 2, 1]
sage: p.is_homogeneous()
˓→ # needs sage.modules
True
sage: p.degree()
˓→ # needs sage.modules
6
```

\texttt{basis}(d=None)

Return the basis for (the \(d\)-th homogeneous component of) \texttt{self}.

**INPUT:**

• \(d\) – (optional, default \texttt{None}) nonnegative integer or \texttt{None}

**OUTPUT:**

If \(d\) is \texttt{None}, returns the basis of the module. Otherwise, returns the basis of the homogeneous component of degree \(d\) (i.e., the subfamily of the basis of the whole module which consists only of the basis vectors lying in \(F_d \setminus \bigcup_{i<d} F_i\)).
The basis is always returned as a family.

**EXAMPLES:**

```sage
sage: A = ModulesWithBasis(ZZ).Filtered().example()
sage: A.basis(4)
Lazy family (Term map from Partitions to An example of a filtered module with basis: the free module on partitions over Integer Ring(i))_{i in Partitions of the integer 4}
```

Without arguments, the full basis is returned:

```sage
sage: A.basis()
Lazy family (Term map from Partitions to An example of a filtered module with basis: the free module on partitions over Integer Ring(i))_{i in Partitions}
```

Checking this method on a filtered algebra. Note that this will typically raise a `NotImplementedError` when this feature is not implemented.

```sage
sage: A = AlgebrasWithBasis(ZZ).Filtered().example()
sage: A.basis(4)
Traceback (most recent call last):
  ...  
NotImplementedError: infinite set
```

Without arguments, the full basis is returned:

```sage
sage: A.basis()
Lazy family (Term map from Free abelian monoid indexed by \{'x', 'y', 'z'\} to An example of a filtered algebra with basis: the universal enveloping algebra of Lie algebra of RR^3 with cross product over Integer Ring(i))_{i in Free abelian monoid indexed by \{'x', 'y', 'z'\}}
```

An example with a graded algebra:

```sage
sage: E.<x,y> = ExteriorAlgebra(QQ)
sage: E.basis()
Lazy family (Term map from Subsets of \{0,1\} to The exterior algebra of rank 2 over Rational Field(i))_{i in Subsets of \{0,1\}}
```

**degree_on_basis**(t)

The degree of the element determined by the partition t in this graded module.

**INPUT:**

- t – the index of an element of the basis of this module, i.e. a partition

**OUTPUT:** an integer, the degree of the corresponding basis element

**EXAMPLES:**
6.17 Examples of graphs

```python
class sage.categories.examples.graphs.Cycle(n=5):
    Bases: UniqueRepresentation, Parent

    An example of a graph: the cycle of length $n$.

    This class illustrates a minimal implementation of a graph.

    EXAMPLES:

    sage: from sage.categories.graphs import Graphs
    sage: C = Graphs().example(); C
    An example of a graph: the 5-cycle
    sage: C.category()
    Category of graphs

    We conclude by running systematic tests on this graph:

    sage: TestSuite(C).run()
```

```python
class Element
    Bases: ElementWrapper

    dimension() ->
        Return the dimension of self.

    EXAMPLES:

    sage: from sage.categories.graphs import Graphs
    sage: C = Graphs().example()
    sage: e = C.edges()[0]
    sage: e.dimension()
    2
    sage: v = C.vertices()[0]
    sage: v.dimension()
    1

    an_element() ->
        Return an element of the graph, as per Sets.ParentMethods.an_element().

    EXAMPLES:

    sage: from sage.categories.graphs import Graphs
    sage: C = Graphs().example()
```

(continues on next page)
edges()
Return the edges of self.

EXAMPLES:

```python
sage: from sage.categories.graphs import Graphs
sage: C = Graphs().example()
sage: C.edges()
[(0, 1), (1, 2), (2, 3), (3, 4), (4, 0)]
```

vertices()
Return the vertices of self.

EXAMPLES:

```python
sage: from sage.categories.graphs import Graphs
sage: C = Graphs().example()
sage: C.vertices()
[0, 1, 2, 3, 4]
```

sage.categories.examples.graphs.Example
alias of Cycle

## 6.18 Examples of Hopf algebras with basis

class sage.categories.examples.hopf_algebras_with_basis.MyGroupAlgebra(R, G)
Bases: CombinatorialFreeModule

An example of a Hopf algebra with basis: the group algebra of a group

This class illustrates a minimal implementation of a Hopf algebra with basis.

algebra_generators()
Return the generators of this algebra, as per `algebra_generators()`.

They correspond to the generators of the group.

EXAMPLES:

```python
sage: A = HopfAlgebrasWithBasis(QQ).example(); A
An example of Hopf algebra with basis: the group algebra of the Dihedral group of order 6 as a permutation group over Rational Field
sage: A.algebra_generators()
Finite family {(1,2,3): B[(1,2,3)], (1,3): B[(1,3)]}
```

antipode_on_basis(g)
Antipode, on basis elements, as per `HopfAlgebrasWithBasis.ParentMethods.antipode_on_basis()`.

It is given, on basis elements, by $\nu(g) = g^{-1}$

EXAMPLES:
sage: A = HopfAlgebrasWithBasis(QQ).example()
sage: (a, b) = A._group.gens()
sage: A.antipode_on_basis(a)
B[(1,3,2)]

\textbf{coproduct\_on\_basis}(g)

Coprodct, on basis elements, as per \texttt{HopfAlgebrasWithBasis.ParentMethods.coproduct\_on\_basis}().

The basis elements are group like: $\Delta(g) = g \otimes g$.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: A = HopfAlgebrasWithBasis(QQ).example()
sage: (a, b) = A._group.gens()
sage: A.coproduct_on_basis(a)
B[(1,2,3)] # B[(1,2,3)]
\end{verbatim}

\textbf{counit\_on\_basis}(g)

Counit, on basis elements, as per \texttt{HopfAlgebrasWithBasis.ParentMethods.counit\_on\_basis}().

The counit on the basis elements is 1.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: A = HopfAlgebrasWithBasis(QQ).example()
sage: (a, b) = A._group.gens()
sage: A.counit_on_basis(a)
1
\end{verbatim}

\textbf{one\_basis}()

Returns the one of the group, which index the one of this algebra, as per \texttt{AlgebrasWithBasis.ParentMethods.one\_basis}().

\textbf{EXAMPLES:}

\begin{verbatim}
sage: A = HopfAlgebrasWithBasis(QQ).example()
sage: A.one_basis()
()
sage: A.one()
B[()]
\end{verbatim}

\textbf{product\_on\_basis}(g1, g2)

Product, on basis elements, as per \texttt{AlgebrasWithBasis.ParentMethods.product\_on\_basis}().

The product of two basis elements is induced by the product of the corresponding elements of the group.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: A = HopfAlgebrasWithBasis(QQ).example()
sage: (a, b) = A._group.gens()
sage: a*b
(1,2)
sage: A.product_on_basis(a, b)
B[(1,2)]
\end{verbatim}
6.19 Examples of infinite enumerated sets

sage.categories.examples.infinite_enumerated_sets.Example
alias of NonNegativeIntegers
class sage.categories.examples.infinite_enumerated_sets.NonNegativeIntegers
  Bases: UniqueRepresentation, Parent
  An example of infinite enumerated set: the non negative integers

This class provides a minimal implementation of an infinite enumerated set.

EXAMPLES:

```python
sage: NN = InfiniteEnumeratedSets().example()
sage: NN
An example of an infinite enumerated set: the non negative integers
sage: NN.cardinality()
+Infinity
sage: NN.list()
Traceback (most recent call last):
... NotImplementedError: cannot list an infinite set
sage: NN.element_class
<class 'sage.rings.integer.Integer'>
sage: it = iter(NN)
sage: [next(it), next(it), next(it), next(it), next(it)]
[0, 1, 2, 3, 4]
sage: x = next(it); type(x)
<class 'sage.rings.integer.Integer'>
sage: x.parent()
Integer Ring
sage: x+3
8
sage: NN(15)
15
sage: NN.first()
0
```

This checks that the different methods of \( \mathbb{N} \) return consistent results:

```python
sage: TestSuite(NN).run(verbos...)
```

(continues on next page)
running ._test_elements_neq() ... pass
running ._test_enumerated_set_contains() ... pass
running ._test_enumerated_set_iter_cardinality() ... pass
running ._test_enumerated_set_iter_list() ... pass
running ._test_eq() ... pass
running ._test_new() ... pass
running ._test_not_implemented_methods() ... pass
running ._test_pickling() ... pass
running ._test_some_elements() ... pass

Element
alias of Integer

an_element()
EXAMPLES:

sage: InfiniteEnumeratedSets().example().an_element()
42

next (o)
EXAMPLES:

sage: NN = InfiniteEnumeratedSets().example()
sage: NN.next(3)
4

6.20 Examples of a Lie algebra

sage.categories.examples.lie_algebras.Example
alias of LieAlgebraFromAssociative
class sage.categories.examples.lie_algebras.LieAlgebraFromAssociative (gens)
Bases: Parent, UniqueRepresentation

An example of a Lie algebra: a Lie algebra generated by a set of elements of an associative algebra.
This class illustrates a minimal implementation of a Lie algebra.
Let \( R \) be a commutative ring, and \( A \) an associative \( R \)-algebra. The Lie algebra \( A^- \) (sometimes denoted \( A^- \)) is
defined to be the \( R \)-module \( A \) with Lie bracket given by the commutator in \( A \): that is, \([a, b] := ab - ba\) for all \( a, b \in A \).

What this class implements is not precisely \( A^- \), however; it is the Lie subalgebra of \( A^- \) generated by the elements of
the iterable \( \text{gens} \). This specific implementation does not provide a reasonable containment test (i.e., it does not allow you to check if a given element \( a \) of \( A^- \) belongs to this Lie subalgebra); it, however, allows computing inside it.

INPUT:

- \( \text{gens} \) – a nonempty iterable consisting of elements of an associative algebra \( A \)

OUTPUT:
The Lie subalgebra of \( A^- \) generated by the elements of \( \text{gens} \)

EXAMPLES:
We create a model of $\mathfrak{sl}_2$ using matrices:

```
sage: gens = [matrix([[0,1],[0,0]]), matrix([[0,0],[1,0]]), matrix([[1,0],[0,-1]])]
sage: for g in gens:
    ....:     g.set_immutable()
sage: L = LieAlgebras(QQ).example(gens)
sage: e,f,h = L.lie_algebra_generators()
sage: e.bracket(f) == h
True
sage: h.bracket(e) == 2*e
True
sage: h.bracket(f) == -2*f
True
```

class Element
Bases: ElementWrapper

Wrap an element as a Lie algebra element.

\texttt{lie\_algebra\_generators()}
Return the generators of \texttt{self} as a Lie algebra.

\textbf{EXAMPLES:}

```
sage: L = LieAlgebras(QQ).example()  # needs sage.combinat, sage.groups
sage: L.lie_algebra_generators()  # needs sage.combinat, sage.groups
Family ([2, 1, 3], [2, 3, 1])
```

\texttt{zero()}
Return the element 0.

\textbf{EXAMPLES:}

```
sage: L = LieAlgebras(QQ).example()  # needs sage.combinat, sage.groups
sage: L.zero()  # needs sage.combinat, sage.groups
0
```

### 6.21 Examples of a Lie algebra with basis

class \texttt{sage.categories.examples.lie_algebras_with_basis.AbelianLieAlgebra}(R, gens)

Bases: CombinatorialFreeModule

An example of a Lie algebra: the abelian Lie algebra.

This class illustrates a minimal implementation of a Lie algebra with a distinguished basis.

class Element
Bases: IndexedFreeModuleElement
lift()

Return the lift of self to the universal enveloping algebra.

EXAMPLES:

```python
sage: L = LieAlgebras(QQ).WithBasis().example()
sage: elt = L.an_element()
sage: elt.lift()
3*P[F[2]] + 2*P[F[1]] + 2*P[F[]]
```

bracket_on_basis(x, y)

Return the Lie bracket on basis elements indexed by x and y.

EXAMPLES:

```python
sage: L = LieAlgebras(QQ).WithBasis().example()
sage: L.bracket_on_basis(Partition([4,1]), Partition([2,2,1]))
0
```

lie_algebra_generators()

Return the algebra generators of self.

EXAMPLES:

```python
sage: L = LieAlgebras(QQ).WithBasis().example()
sage: UEA = L.universal_enveloping_algebra()
sage: UEA.algebra_generators()
Lazy family (algebra generator map(i))_{i in Partitions}
```

Todo: Currently this is just used as the universal enveloping algebra for the example of the abelian Lie algebra. This should be factored out into a more complete class.
one_basis()

Return the index of element 1.

EXAMPLES:

```
sage: L = LieAlgebras(QQ).WithBasis().example()
sage: UEA = L.universal_enveloping_algebra()
sage: UEA.one_basis()
1
sage: UEA.one_basis().parent()
Free abelian monoid indexed by Partitions
```

product_on_basis(x, y)

Return the product of the monomials indexed by $x$ and $y$.

EXAMPLES:

```
sage: L = LieAlgebras(QQ).WithBasis().example()
sage: UEA = L.universal_enveloping_algebra()
sage: I = UEA._indices
sage: UEA.product_on_basis(I.an_element(), I.an_element())
```

6.22 Examples of magmas

```
sage.categories.examples.magas.Example

alias of FreeMagma
class sage.categories.examples.magas.FreeMagma(alphabet=('a', 'b', 'c', 'd'))

Bases: UniqueRepresentation, Parent

An example of magma.

The purpose of this class is to provide a minimal template for implementing a magma.

EXAMPLES:

```
sage: M = Magmas().example(); M
An example of a magma: the free magma generated by ('a', 'b', 'c', 'd')

This is the free magma generated by:

```
sage: M.magma_generators()
Family ('a', 'b', 'c', 'd')
sage: a, b, c, d = M.magma_generators()
```

and with a non-associative product given by:

```
sage: a * (b * c) * (d * a * b)
'((a*b*c)*)((d*a)*b))'
sage: a * (b * c) == (a * b) * c
False
```

class Element

Bases: ElementWrapper

The class for elements of the free magma.
```
wrapped_class

    alias of str

an_element()

    Return an element of the magma.

    EXAMPLES:

    sage: F = Magmas().example()
    sage: F.an_element()
    '((a*b)*c)*d'

magma_generators()

    Return the generators of the magma.

    EXAMPLES:

    sage: F = Magmas().example()
    sage: F.magma_generators()
    Family ('a', 'b', 'c', 'd')

product (x, y)

    Return the product of \( x \) and \( y \) in the magma, as per `Magmas.ParentMethods.product()`.

    EXAMPLES:

    sage: F = Magmas().example()
    sage: F('a') * F.an_element()
    'a*(((a*b)*c)*d)'

6.23 Examples of manifolds

sage.categories.examples.manifolds.Example

    alias of Plane

class sage.categories.examples.manifolds.Plane(n=3, base_ring=None)

    Bases: UniqueRepresentation, Parent

    An example of a manifold: the \( n \)-dimensional plane.

    This class illustrates a minimal implementation of a manifold.

    EXAMPLES:

    sage: from sage.categories.manifolds import Manifolds
    sage: M = Manifolds(QQ).example(); M
    Manifolds over Rational Field
    An example of a Rational Field manifold: the 3-dimensional plane

    sage: M.category()
    Category of manifolds over Rational Field

    We conclude by running systematic tests on this manifold:

    sage: TestSuite(M).run()
The `Element` function is an alias of `ElementWrapper`.

`an_element()` function returns an element of the manifold, as per `Sets.ParentMethods.an_element()`.

**EXAMPLES:**

```sage
def main():
    from sage.categories.manifolds import Manifolds
    M = Manifolds(QQ).example()
    M.an_element()

if __name__ == '__main__':
    main()
```

The `dimension()` function returns the dimension of `self`.

**EXAMPLES:**

```sage
def main():
    from sage.categories.manifolds import Manifolds
    M = Manifolds(QQ).example()
    M.dimension()

if __name__ == '__main__':
    main()
```

### 6.24 Examples of monoids

The `FreeMonoid` class illustrates a minimal implementation of a monoid. For a full featured implementation of free monoids, see `FreeMonoid()`.

**EXAMPLES:**

```sage
def main():
    S = Monoids().example(); S
    S.category()
    S.semidirect_generators()
    S('dab') * S('acb')

if __name__ == '__main__':
    main()
```
We conclude by running systematic tests on this monoid:

```
sage: TestSuite(S).run(verbosity = True)
running _test_an_element() ... pass
running _test_associativity() ... pass
running _test_cardinality() ... pass
running _test_category() ... pass
running _test_construction() ... pass
running _test_elements() ... 
    Running the test suite of self.an_element()
    running _test_category() ... pass
    running _test_eq() ... pass
    running _test_new() ... pass
    running _test_not_implemented_methods() ... pass
    running _test_pickling() ... pass
    pass
running _test_elements_eq_reflexive() ... pass
running _test_elements_eq_symmetric() ... pass
running _test_elements_eq_transitive() ... pass
running _test_elements_neq() ... pass
running _test_eq() ... pass
running _test_new() ... pass
running _test_not_implemented_methods() ... pass
running _test_one() ... pass
running _test_pickling() ... pass
running _test_prod() ... pass
running _test_some_elements() ... pass
```

class Element
    Bases: ElementWrapper

    wrapped_class
        alias of str

    monoid_generators()
        Return the generators of this monoid.

    EXAMPLES:

        sage: M = Monoids().example(); M
        An example of a monoid: the free monoid generated by ('a', 'b', 'c', 'd')
        sage: M.monoid_generators()
        Finite family {'a': 'a', 'b': 'b', 'c': 'c', 'd': 'd'}
        sage: a,b,c,d = M.monoid_generators()
        sage: a*d*c*b
        'adcb'

    one()
        Returns the one of the monoid, as per Monoids.ParentMethods.one().

    EXAMPLES:

        sage: M = Monoids().example(); M
        An example of a monoid: the free monoid generated by ('a', 'b', 'c', 'd')
        (continues on next page)
6.25 Examples of posets

```python
class sage.categories.examples.posets.FiniteSetsOrderedByInclusion:
    Bases: UniqueRepresentation, Parent

    An example of a poset: finite sets ordered by inclusion
    This class provides a minimal implementation of a poset

    EXAMPLES:

    sage: P = Posets().example(); P
    An example of a poset: sets ordered by inclusion

    We conclude by running systematic tests on this poset:

    sage: TestSuite(P).run(verbosity = True)
    running ._test_an_element() . . . pass
    running ._test_cardinality() . . . pass
    running ._test_category() . . . pass
    running ._test_construction() . . . pass
    running ._test_elements() . .
    Running the test suite of self.an_element()
    running ._test_category() . . . pass
    running ._test_eq() . . . pass
    running ._test_new() . . . pass
    running ._test_not_implemented_methods() . . . pass
    running ._test_pickling() . . . pass
    running ._test_elements_eq_reflexive() . . . pass
    running ._test_elements_eq_symmetric() . . . pass
    running ._test_elements_eq_transitive() . . . pass
    running ._test_elements_neq() . . . pass
    running ._test_eq() . . . pass
    running ._test_new() . . . pass
    running ._test_not_implemented_methods() . . . pass
    running ._test_pickling() . . . pass
    running ._test_some_elements() . . . pass
```

```
class Element:
    Bases: ElementWrapper

    wrapped_class
      alias of Set_objectEnumerated

    an_element()
      Returns an element of this poset

    EXAMPLES:
```
```
sage: B = Posets().example()
sage: B.an_element()
{1, 4, 6}
```

\texttt{le}(x, y)

Returns whether \(x\) is a subset of \(y\)

\textbf{EXAMPLES:}

```
sage: P = Posets().example()
sage: P.le( P(Set([1,3])), P(Set([1,2,3])) )
True
sage: P.le( P(Set([1,3])), P(Set([1,3])) )
True
sage: P.le( P(Set([1,2])), P(Set([1,3])) )
False
```

\textbf{class}\n
\texttt{sage.categories.examples.posets.PositiveIntegersOrderedByDivisibilityFacade}

\textbf{Bases:} \texttt{UniqueRepresentation, Parent}

An example of a facade poset: the positive integers ordered by divisibility

This class provides a minimal implementation of a facade poset

\textbf{EXAMPLES:}

```
sage: P = Posets().example("facade"); P
An example of a facade poset: the positive integers ordered by divisibility
sage: P(5)
5
sage: P(0)
Traceback (most recent call last):
... ValueError: Can't coerce \`0\' in any parent \`An example of a facade poset: the positive integers ordered by divisibility\' is a facade for
sage: 3 in P
True
sage: 0 in P
False
```

\textbf{class element_class}(X, category=None)

\textbf{Bases:} \texttt{Set_object_enumerated, parent_class}

A finite enumerated set.

\texttt{le}(x, y)

Returns whether \(x\) is divisible by \(y\)

\textbf{EXAMPLES:}

```
sage: P = Posets().example("facade")
sage: P.le(3, 6)
True
sage: P.le(3, 3)
True
```

(continues on next page)
6.26 Examples of semigroups

class sage.categories.examples.semigroups.FreeSemigroup(alphabet=('a', 'b', 'c', 'd'))

    Bases: UniqueRepresentation, Parent

    An example of semigroup.

    The purpose of this class is to provide a minimal template for implementing of a semigroup.

    EXAMPLES:

    sage: S = Semigroups().example("free"); S
    An example of a semigroup: the free semigroup generated by ('a', 'b', 'c', 'd')

    This is the free semigroup generated by:

    sage: S.semigroup_generators()
    Family ('a', 'b', 'c', 'd')

    and with product given by concatenation:

    sage: S('dab') * S('acb')
    'dabacb'

class Element

    Bases: ElementWrapper

    The class for elements of the free semigroup.

    wrapped_class
        alias of str

    an_element()
        Returns an element of the semigroup.

        EXAMPLES:

        sage: F = Semigroups().example('free')
        sage: F.an_element()
        'abcd'

    product(x, y)
        Returns the product of x and y in the semigroup, as per Semigroups.ParentMethods.product().

        EXAMPLES:

        sage: F = Semigroups().example('free')
        sage: F.an_element() * F('a')^5
        'abcdaaaaa'
**semigroup_generators()**

Returns the generators of the semigroup.

EXAMPLES:

```python
sage: F = Semigroups().example('free')
sage: F.semigroup_generators()
Family (a, b, c, d)
```

**class** `sage.categories.examples.semigroups.IncompleteSubquotientSemigroup` (*category=None*)

Bases: `UniqueRepresentation, Parent`

An incompletely implemented subquotient semigroup, for testing purposes

EXAMPLES:

```python
sage: S = sage.categories.examples.semigroups.IncompleteSubquotientSemigroup()
sage: S
A subquotient of An example of a semigroup: the left zero semigroup
```

**class** `Element`

Bases: `ElementWrapper`

**ambient()**

Returns the ambient semigroup.

EXAMPLES:

```python
sage: S = sage.categories.examples.semigroups.IncompleteSubquotientSemigroup()
sage: S
A subquotient of An example of a semigroup: the left zero semigroup
```

**class** `sage.categories.examples.semigroups.LeftZeroSemigroup`

Bases: `UniqueRepresentation, Parent`

An example of a semigroup.

This class illustrates a minimal implementation of a semigroup.

EXAMPLES:

```python
sage: S = Semigroups().example(); S
An example of a semigroup: the left zero semigroup
```

This is the semigroup that contains all sorts of objects:

```python
sage: S.some_elements()
[3, 42, 'a', 3.4, 'raton laveur']
```

with product rule given by \(a \times b = a\) for all \(a, b\):

```python
sage: S('hello') * S('world')
'hello'
sage: S(3)*S(1)*S(2)
3
sage: S(3)^12312321312321
3
```
class Element
    Bases: ElementWrapper

    is_idempotent()
    Trivial implementation of Semigroups.Element.is_idempotent since all elements of this semigroup are idempotent!

    EXAMPLES:
    sage: S = Semigroups().example()
    sage: S.an_element().is_idempotent()    
    True
    sage: S(17).is_idempotent()            
    True

an_element()
    Returns an element of the semigroup.

    EXAMPLES:
    sage: Semigroups().example().an_element()  
    42

product(x, y)
    Returns the product of x and y in the semigroup, as per Semigroups.ParentMethods.product().

    EXAMPLES:
    sage: S = Semigroups().example()
    sage: S('hello') * S('world')  
    'hello'
    sage: S(3)*S(1)*S(2)             
    3

some_elements()
    Returns a list of some elements of the semigroup.

    EXAMPLES:
    sage: Semigroups().example().some_elements()  
    [3, 42, 'a', 3.4, 'raton laveur']

class sage.categories.examples.semigroups.QuotientOfLeftZeroSemigroup (category=None)
    Bases: UniqueRepresentation, Parent

    Example of a quotient semigroup

    EXAMPLES:
    sage: S = Semigroups().Subquotients().example(); S
    An example of a (sub)quotient semigroup: a quotient of the left zero semigroup

    This is the quotient of:
    sage: S.ambient()
    An example of a semigroup: the left zero semigroup

    obtained by setting x = 42 for any x ≥ 42:
The product is inherited from the ambient semigroup:

```
sage: S(1)*S(2) == S(1)
True
```

```python
class Element
    
    ambient()

    Returns the ambient semigroup.

    EXAMPLES:

    sage: S = Semigroups().Subquotients().example()
    sage: S.ambient()
    An example of a semigroup: the left zero semigroup

    an_element()

    Returns an element of the semigroup.

    EXAMPLES:

    sage: S = Semigroups().Subquotients().example()
    sage: S.an_element()
    42

    lift(x)

    Lift the element $x$ into the ambient semigroup.

    INPUT:

    • $x$ – an element of $self$.

    OUTPUT:

    • an element of $self.ambient$.

    EXAMPLES:

    sage: S = Semigroups().Subquotients().example()
    sage: x = S.an_element(); x
    42
    sage: S.lift(x)
    42
    sage: S.lift(x) in S.ambient()
    True
    sage: y = S.ambient()(100); y
    100
    sage: S.lift(S(y))
    42

    retract(x)

    Returns the retract $x$ onto an element of this semigroup.

    INPUT:
• \( x \) – an element of the ambient semigroup \( \text{self.ambient}() \).

OUTPUT:

• an element of \( \text{self} \).

EXAMPLES:

```python
sage: S = Semigroups().Subquotients().example()
sage: L = S.ambient()
sage: S.retract(L(17))
17
sage: S.retract(L(42))
42
sage: S.retract(L(171))
42
```

**some_elements()**

Returns a list of some elements of the semigroup.

EXAMPLES:

```python
sage: S = Semigroups().Subquotients().example()
sage: S.some_elements()
[1, 2, 3, 8, 42, 42]
```

**the_answer()**

Returns the Answer to Life, the Universe, and Everything as an element of this semigroup.

EXAMPLES:

```python
sage: S = Semigroups().Subquotients().example()
sage: S.the_answer()
42
```

### 6.27 Examples of semigroups in cython

**class** `sage.categories.examples.semigroups_cython.IdempotentSemigroups`

Bases: `Category`

**class** `ElementMethods`

Bases: `object`

**is_idempotent()**

EXAMPLES:

```python
sage: from sage.categories.examples.semigroups_cython import...
sage: S = LeftZeroSemigroup()
sage: S(2).is_idempotent()
True
```

**super_categories()**

EXAMPLES:
class sage.categories.examples.semigroups_cython.LeftZeroSemigroup

Bases: LeftZeroSemigroup

An example of semigroup

This class illustrates a minimal implementation of a semi-group where the element class is an extension type, and still gets code from the category. The category itself must be a Python class though.

This is purely a proof of concept. The code obviously needs refactorisation!

Comments:

- one cannot play ugly class surgery tricks (as with \_mul\_parent). available operations should really be declared to the coercion model!

EXAMPLES:

```
sage: from sage.categories.examples.semigroups_cython import LeftZeroSemigroup
sage: S = LeftZeroSemigroup(); S
An example of a semigroup: the left zero semigroup

This is the semigroup which contains all sort of objects:

sage: S.some_elements()
[3, 42, 'a', 3.4, 'raton laveur']

with product rule given by \(a \times b = a\) for all \(a, b\).

sage: S('hello') * S('world')
'hello'

sage: S(3)*S(1)*S(2)
3

sage: S(3)**12312321312321
3

sage: TestSuite(S).run(\_test\_associativity() . . . pass
running \_test\_cardinality() . . . pass
running \_test\_category() . . . pass
running \_test\_construction() . . . pass
running \_test\_elements() . . .
Running the test suite of self.an_element()
running \_test\_eq() . . . pass
running \_test\_new() . . . pass
running \_test\_not\_implemented\_methods() . . . pass
running \_test\_pickling() . . . pass
pass
running \_test\_elements\_eq\_reflexive() . . . pass
running \_test\_elements\_eq\_symmetric() . . . pass
running \_test\_elements\_eq\_transitive() . . . pass
```

(continues on next page)
That's really the only method which is obtained from the category ...

```
sage: S(42).is_idempotent
<bound method IdempotentSemigroups.ElementMethods.is_idempotent of 42>
sage: S(42).is_idempotent()
True

sage: S(42)._pow_int
<bound method IdempotentSemigroups.ElementMethods._pow_int of 42>
sage: S(42)^10
42

sage: S(42).is_idempotent
<bound method IdempotentSemigroups.ElementMethods.is_idempotent of 42>
sage: S(42).is_idempotent()
True
```

**Element**

alias of *LeftZeroSemigroupElement*

class sage.categories.examples.semigroups_cython.LeftZeroSemigroupElement

Bases: *Element*

EXAMPLES:

```
sage: from sage.categories.examples.semigroups_cython import LeftZeroSemigroup
sage: S = LeftZeroSemigroup()
sage: x = S(3)
sage: TestSuite(x).run()
```

### 6.28 Examples of sets

class sage.categories.examples.sets_cat.PrimeNumbers

Bases: *UniqueRepresentation, Parent*

An example of parent in the category of sets: the set of prime numbers.

The elements are represented as plain integers in $\mathbb{Z}$ (facade implementation).

This is a minimal implementations. For more advanced examples of implementations, see also:

```
sage: P = Sets().example("facade")
sage: P = Sets().example("inherits")
sage: P = Sets().example("wrapper")
```

EXAMPLES:
sage: P = Sets().example()
sage: P(12)
Traceback (most recent call last):
  ...  
AssertionError: 12 is not a prime number
sage: a = P.an_element()
sage: a.parent()
Integer Ring
sage: x = P(13); x
13
sage: type(x)
<class sage.rings.integer.Integer'>
sage: x.parent()
Integer Ring
sage: 13 in P
True
sage: 12 in P
False
sage: y = x+1; y
14
sage: type(y)
<class sage.rings.integer.Integer'>

sage: TestSuite(P).run(\texttt{verbose=True})
running \_\_test\_an\_element() . . . pass
running \_\_test\_cardinality() . . . pass
running \_\_test\_category() . . . pass
running \_\_test\_construction() . . . pass
running \_\_test\_elements() . . .
  Running the test suite of self.an_element()
running \_\_test\_category() . . . pass
running \_\_test\_eq() . . . pass
running \_\_test\_new() . . . pass
running \_\_test\_nonzero\_equal() . . . pass
running \_\_test\_not\_implemented\_methods() . . . pass
running \_\_test\_pickling() . . . pass
  pass
running \_\_test\_elements\_eq\_reflexive() . . . pass
running \_\_test\_elements\_eq\_symmetric() . . . pass
running \_\_test\_elements\_eq\_transitive() . . . pass
running \_\_test\_elements\_neq() . . . pass
running \_\_test\_eq() . . . pass
running \_\_test\_new() . . . pass
running \_\_test\_not\_implemented\_methods() . . . pass
running \_\_test\_pickling() . . . pass
running \_\_test\_some\_elements() . . . pass

\texttt{an\_element}()
  Implements \texttt{Sets.ParentMethods.an\_element}.

\texttt{element\_class}
  alias of \texttt{Integer}

class sage.categories.examples.sets_cat.PrimeNumbers_Abstract
  Bases: UniqueRepresentation, Parent

This class shows how to write a parent while keeping the choice of the datastructure for the children open. Different class with fixed datastructure will then be constructed by inheriting from \texttt{PrimeNumbers\_Abstract}. 
This is used by:

```python
sage: P = Sets().example("facade")
sage: P = Sets().example("inherits")
sage: P = Sets().example("wrapper")
```

```python
class Element
    Bases: Element

    is_prime()
    Return whether self is a prime number.

    EXAMPLES:
    sage: P = Sets().example("inherits")
    sage: x = P.an_element()
    sage: P.an_element().is_prime()
    True

    next()
    Return the next prime number.

    EXAMPLES:
    sage: P = Sets().example("inherits")
    sage: p = P.an_element(); p
    47
    sage: p.next()
    53

    Note: This method is not meant to implement the protocol iterator, and thus not subject to Python 2 vs Python 3 incompatibilities.

    an_element()
    Implements Sets.ParentMethods.an_element().

    next(i)
    Return the next prime number.

    EXAMPLES:
    sage: P = Sets().example("inherits")
    sage: x = P.next(P.an_element()); x
    53
    sage: x.parent()
    Set of prime numbers

    some_elements()
    Return some prime numbers.

    EXAMPLES:
    sage: P = Sets().example("inherits")
    sage: P.some_elements()
    [47, 53, 59, 61, 67, 71, 73, 79, 83, 89, 97]
```

6.28. Examples of sets
class sage.categories.examples.sets_cat.PrimeNumbers_Facade

Bases: PrimeNumbers_Abstract

An example of parent in the category of sets: the set of prime numbers.

In this alternative implementation, the elements are represented as plain integers in \( \mathbb{Z} \) (facade implementation).

**EXAMPLES:**

```python
sage: P = Sets().example("facade")
sage: P(12)
Traceback (most recent call last):
  ...  
ValueError: 12 is not a prime number
sage: a = P.an_element()
sage: a.parent()
Integer Ring
sage: x = P(13); x
13
sage: type(x)
<class 'sage.rings.integer.Integer'>
sage: x.parent()
Integer Ring
sage: 13 in P
True
sage: 12 in P
False
sage: y = x+1; y
14
sage: type(y)
<class 'sage.rings.integer.Integer'>
sage: z = P.next(x); z
17
sage: type(z)
<class 'sage.rings.integer.Integer'>
sage: z.parent()
Integer Ring
```

The disadvantage of this implementation is that the elements do not know that they are prime, so that prime testing is slow:

```python
sage: pf = Sets().example("facade").an_element()
sage: timeit("pf.is_prime()")  # random
625 loops, best of 3: 4.1 us per loop
```

compared to the other implementations where prime testing is only done if needed during the construction of the element, and later on the elements “know” that they are prime:

```python
sage: pw = Sets().example("wrapper").an_element()
sage: timeit("pw.is_prime()")  # random
625 loops, best of 3: 859 ns per loop
sage: pi = Sets().example("inherits").an_element()
sage: timeit("pi.is_prime()")  # random
625 loops, best of 3: 854 ns per loop
```

Note also that the `next` method for the elements does not exist:
Unlike in the other implementations:

```python
sage: pw.next()
53
sage: pi.next()
53
```

**element_class**

alias of `Integer`

class `sage.categories.examples.sets_cat.PrimeNumbers_Inherits`

Bases: `PrimeNumbers_Abstract`

An example of parent in the category of sets: the set of prime numbers. In this implementation, the element are stored as object of a new class which inherits from the class `Integer` (technically `IntegerWrapper`).

**EXAMPLES:**

```python
sage: P = Sets().example("inherits")
sage: P
Set of prime numbers
sage: P(12)
Traceback (most recent call last):
...
ValueError: 12 is not a prime number
sage: a = P.an_element()
sage: a.parent()
Set of prime numbers
sage: x = P(13); x
13
sage: x.is_prime()
True
sage: type(x)
<class 'sage.categories.examples.sets_cat.PrimeNumbers_Inherits_with_category.element_class'>
sage: x.parent()
Set of prime numbers
sage: P(13) in P
True
sage: y = x+1; y
14
sage: type(y)
<class 'sage.rings.integer.Integer'>
sage: y.parent()
Integer Ring
sage: type(P(13)+P(17))
<class 'sage.rings.integer.Integer'>
```

(continues on next page)
<class 'sage.categories.examples.sets_cat.PrimeNumbers_Inherits_with_category.
˓element_class'>

sage: z.parent()
Set of prime numbers

sage: TestSuite(P).run(verify=True)
running ._test_an_element() . . . pass
running ._test_cardinality() . . . pass
running ._test_category() . . . pass
running ._test_construction() . . . pass
running ._test_elements() . . .
    Running the test suite of self.an_element()
    running ._test_category() . . . pass
    running ._test_eq() . . . pass
    running ._test_new() . . . pass
    running ._test_not_implemented_methods() . . . pass
    running ._test_pickling() . . . pass
    pass
running ._test_elements_eq_reflexive() . . . pass
running ._test_elements_eq_symmetric() . . . pass
running ._test_elements_eq_transitive() . . . pass
running ._test_elements_neq() . . . pass
running ._test_eq() . . . pass
running ._test_new() . . . pass
running ._test_not_implemented_methods() . . . pass
running ._test_pickling() . . . pass
running ._test_some_elements() . . . pass

See also:

sage: P = Sets().example("facade")
sage: P = Sets().example("inherits")
sage: P = Sets().example("wrapper")

class Element (parent, p)
    Bases: IntegerWrapper, Element
class sage.categories.examples.sets_cat.PrimeNumbers_Wrapper
    Bases: PrimeNumbers_Abstract

An example of parent in the category of sets: the set of prime numbers.

In this second alternative implementation, the prime integer are stored as a attribute of a sage object by inheriting from ElementWrapper. In this case we need to ensure conversion and coercion from this parent and its element to ZZ and Integer.

EXAMPLES:

sage: P = Sets().example("wrapper")
sage: P(12)
Traceback (most recent call last):
  ...
ValueError: 12 is not a prime number
sage: a = P.an_element()
sage: a.parent()
Set of prime numbers (wrapper implementation)
sage: x = P(13); x
class Element
    Bases: ElementWrapper, Element

ElementWrapper
    alias of ElementWrapper

6.29 Example of a set with grading

sage.categories.examples.sets_with_grading.Example
    alias of NonNegativeIntegers
class sage.categories.examples.sets_with_grading.NonNegativeIntegers
    Bases: UniqueRepresentation, Parent

Non negative integers graded by themselves.

EXAMPLES:
sage: E = SetsWithGrading().example(); E
Non negative integers
sage: E in Sets().Infinite()
True
sage: E.graded_component(0)
{0}
sage: E.graded_component(100)
{100}

an_element()
    Return 0.

EXAMPLES:
generating_series\( (\text{var='z'}) \)
Return \(1/(1 - z)\).

EXAMPLES:
```
sage: N = SetsWithGrading().example(); N
Non negative integers
sage: f = N.generating_series(); f
1/(-z + 1)
sage: LaurentSeriesRing(ZZ, 'z')(f)
1 + z + z^2 + z^3 + z^4 + z^5 + z^6 + z^7 + z^8 + z^9 + z^10 + z^11 + z^12 +...
   + z^13 + z^14 + z^15 + z^16 + z^17 + z^18 + z^19 + O(z^20)
```

graded_component\( (\text{grade}) \)
Return the component with grade \text{grade}.

EXAMPLES:
```
sage: N = SetsWithGrading().example()
sage: N.graded_component(65)
{65}
```

grading\( (\text{elt}) \)
Return the grade of \text{elt}.

EXAMPLES:
```
sage: N = SetsWithGrading().example()
sage: N.grading(10)
10
```

6.30 Examples of parents endowed with multiple realizations

class sage.categories.examples.with_realizations.SubsetAlgebra\( (R, S) \)
Bases: UniqueRepresentation, Parent

An example of parent endowed with several realizations

We consider an algebra \(A(S)\) whose bases are indexed by the subsets \(s\) of a given set \(S\). We consider three natural basis of this algebra: \(F\), In, and Out. In the first basis, the product is given by the union of the indexing sets. That is, for any \(s, t \subseteq S\)

\[
F_s F_t = F_{s \cup t}
\]

The In basis and Out basis are defined respectively by:

\[
In_s = \sum_{t \subseteq s} F_t \quad \text{and} \quad F_s = \sum_{t \supset s} \text{Out}_t
\]

Each such basis gives a realization of \(A\), where the elements are represented by their expansion in this basis.

This parent, and its code, demonstrate how to implement this algebra and its three realizations, with coercions and mixed arithmetic between them.

See also:
• Sets().WithRealizations
• the Implementing Algebraic Structures thematic tutorial.

EXAMPLES:

```python
sage: A = Sets().WithRealizations().example(); A
The subset algebra of {1, 2, 3} over Rational Field
sage: A.base_ring()
Rational Field
```

The three bases of A:

```python
sage: F = A.F() ; F
The subset algebra of {1, 2, 3} over Rational Field in the Fundamental basis
sage: In = A.In() ; In
The subset algebra of {1, 2, 3} over Rational Field in the In basis
sage: Out = A.Out(); Out
The subset algebra of {1, 2, 3} over Rational Field in the Out basis
```

One can quickly define all the bases using the following shortcut:

```python
sage: A.inject_shorthands()
Defining F as shorthand for The subset algebra of {1, 2, 3} over Rational Field...
Defining In as shorthand for The subset algebra of {1, 2, 3} over Rational Field...
Defining Out as shorthand for The subset algebra of {1, 2, 3} over Rational Field...
```

Accessing the basis elements is done with basis() method:

```python
sage: F.basis().list()
[F[{}], F[{1}], F[{2}], F[{3}], F[{1, 2}], F[{1, 3}], F[{2, 3}], F[{1, 2, 3}]]
```

To access a particular basis element, you can use the from_set() method:

```python
sage: F.from_set(2,3)
F[{2, 3}]
sage: In.from_set(1,3)
In[{1, 3}]
```

or as a convenient shorthand, one can use the following notation:

```python
sage: F[2,3]
F[{2, 3}]
sage: In[1,3]
In[{1, 3}]
```

Some conversions:

```python
sage: F(In[2,3])
F[{}] + F[{2}] + F[{3}] + F[{2, 3}]
sage: In(F[2,3])
In[{}] - In[{2}] - In[{3}] + In[{2, 3}]
sage: Out(F[3])
Out[{3}] + Out[{1, 3}] + Out[{2, 3}] + Out[{1, 2, 3}]
```

(continues on next page)
We can now mix expressions:

\[
\text{sage: } (1 + \text{Out}[1]) \cdot \text{In}[2, 3]
\]

\[
\text{Out}[] + 2\cdot \text{Out}[1] + 2\cdot \text{Out}[2] + 2\cdot \text{Out}[3] + 2\cdot \text{Out}[1, 2] + 2\cdot \text{Out}[1, 3] + \ldots
\]
\[
\rightarrow 4\cdot \text{Out}[2, 3] + 4\cdot \text{Out}[1, 2, 3]
\]

class Bases (parent_with_realization)

Bases: Category_realization_of_parent

The category of the realizations of the subset algebra
class ParentMethods

Bases: object

from_set (*args)

Construct the monomial indexed by the set containing the elements passed as arguments.

EXAMPLES:

\[
\text{sage: } \text{In} = \text{Sets().WithRealizations().example().In(); In}
\]
The subset algebra of \{1, 2, 3\} over Rational Field in the In basis
\[
\text{sage: } \text{In.from_set}(2, 3)
\]
\[
\text{In}\{2, 3\}
\]

As a shorthand, one can construct elements using the following notation:

\[
\text{sage: } \text{In}[2, 3]
\]
\[
\text{In}\{2, 3\}
\]

one ()

Returns the unit of this algebra.

This default implementation takes the unit in the fundamental basis, and coerces it in \text{self}.

EXAMPLES:

\[
\text{sage: } \text{A = Sets().WithRealizations().example(); A}
\]
The subset algebra of \{1, 2, 3\} over Rational Field
\[
\text{sage: } \text{In = A.In(); Out = A.Out()}
\]
\[
\text{sage: } \text{In.one()}
\]
\[
\text{In}[]
\]
\[
\text{sage: } \text{Out.one()}
\]
\[
\text{Out}[] + \text{Out}[1] + \text{Out}[2] + \text{Out}[3] + \text{Out}[1, 2] + \text{Out}[1, 3] + \ldots
\]
\[
\rightarrow \text{Out}[2, 3] + \text{Out}[1, 2, 3]
\]

super_categories ()

EXAMPLES:
sage: A = Sets().WithRealizations().example(); A
The subset algebra of {1, 2, 3} over Rational Field
sage: C = A.Bases(); C
Category of bases of The subset algebra of {1, 2, 3} over Rational Field
sage: C.super_categories()
[Category of realizations of The subset algebra of {1, 2, 3} over Rational Field,
 Join of Category of algebras with basis over Rational Field and
 Category of commutative algebras over Rational Field and
 Category of realizations of unital magmas]

F

alias of Fundamental
class Fundamental(A)
    Bases: CombinatorialFreeModule, BindableClass
    The Subset algebra, in the fundamental basis
    INPUT:
    • A – a parent with realization in SubsetAlgebra
    EXAMPLES:

sage: A = Sets().WithRealizations().example()
sage: A.F()
The subset algebra of {1, 2, 3} over Rational Field in the Fundamental basis
sage: A.Fundamental()
The subset algebra of {1, 2, 3} over Rational Field in the Fundamental basis

one()

Return the multiplicative unit element.

EXAMPLES:

sage: A = AlgebrasWithBasis(QQ).example()  # needs sage.combinat sage.modules
sage: A.one_basis()
word:
sage: A.one()  # needs sage.combinat sage.modules
B[word: ]

one_basis()

Returns the index of the basis element which is equal to ‘1’.

EXAMPLES:

sage: F = Sets().WithRealizations().example().F(); F
The subset algebra of {1, 2, 3} over Rational Field in the Fundamental basis
sage: F.one_basis()
{}
sage: F.one()
F[{}]
**product_on_basis** *(left, right)*

Product of basis elements, as per `AlgebrasWithBasis.ParentMethods.product_on_basis()`.

**INPUT:**
- `left, right` – sets indexing basis elements

**EXAMPLES:**

```python
sage: F = Sets().WithRealizations().example().F(); F
The subset algebra of {1, 2, 3} over Rational Field in the Fundamental basis
sage: S = F.basis().keys(); S
Subsets of {1, 2, 3}
```

```python
type(S[{}])
```

```python
The subset algebra of {1, 2, 3} over Rational Field
```

```python
sage: F.product_on_basis(S([1]), S([3]))
F[{1, 3}]
```

```python
sage: F.product_on_basis(S({2}), S({3}))
F[{2, 3}]
```

**class In(A)**

**Bases:** `CombinatorialFreeModule, BindableClass`

The Subset Algebra, in the In basis

**INPUT:**
- `A` – a parent with realization in `SubsetAlgebra`

**EXAMPLES:**

```python
sage: A = Sets().WithRealizations().example()
sage: A.In()
The subset algebra of {1, 2, 3} over Rational Field in the In basis
```

**class Out(A)**

**Bases:** `CombinatorialFreeModule, BindableClass`

The Subset Algebra, in the Out basis

**INPUT:**
- `A` – a parent with realization in `SubsetAlgebra`

**EXAMPLES:**

```python
sage: A = Sets().WithRealizations().example()
sage: A.Out()
The subset algebra of {1, 2, 3} over Rational Field in the Out basis
```

**a_realization()**

Returns the default realization of `self`

**EXAMPLES:**

```python
sage: A = Sets().WithRealizations().example(); A
The subset algebra of {1, 2, 3} over Rational Field
sage: A.a_realization()
The subset algebra of {1, 2, 3} over Rational Field in the Fundamental basis
```
\textbf{base\_set}() 

**EXAMPLES:**

```python
sage: A = Sets().WithRealizations().example(); A
The subset algebra of \{1, 2, 3\} over Rational Field
sage: A.base_set()
\{1, 2, 3\}
```

\textbf{indices}() 

The objects that index the basis elements of this algebra.

**EXAMPLES:**

```python
sage: A = Sets().WithRealizations().example(); A
The subset algebra of \{1, 2, 3\} over Rational Field
sage: A.indices()
Subsets of \{1, 2, 3\}
```

\textbf{indices\_key}(x) 

A key function on a set which gives a linear extension of the inclusion order.

**INPUT:**

- \(x\) – set

**EXAMPLES:**

```python
sage: A = Sets().WithRealizations().example(); A
The subset algebra of \{1, 2, 3\} over Rational Field
sage: sorted(A.indices(), key=A.indices_key)
[\{\}, \{1\}, \{2\}, \{3\}, \{1, 2\}, \{1, 3\}, \{2, 3\}, \{1, 2, 3\}]
```

\textbf{supsets}(set) 

Returns all the subsets of \(S\) containing \(set\)

**INPUT:**

- \(set\) – a subset of the base set \(S\) of self

**EXAMPLES:**

```python
sage: A = Sets().WithRealizations().example(); A
The subset algebra of \{1, 2, 3\} over Rational Field
sage: A.supsets(Set((2,)))
[\{\{1, 2, 3\}, \{2\}, \{1, 2\}, \{2\}]
```
7.1 Specific category classes

This is placed in a separate file from categories.py to avoid circular imports (as morphisms must be very low in the hierarchy with the new coercion model).

class sage.categories.category_types.AbelianCategory
    Bases: Category

    is_abelian()
    Return True as self is an abelian category.

    EXAMPLES:
    sage: CommutativeAdditiveGroups().is_abelian()
    True

class sage.categories.category_types.Category_ideal(ambient, name=None)
    Bases: Category_in_ambient

classmethod an_instance()
    Return an instance of this class.

    EXAMPLES:
    sage: AlgebraIdeals.an_instance()
    Category of algebra ideals in Univariate Polynomial Ring in x over Rational
    → Field

    ring()
    Return the ambient ring used to describe objects self.

    EXAMPLES:
    sage: C = Ideals(IntegerRing())
    sage: C.ring()
    Integer Ring

class sage.categories.category_types.Category_in_ambient(ambient, name=None)
    Bases: Category

    Initialize self.
    The parameter name is ignored.

    EXAMPLES:
ambient()

Return the ambient object in which objects of this category are embedded.

EXAMPLES:

```python
sage: C = Ideals(IntegerRing())
sage: C.ambient()
Integer Ring
```

class sage.categories.category_types.Category_module(base, name=None)

Bases: AbelianCategory, Category_over_base_ring

class sage.categories.category_types.Category_over_base(base, name=None)

A base class for categories over some base object

INPUT:

- `base` – a category \( C \) or an object of such a category

Assumption: the classes for the parents, elements, morphisms, of `self` should only depend on \( C \). See [github issue #11935](https://github.com/) for details.

EXAMPLES:

```python
sage: Algebras(GF(2)).element_class is Algebras(GF(3)).element_class
True
sage: C = GF(2).category()
sage: Algebras(GF(2)).parent_class is Algebras(C).parent_class
True
sage: C = ZZ.category()
sage: Algebras(ZZ).element_class is Algebras(C).element_class
True
```

classmethod an_instance()

Returns an instance of this class

EXAMPLES:

```python
sage: Algebras.an_instance()
Category of algebras over Rational Field
```

base()

Return the base over which elements of this category are defined.

EXAMPLES:

```python
sage: C = Algebras(QQ)
sage: C.base()
Rational Field
```
class sage.categories.category_types.Category_over_base_ring(base, name=None)

Bases: Category_over_base

Initialize self.

EXAMPLES:

```
sage: C = Algebras(GF(2)); C
Category of algebras over Finite Field of size 2
sage: TestSuite(C).run()
```

base_ring()  
Return the base ring over which elements of this category are defined.

EXAMPLES:

```
sage: C = Algebras(GF(2))
sage: C.base_ring()
Finite Field of size 2
```

class sage.categories.category_types.Elements(object)

Bases: Category

The category of all elements of a given parent.

EXAMPLES:

```
sage: a = IntegerRing()(5)
sage: C = a.category(); C
Category of elements of Integer Ring
sage: a in C
True
sage: 2/3 in C
False
sage: loads(C.dumps()) == C
True
```

classmethod an_instance()  
Returns an instance of this class

EXAMPLES:

```
sage: Elements.an_instance()
Category of elements of Rational Field
```

object()  
EXAMPLES:

```
sage: Elements(ZZ).object()
Integer Ring
```

super_categories()  
EXAMPLES:

```
sage: Elements(ZZ).super_categories()
[Category of objects]
```
7.2 Singleton categories

class sage.categories.category_singleton.Category_contains_method_by_parent_class

Bases: object

Returns whether \( x \) is an object in this category.

More specifically, returns True if and only if \( x \) has a category which is a subcategory of this one.

EXAMPLES:

```python
sage: ZZ in Sets()
True
```

class sage.categories.category_singleton.Category_singleton

Bases: Category

A base class for implementing singleton category

A singleton category is a category whose class takes no parameters like Fields() or Rings(). See also the Singleton design pattern.

This is a subclass of Category, with a couple optimizations for singleton categories.

The main purpose is to make the idioms:

```python
sage: QQ in Fields()
True
sage: ZZ in Fields()
False
```

as fast as possible, and in particular competitive to calling a constant Python method, in order to foster its systematic use throughout the Sage library. Such tests are time critical, in particular when creating a lot of polynomial rings over small fields like in the elliptic curve code.

EXAMPLES:

```python
sage: from sage.categories.category_singleton import Category_singleton
test::
sage: class MyRings(Category):
....:     def super_categories(self): return Rings().super_categories()

test::
sage: class MyRingsSingleton(Category_singleton):
....:     def super_categories(self): return Rings().super_categories()
```

We create three rings. One of them is contained in the usual category of rings, one in the category of “my rings” and the third in the category of “my rings singleton”:

```python
sage: R = QQ['x,y']
sage: R1 = Parent(category = MyRings())
sage: R2 = Parent(category = MyRingsSingleton())
sage: R in MyRings()
False
sage: R1 in MyRings()
```

(continues on next page)
One sees that containment tests for the singleton class is a lot faster than for a usual class:

```
sage: # not tested
sage: timeit("R in MyRings()", number=10000)
10000 loops, best of 3: 7.12 µs per loop
sage: timeit("R1 in MyRings()", number=10000)
10000 loops, best of 3: 6.98 µs per loop
sage: timeit("R in MyRingsSingleton()", number=10000)
10000 loops, best of 3: 3.08 µs per loop
sage: timeit("R2 in MyRingsSingleton()", number=10000)
10000 loops, best of 3: 2.99 µs per loop
```

So this is an improvement, but not yet competitive with a pure Cython method:

```
sage: timeit("R.is_ring()", number=10000) # not tested
10000 loops, best of 3: 383 ns per loop
```

However, it is competitive with a Python method. Actually it is faster, if one stores the category in a variable:

```
sage: _Rings = Rings()
sage: R3 = Parent(category = _Rings)
sage: R3.is_ring.__module__
'sage.categories.rings'
sage: timeit("R3.is_ring()", number=10000) # not tested
10000 loops, best of 3: 383 ns per loop
sage: timeit("R3 in Rings()", number=10000) # not tested
10000 loops, best of 3: 3.01 µs per loop
sage: timeit("R3 in _Rings", number=10000) # not tested
10000 loops, best of 3: 652 ns per loop
```

This might not be easy to further optimize, since the time is consumed in many different spots:

```
sage: timeit("MyRingsSingleton.__classcall__()", number=10000)# not tested
10000 loops, best of 3: 306 ns per loop
sage: X = MyRingsSingleton()
sage: timeit("R in X ", number=10000) # not tested
10000 loops, best of 3: 699 ns per loop
sage: c = MyRingsSingleton().__contains__
sage: timeit("c(R)", number = 10000) # not tested
10000 loops, best of 3: 661 ns per loop
```

**Warning:** A singleton concrete class $A$ should not have a subclass $B$ (necessarily concrete). Otherwise, creating an instance $a$ of $A$ and an instance $b$ of $B$ would break the singleton principle: $A$ would have two instances $a$ and $b$.

With the current implementation only direct subclasses of `Category_singleton` are supported:
```python
sage: class MyRingsSingleton(Category_singleton):
    ....:    def super_categories(self):
    return Rings().super_categories()
```

sage: class Disaster(MyRingsSingleton):
pass

sage: Disaster()
Traceback (most recent call last):
...
AssertionError: <class '__main__.Disaster'> is not a direct subclass of <class 'sage.categories.category_singleton.Category_singleton'>

However, it is acceptable for a direct subclass $R$ of Category_singleton to create its unique instance as an instance of a subclass of itself (in which case, its the subclass of $R$ which is concrete, not $R$ itself). This is used for example to plug in extra category code via a dynamic subclass:

```python
sage: from sage.categories.category_singleton import Category_singleton
sage: class R(Category_singleton):
    ....:    def super_categories(self):
    return [Sets()]
```

```python
sage: R()
Category of r
```

```python
sage: R().__class__
<class '__main__.R_with_category'>
```

```python
sage: R().__class__.mro()
[<class '__main__.R_with_category'>,
 <class '__main__.R'>,
 <class 'sage.categories.category_singleton.Category_singleton'>,
 <class 'sage.categories.category.Category'>,
 <class 'sage.categories.structure.unique_representation.UniqueRepresentation'>,
 <class 'sage.categories.structure.unique_representation.CachedRepresentation'>,
 <class 'sage.misc.fast_methods.WithEqualityById'>,
 <class 'sage.categories.sage_object.SageObject'>,
 <__main__.Rsubcategory_class>,
 <class 'sage.categories.sets_cat.Setssubcategory_class'>,
 <class 'sage.categories.sets_with_partial_maps.SetsWithPartialMapssubcategory_class'>,
 <class 'sage.categories.objects.Objectssubcategory_class'>,
 <... 'object'>]
```

```python
sage: R() is R()
True
```

```python
sage: R() is R().__class__
True
```

In that case, $R$ is an abstract class and has a single concrete subclass, so this does not break the Singleton design pattern.

See also:

Category.__classcall__, Category.__init__
```

Note: The __test_category test is failing because MyRingsSingleton() is not a subcategory of the join of its super categories:

```python
sage: C = MyRingsSingleton()
sage: C.super_categories()
[Category of rngs, Category of semirings]
sage: Rngs() & Semirings()
Category of rings
sage: C.is_subcategory(Rings())
False
```
Oh well; it's not really relevant for those tests.

## 7.3 Fast functions for the category framework

**AUTHOR:**

- Simon King (initial version)

```python
class sage.categories.category_cy_helper.AxiomContainer
    Bases: dict
    A fast container for axioms.
    This is derived from dict. A key is the name of an axiom. The corresponding value
    is the “rank” of this axiom, that is used to order the axioms in canonicalize_axioms().
```

**EXAMPLES:**

```python
sage: all_axioms = sage.categories.category_with_axiom.all_axioms
sage: isinstance(all_axioms, sage.categories.category_with_axiom.AxiomContainer)
True

sage: add(axiom)
Add a new axiom name, of the next rank.

**EXAMPLES:**

```python
sage: all_axioms = sage.categories.category_with_axiom.all_axioms
sage: m = max(all_axioms.values())
```

```python
sage: all_axioms.add('Awesome')
```

```python
sage: all_axioms['Awesome'] == m + 1
True
```

To avoid side effects, we remove the added axiom:

```python
sage: del all_axioms['Awesome']
```

**sage.categories.category_cy_helper.canonicalize_axioms**(*all_axioms, axioms*)

Canonicalize a set of axioms.

**INPUT:**

- *all_axioms* — all available axioms
- *axioms* — a set (or iterable) of axioms

**Note:** AxiomContainer provides a fast container for axioms, and the collection of axioms is stored in sage.categories.category_with_axiom. In order to avoid circular imports, we expect that the collection of all axioms is provided as an argument to this auxiliary function.

**OUTPUT:**

A set of axioms as a tuple sorted according to the order of the tuple all_axioms in sage.categories.category_with_axiom.

**EXAMPLES:**
```python
sage: from sage.categories.category_with_axiom import canonicalize_axioms, all_axioms
sage: canonicalize_axioms(all_axioms, ['Commutative', 'Connected', 'WithBasis', 'Finite'])
(['Finite', 'Connected', 'WithBasis', 'Commutative'])
sage: canonicalize_axioms(all_axioms, ['Commutative', 'Connected', 'Commutative', 'WithBasis', 'Finite'])
(['Finite', 'Connected', 'WithBasis', 'Commutative'])
```

sage.categories.category_cy_helper.category_sort_key(category)
Return category._cmp_key.

This helper function is used for sorting lists of categories. It is semantically equivalent to `operator.attrgetter()`('_cmp_key'), but currently faster.

EXAMPLES:
```python
sage: from sage.categories.category_cy_helper import category_sort_key
sage: category_sort_key(Rings()) is Rings()._cmp_key
True
```

sage.categories.category_cy_helper.get_axiom_index(all_axioms, axiom)
Helper function: Return the rank of an axiom.

INPUT:
- all_axioms – the axiom collection
- axiom – string, name of an axiom

EXAMPLES:
```python
sage: all_axioms = sage.categories.category_with_axiom.all_axioms
sage: from sage.categories.category_cy_helper import get_axiom_index
sage: get_axiom_index(all_axioms, 'AdditiveCommutative') == all_axioms['AdditiveCommutative']
True
```

sage.categories.category_cy_helper.join_as_tuple(categories, axioms, ignore_axioms)
Helper for `join()`.

INPUT:
- categories – tuple of categories to be joined,
- axioms – tuple of strings; the names of some supplementary axioms.
- ignore_axioms – tuple of pairs (cat, axiom), such that axiom will not be applied to cat, should cat occur in the algorithm.

EXAMPLES:
```python
sage: from sage.categories.category_cy_helper import join_as_tuple
sage: T = (Coalgebras(QQ), Sets().Finite(), Algebras(ZZ), SimplicialComplexes())
```

(continues on next page)
7.4 Coercion methods for categories

The purpose of this Cython module is to hold special coercion methods, which are inserted by their respective categories.

7.5 Poor Man’s map

```python
class sage.categories.poor_man_map.PoorManMap (function, domain=None, codomain=None, name=None)
```

Bases: SageObject

A class for maps between sets which are not (yet) modeled by parents

Could possibly disappear when all combinatorial classes / enumerated sets will be parents

INPUT:

- function – a callable or an iterable of callables. This represents the underlying function used to implement this map. If it is an iterable, then the callables will be composed to implement this map.
- domain – the domain of this map or None if the domain is not known or should remain unspecified
- codomain – the codomain of this map or None if the codomain is not known or should remain unspecified
- name – a name for this map or None if this map has no particular name

EXAMPLES:

```python
sage: from sage.categories.poor_man_map import PoorManMap
sage: f = PoorManMap(factorial, domain=(1, 2, 3), codomain=(1, 2, 6))
sage: f
A map from (1, 2, 3) to (1, 2, 6)
sage: f(3)
6
```

The composition of several functions can be created by passing in a tuple of functions:

```python
sage: i = PoorManMap((factorial, sqrt), domain=(1, 4, 9), codomain=(1, 2, 6))
```

However, the same effect can also be achieved by just composing maps:
sage: g = PoorManMap(factorial, domain=(1, 2, 3), codomain=(1, 2, 6))
sage: h = PoorManMap(sqrt, domain=(1, 4, 9), codomain=(1, 2, 3))
sage: i == g*h
True

codomain()
Returns the codomain of self

EXAMPLES:

```
sage: from sage.categories.poor_man_map import PoorManMap
sage: PoorManMap(lambda x: x+1, domain=(1,2,3), codomain=(2,3,4)).codomain()
(2, 3, 4)
```

domain()
Returns the domain of self

EXAMPLES:

```
sage: from sage.categories.poor_man_map import PoorManMap
sage: PoorManMap(lambda x: x+1, domain=(1,2,3), codomain=(2,3,4)).domain()
(1, 2, 3)
```
CHAPTER
EIGHT

INDICES AND TABLES

- Index
- Module Index
- Search Page
<table>
<thead>
<tr>
<th>Module</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>sage.categories.action</td>
<td>159</td>
</tr>
<tr>
<td>sage.categories.additive_groups</td>
<td>162</td>
</tr>
<tr>
<td>sage.categories.additive_magmas</td>
<td>164</td>
</tr>
<tr>
<td>sage.categories.additive_monoids</td>
<td>175</td>
</tr>
<tr>
<td>sage.categories.additive_semigroups</td>
<td>176</td>
</tr>
<tr>
<td>sage.categories.affine_weyl_groups</td>
<td>178</td>
</tr>
<tr>
<td>sage.categories.algebra_functor</td>
<td>827</td>
</tr>
<tr>
<td>sage.categories.algebra_ideals</td>
<td>181</td>
</tr>
<tr>
<td>sage.categories.algebra_modules</td>
<td>182</td>
</tr>
<tr>
<td>sage.categories.algebras</td>
<td>183</td>
</tr>
<tr>
<td>sage.categories.algebras_with_basis</td>
<td>187</td>
</tr>
<tr>
<td>sage.categories.all</td>
<td>1</td>
</tr>
<tr>
<td>sage.categories.aperiodic_semigroups</td>
<td>192</td>
</tr>
<tr>
<td>sage.categories.associative_algebras</td>
<td>192</td>
</tr>
<tr>
<td>sage.categories.bialgebras</td>
<td>193</td>
</tr>
<tr>
<td>sage.categories.bialgebras_with_basis</td>
<td>194</td>
</tr>
<tr>
<td>sage.categories.bimodules</td>
<td>199</td>
</tr>
<tr>
<td>sage.categories.cartesian_product</td>
<td>823</td>
</tr>
<tr>
<td>sage.categories.category</td>
<td>29</td>
</tr>
<tr>
<td>sage.categories.category_cy_helper</td>
<td>913</td>
</tr>
<tr>
<td>sage.categories.category_singleton</td>
<td>910</td>
</tr>
<tr>
<td>sage.categories.category_types</td>
<td>907</td>
</tr>
<tr>
<td>sage.categories.category_with_axiom</td>
<td>66</td>
</tr>
<tr>
<td>sage.categories.classical_crystals</td>
<td>200</td>
</tr>
<tr>
<td>sage.categories.coalgebras</td>
<td>204</td>
</tr>
<tr>
<td>sage.categories.coalgebras_with_basis</td>
<td>209</td>
</tr>
<tr>
<td>sage.categories.coercion_methods</td>
<td>915</td>
</tr>
<tr>
<td>sage.categories.commutative_additive_groups</td>
<td>212</td>
</tr>
<tr>
<td>sage.categories.commutative_additive_monoids</td>
<td>213</td>
</tr>
<tr>
<td>sage.categories.commutative_additive_semigroups</td>
<td>213</td>
</tr>
<tr>
<td>sage.categories.commutative_algebra_ideals</td>
<td>214</td>
</tr>
<tr>
<td>sage.categories.commutative_algebras</td>
<td>215</td>
</tr>
<tr>
<td>sage.categories.commutative_ring_ideals</td>
<td>215</td>
</tr>
<tr>
<td>sage.categories.commutative_rings</td>
<td>216</td>
</tr>
<tr>
<td>sage.categories.complete_discretevaluation</td>
<td>221</td>
</tr>
<tr>
<td>sage.categories.complex_reflection_groups</td>
<td>225</td>
</tr>
<tr>
<td>sage.categories.complex_reflection_or_generalized_coxeter_groups</td>
<td>227</td>
</tr>
<tr>
<td>sage.categories.covariant_functorial_construction</td>
<td>817</td>
</tr>
<tr>
<td>sage.categories.coxeter_group_algebras</td>
<td>243</td>
</tr>
<tr>
<td>sage.categories.coxeter_groups</td>
<td>246</td>
</tr>
<tr>
<td>sage.categories.crystals</td>
<td>283</td>
</tr>
<tr>
<td>sage.categories.cw_complexes</td>
<td>306</td>
</tr>
<tr>
<td>sage.categories.discretevaluation</td>
<td>309</td>
</tr>
<tr>
<td>sage.categories.distributive_magmas_and_additive_magmas</td>
<td>312</td>
</tr>
<tr>
<td>sage.categories.division_rings</td>
<td>313</td>
</tr>
<tr>
<td>sage.categories.domains</td>
<td>314</td>
</tr>
<tr>
<td>sage.categories.dual</td>
<td>827</td>
</tr>
<tr>
<td>sage.categories.enumerated_sets</td>
<td>315</td>
</tr>
<tr>
<td>sage.categories.euclidean_domains</td>
<td>321</td>
</tr>
<tr>
<td>sage.categories.examples.algebras_with_basis</td>
<td>847</td>
</tr>
<tr>
<td>sage.categories.examples.commutative_additive_monoids</td>
<td>848</td>
</tr>
<tr>
<td>sage.categories.examples.commutative_additive_semigroups</td>
<td>849</td>
</tr>
<tr>
<td>sage.categories.examples.coxeter_groups</td>
<td>851</td>
</tr>
<tr>
<td>sage.categories.examples.cw_complexes</td>
<td>853</td>
</tr>
<tr>
<td>sage.categories.examples.facade_sets</td>
<td>854</td>
</tr>
<tr>
<td>sage.categories.examples.finite_coxeter_groups</td>
<td>855</td>
</tr>
<tr>
<td>sage.categories.examples.finite_dimensional_algebras_with_basis,</td>
<td></td>
</tr>
</tbody>
</table>
sage.categories.graded_bialgebras, 499
sage.categories.graded_bialgebras_with_basis, 499
sage.categories.graded_coalgebras, 500
sage.categories.graded_coalgebras_with_basis, 500
sage.categories.graded_hopf_algebras, 501
sage.categories.graded_hopf_algebras_with_basis, 501
sage.categories.graded_lie_algebras, 503
sage.categories.graded_lie_algebras_with_basis, 504
sage.categories.graded_lie_conformal_algebras, 505
sage.categories.graded_modules, 505
sage.categories.graded_modules_with_basis, 507
sage.categories.graphs, 512
sage.categories.group_algebras, 513
sage.categories.groupoid, 518
sage.categories.groups, 519
sage.categories.h_trivial_semigroups, 542
sage.categories.hecke_modules, 528
sage.categories.highest_weight_crystals, 529
sage.categories.homset, 115
sage.categories.homsets, 836
sage.categories.hopf_algebras, 536
sage.categories.hopf_algebras_with_basis, 538
sage.categories.infinite enumerated_sets, 543
sage.categories.integral_domains, 544
sage.categories.isomorphic_objects, 835
sage.categories.j_trivial_semigroups, 545
sage.categories.kac_moody_algebras, 545
sage.categories.l_trivial_semigroups, 545
sage.categories.lambda_bracket_algebras, 546
sage.categories.lambda_bracket_algebras_with_basis, 548
sage.categories.lattice_posets, 550
sage.categories.left_modules, 551
sage.categories.lie_algebras, 551
sage.categories.lie_algebras_with_basis, 564
sage.categories.lie_conformal_algebras, 567
sage.categories.lie_conformal_algebras_with_basis, 570
sage.categories.lie_groups, 572
sage.categories.loop_crystals, 573
sage.categories.magnas, 586
sage.categories.magnas_and_additive_magnas, 600
sage.categories.magmatic_algebras, 602
sage.categories.manifolds, 606
sage.categories.map, 105
sage.categories.metric_spaces, 611
sage.categories.modular_abelian_varieties, 615
sage.categories.modules, 616
sage.categories.modules_with_basis, 628
sage.categories.monoid_algebras, 657
sage.categories.monoids, 658
sage.categories.morphism, 123
sage.categories.number_fields, 665
sage.categories.objects, 667
sage.categories.partiallyOrdered_monoids, 668
sage.categories.permutation_groups, 669
sage.categories.pointed_sets, 670
sage.categories.polyhedra, 670
sage.categories.posets, 670
sage.categories.primer, 3
sage.categories.principal_ideal_domains, 680
sage.categories.pushout, 127
sage.categories.quantum_group_representations, 687
sage.categories.quotient_fields, 681
sage.categories.quotients, 834
sage.categories.r_trivial_semigroups, 715
sage.categories.realizations, 840
sage.categories.regular_crystals, 693
sage.categories.regular_supercrystals, 701
sage.categories.right_modules, 702
sage.categories.schemes, 703
sage.categories.rings, 704
sage.categories.rngs, 714
sage.categories.semigroups, 715
sage.categories.semirings, 717
sage.categories.semisimple_algebras, 730
sage.categories.sets_cat, 732
sage.categories.shephard_groups, 762
sage.categories.signed_tensor, 826
Category Framework, Release 10.3

sage.categories.simplicial_complexes,
    762
sage.categories.simplicial_sets, 764
sage.categories.subobjects, 835
sage.categories.subquotients, 834
sage.categories.super_algebras, 776
sage.categories.super_algebras_with_basis, 778
sage.categories.super_hopf_algebras_with_basis, 780
sage.categories.super_lie_conformal_algebras, 780
sage.categories.super_modules, 782
sage.categories.super_modules_with_basis, 784
sage.categories.supercommutative_algebras, 786
sage.categories.supercrystals, 787
sage.categories.tensor, 825
sage.categories.topological_spaces, 792
sage.categories.triangular_kac_moody_algebras, 793
sage.categories.tutorial, 103
sage.categories.unique_factorization_domains, 795
sage.categories.unital_algebras, 797
sage.categories.vector_bundles, 800
sage.categories.vector_spaces, 801
sage.categories.weyl_groups, 805
sage.categories.with_realizations, 842
### Non-alphabetical

<table>
<thead>
<tr>
<th>Method</th>
<th>Class/Category</th>
<th>Category</th>
<th>Line</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>__classcall__()</code></td>
<td><code>sage.categories.category_with_axiom.CategoryWithAxiom.static method</code></td>
<td>90</td>
<td></td>
</tr>
<tr>
<td><code>__classcall__()</code></td>
<td><code>sage.categories.category.Category.static method</code></td>
<td>42</td>
<td></td>
</tr>
<tr>
<td><code>__classget__()</code></td>
<td><code>sage.categories.category_with_axiom.CategoryWithAxiom.static method</code></td>
<td>90</td>
<td></td>
</tr>
<tr>
<td><code>__init__()</code></td>
<td><code>sage.categories.category_with_axiom.CategoryWithAxiom.method</code></td>
<td>91</td>
<td></td>
</tr>
<tr>
<td><code>__init__()</code></td>
<td><code>sage.categories.category.Category.method</code></td>
<td>42</td>
<td></td>
</tr>
<tr>
<td><code>_all_super_categories()</code></td>
<td><code>sage.categories.category.Category.method</code></td>
<td>36</td>
<td></td>
</tr>
<tr>
<td><code>_all_super_categories_proper()</code></td>
<td><code>sage.categories.category.Category.method</code></td>
<td>36</td>
<td></td>
</tr>
<tr>
<td><code>_make_named_class()</code></td>
<td><code>sage.categories.category.Category.method</code></td>
<td>37</td>
<td></td>
</tr>
<tr>
<td><code>_make_named_class()</code></td>
<td><code>sage.categories.category.CategoryWithParameters.Category.method</code></td>
<td>61</td>
<td></td>
</tr>
<tr>
<td><code>_repr_()</code></td>
<td><code>sage.categories.category.Category.method</code></td>
<td>38</td>
<td></td>
</tr>
<tr>
<td><code>_repr_()</code></td>
<td><code>sage.categories.category.JoinCategory.Category.method</code></td>
<td>63</td>
<td></td>
</tr>
<tr>
<td><code>_repr_object_names()</code></td>
<td><code>sage.categories.category_with_axiom.CategoryWithAxiom.Category.method</code></td>
<td>91</td>
<td></td>
</tr>
<tr>
<td><code>_repr_object_names()</code></td>
<td><code>sage.categories.category.Category.method</code></td>
<td>38</td>
<td></td>
</tr>
<tr>
<td><code>_repr_object_names()</code></td>
<td><code>sage.categories.category.JoinCategory.Category.method</code></td>
<td>63</td>
<td></td>
</tr>
<tr>
<td><code>_repr_object_names_static()</code></td>
<td><code>sage.categories.category_with_axiom.CategoryWithAxiom.static method</code></td>
<td>92</td>
<td></td>
</tr>
<tr>
<td><code>_set_of_super_categories()</code></td>
<td><code>sage.categories.category.Category.method</code></td>
<td>37</td>
<td></td>
</tr>
<tr>
<td><code>_sort()</code></td>
<td><code>sage.categories.category.Category.static method</code></td>
<td>40</td>
<td></td>
</tr>
<tr>
<td><code>_sort_uniq()</code></td>
<td><code>sage.categories.category.Category.static method</code></td>
<td>41</td>
<td></td>
</tr>
<tr>
<td><code>_super_categories()</code></td>
<td><code>sage.categories.category.Category.method</code></td>
<td>35</td>
<td></td>
</tr>
<tr>
<td><code>_super_categories_for_classes()</code></td>
<td><code>sage.categories.category.Category.method</code></td>
<td>35</td>
<td></td>
</tr>
<tr>
<td><code>_test_category()</code></td>
<td><code>sage.categories.category.Category.method</code></td>
<td>38</td>
<td></td>
</tr>
<tr>
<td><code>_test_category_with_axiom()</code></td>
<td><code>sage.categories.category_with_axiom.CategoryWithAxiom.Category.method</code></td>
<td>92</td>
<td></td>
</tr>
<tr>
<td><code>_with_axiom()</code></td>
<td><code>sage.categories.category.Category.method</code></td>
<td>39</td>
<td></td>
</tr>
<tr>
<td><code>_with_axiom_as_tuple()</code></td>
<td><code>sage.categories.category.Category.method</code></td>
<td>40</td>
<td></td>
</tr>
<tr>
<td><code>_without_axioms()</code></td>
<td><code>sage.categories.category_with_axiom.CategoryWithAxiom.Category.method</code></td>
<td>93</td>
<td></td>
</tr>
<tr>
<td><code>_without_axioms()</code></td>
<td><code>sage.categories.category.Category.method</code></td>
<td>40</td>
<td></td>
</tr>
<tr>
<td><code>_without_axioms()</code></td>
<td><code>sage.categories.category.JoinCategory.Category.method</code></td>
<td>63</td>
<td></td>
</tr>
</tbody>
</table>

### A

<table>
<thead>
<tr>
<th>Method</th>
<th>Class/Category</th>
<th>Category</th>
<th>Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>a_realization()</td>
<td><code>sage.categories.examples.with_realizations.SubsetAlgebra.method</code></td>
<td>904</td>
<td></td>
</tr>
<tr>
<td>AbelianCategory</td>
<td><code>class in sage.categories.category_types</code></td>
<td>907</td>
<td></td>
</tr>
<tr>
<td>AbelianLieAlgebra</td>
<td><code>class in sage.categories.examples.finite_dimensional_lie_algebras_with_basis</code></td>
<td>858</td>
<td></td>
</tr>
<tr>
<td>AbelianLieAlgebra</td>
<td><code>class in sage.categories.examples.lie_algebras_with_basis</code></td>
<td>879</td>
<td></td>
</tr>
<tr>
<td>AbelianLieAlgebra.Element</td>
<td><code>class in sage.categories.examples.finite_dimensional_lie_algebras_with_basis</code></td>
<td>859</td>
<td></td>
</tr>
<tr>
<td>AbelianLieAlgebra.Element</td>
<td><code>class in sage.categories.examples.lie_algebras_with_basis</code></td>
<td>879</td>
<td></td>
</tr>
<tr>
<td>AbelianVarieties</td>
<td><code>class in sage.categories.schemes</code></td>
<td>715</td>
<td></td>
</tr>
<tr>
<td>AbelianVarieties.Homsets</td>
<td><code>class in sage.categories.schemes</code></td>
<td>715</td>
<td></td>
</tr>
<tr>
<td>AbelianVarieties.Homsets.Endset</td>
<td><code>class in sage.categories.schemes</code></td>
<td>715</td>
<td></td>
</tr>
</tbody>
</table>
abs() (sage.categories.metric_spaces.MetricSpaces.ElementMethods method), 612
absolute_chain() (sage.categories.coxeter_groups.CoxeterGroups.ElementMethods method), 247
absolute_chain_reflections() (sage.categories.coxeter_groups.CoxeterGroups.ElementMethods method), 247
absolute_covers() (sage.categories.coxeter_groups.CoxeterGroups.ElementMethods method), 248
absolute_le() (sage.categories.coxeter_groups.CoxeterGroups.ElementMethods method), 249
absolute_length() (sage.categories.coxeter_groups.CoxeterGroups.ElementMethods method), 249
absolute_length() (sage.categories.finite_coxeter_groups.FiniteCoxeterGroups.ElementMethods method), 374
absolute_order_ideal() (sage.categories.finite_complex_reflection_groups.FiniteComplexReflectionGroups.Irreducible.ParentMethods method), 358
absolute_poset() (sage.categories.finite_complex_reflection_groups.FiniteComplexReflectionGroups.Irreducible.ParentMethods method), 359
act() (sage.categories.action.Action method), 160
Action (class in sage.categories.action), 159
ActionEndomorphism (class in sage.categories.action), 160
actor() (sage.categories.action.Action method), 160
adams_operator() (sage.categories.bialgebras_with_basis.BialgebrasWithBasis.ElementMethods method), 194
add() (sage.categories.category_cy_helper.AxiomContainer method), 913
addition_table() (sage.categories.additive_magmas.AdditiveMagmas.ParentMethods method), 170
additional_structure() (sage.categories.additive_magmas.AdditiveMagmas.AdditiveUnital method), 168
additional_structure() (sage.categories.affine_weyl_groups.AffineWeylGroups method), 181
additional_structure() (sage.categories.bialgebras.Bialgebras method), 194
additional_structure() (sage.categories.bimodules.Bimodules method), 199
additional_structure() (sage.categories.category_with_axiom.CategoryWithAxiom method), 93
additional_structure() (sage.categories.category_with_axiom.CategoryWithAxiom method), 93
gory.Category method), 47
additional_structure() (sage.categories.cohomology.Homology method), 56
additional_structure() (sage.categories.classical_crystals.ClassicalCrystals method), 203
additional_structure() (sage.categories.complex_reflection_groups.ComplexReflectionGroups method), 226
additional_structure() (sage.categories.complex_reflection_groups.ComplexReflectionGroups method), 226
additional_structure() (sage.categories.covariant_functorial_construction.CovariantConstructionCategory method), 817
additional_structure() (sage.categories.coxeter_groups.CoxeterGroups method), 283
additional_structure() (sage.categories.enumerated_sets.EnumeratedSets method), 321
additional_structure() (sage.categories.gcd_domains.GcdDomains method), 493
additional_structure() (sage.categories.generalized_coxeter_groups.GeneralizedCoxeterGroups method), 495
additional_structure() (sage.categoriesighest_weight_crystals.HighestWeightCrystals method), 535
additional_structure() (sage.categories.lie_groups.LieGroups method), 572
additional_structure() (sage.categories.magmas_and_additive_magmas.MagmasAndAdditiveMagmas method), 602
additional_structure() (sage.categories.magmas.Magmas.Unital method), 600
additional_structure() (sage.categories.magmatic_algebras.MagmaticAlgebras method), 605
additional_structure() (sage.categories.manifolds.Manifolds method), 610
additional_structure() (sage.categories.modules.Modules method), 627
additional_structure() (sage.categories.objects.Objects method), 668
additional_structure() (sage.categories.principal_ideal_domains.PrincipalIdealDomains method), 680
additional_structure() (sage.categories.regular_crystals.RegularCrystals method), 700
additional_structure() (sage.categories.unique_factorization_domains.UniqueFactorizationDomains method), 797
additional_structure() (sage.categories.vector_spaces.VectorSpaces method), 805
additional_structure() (sage.categories.weyl_groups.WeylGroups method), 815
additional_order() (sage.categories.commutative_additive_groups.CommutativeAdditive-
Algebras (class in sage.categories.algebras), 183
Algebras (sage.categories.coxeter_groups.CoxeterGroups attribute), 247
Algebras (sage.categories.groups.Groups attribute), 519
Algebras() (sage.categories.sets_cat.Sets.Subcategories method), 744
Algebras.Category CartesianProducts (class in sage.categories.algebras), 183
AlgebrasCategory (class in sage.categories.algebra_functor), 832
AlgebrasCategory.ParentMethods (class in sage.categories.algebras), 184
Algebras.ElementMethods (class in sage.categories.algebras), 184
Algebras.ParentMethods (class in sage.categories.algebras), 184
Algebras.Quotients (class in sage.categories.algebras), 185
Algebras.Quotients.ParentMethods (class in sage.categories.algebras), 185
Algebras.SubcategoryMethods (class in sage.categories.algebras), 185
Algebras.TensorProducts (class in sage.categories.algebras), 186
Algebras.TensorProducts.ElementMethods (class in sage.categories.algebras), 186
Algebras.TensorProducts.ParentMethods (class in sage.categories.algebras), 186
AlgebrasWithBasis (class in sage.categories.algebras), 187
AlgebrasWithBasis.CartesianProducts (class in sage.categories.algebras), 188
AlgebrasWithBasis.CartesianProducts.ParentMethods (class in sage.categories.algebras), 188
AlgebrasWithBasis.ElementMethods (class in sage.categories.algebras), 189
AlgebrasWithBasis.ParentMethods (class in sage.categories.algebras), 189
AlgebrasWithBasis.TensorProducts (class in sage.categories.algebras), 190
AlgebrasWithBasis.TensorProducts.ElementMethods (class in sage.categories.algebras), 190
AlgebrasWithBasis.TensorProducts.ParentMethods (class in sage.categories.algebras), 190
all_paths_to_highest_weight() (sage.categories.crystals.Crystals.ElementMethods method), 290
all_super_categories() (sage.categories.category attribute), 49
AlmostComplex() (sage.categories.manifolds.Manifolds.SubcategoryMethods method), 608
ambient() (sage.categories.category_types.Category_in_ambient method), 908
ambient() (sage.categories.examples.finite_dimensional_lie_algebras_with_basis.AbelianLieAlgebra method), 859
ambient() (sage.categories.examples.finite EnumeratedSets.IsomorphicObjectOfFiniteEnumeratedSet method), 863
ambient() (sage.categories.examples.semigroups.IncompleteSubquotientSemigroup method), 888
ambient() (sage.categories.examples.semigroups.QuotientOfLeftZeroSemigroup method), 890
ambient() (sage.categories.finite_dimensional_lie_algebras_with_basis.FiniteDimensionalLieAlgebrasWithBasis.Subobjects.ParentMethods method), 428
ambient() (sage.categories.sets_cat.Sets.Subquotients.ParentMethods method), 753
an_element() (sage.categories.examples.commutative_additive_semigroups.FreeCommutativeAdditiveSemigroup method), 851
an_element() (sage.categories.examples.crystals.Crystals.ElementMethods method), 854
an_element() (sage.categories.examples.finite_monoids.IntegerModMonoid method), 865
an_element() (sage.categories.examples.finite_semigroups.LeftRegularBand method), 867
an_element() (sage.categories.examples.graphs.Cycle method), 874
an_element() (sage.categories.examples.infiniteEnumeratedSets.NonNegativeIntegers method), 878
an_element() (sage.categories.examples.magmas.FiniteMagma method), 882
an_element() (sage.categories.examples.manifolds.Plane method), 883
an_element() (sage.categories.examples.posets.FiniteSetsOrderedByInclusion method), 885
an_element() (sage.categories.examples.semigroups.FreeSemigroup method), 887
an_element() (sage.categories.examples.semigroups.LeftZeroSemigroup method), 889
an_element() (sage.categories.examples.semigroups.QuotientOfLeftZeroSemigroup method), 890
an_element() (sage.categories.examples.sets_cat.PrimeNumbers method), 894
an_element() (sage.categories.examples.sets_cat.PrimeNumbers method), 894

Index 927
meNumbers_Abstract method), 895
antipode_on_basis() (sage.categories.enumerations.NonNegativeIntegers method), 889
antipode_on_basis() (sage.categories.sets_cat.SetsWithGrading.NonNegativeIntegers method), 736
antipode_on_basis() (sage.categories.sets_cat.SetsWithGrading.SetWithGrading method), 741
antipode_on_basis() (sage.categories.algebra_modules.AlgebraModules class method), 182
antipode_on_basis() (sage.categories.category_types.Category class method), 199
antipode_on_basis() (sage.categories.category_types.Category class method), 50
antipode_on_basis() (sage.categories.g_sets.GSets class method), 493
antipode_on_basis() (sage.categories.g_sets.GSets class method), 519
Analytic() (sage.categories.g_sets.GSets.SubcategoryMethods method), 608
annihilator() (sage.categories.finite_dimensional_modules_with_basis.FiniteDimensionalModulesWithBasis.ParentMethods method), 432
annihilator_basis() (sage.categories.finite_dimensional_modules_with_basis.FiniteDimensionalModulesWithBasis.ParentMethods method), 433
antipode_on_basis() (sage.categories.group_algebras.GroupAlgebras.PARENTMethods method), 515
antipode_on_basis() (sage.categories.hopf_algebras_with_basis.HopfAlgebrasWithBasis.PARENTMethods method), 541
Aperiodic (sage.categories.semigroups.Semigroups attribute), 720
Aperiodic() (sage.categories.semigroups.Semigroups.SubcategoryMethods method), 726
AperiodicSemigroups (class in sage.categories.aperiodic_semigroups), 192
apply_simple_reflection() (sage.categories.complex_reflection_or_generalized_coxeter_groups.ComplexReflectionOrGeneralizedCoxeterGroups.ElementMethods method), 228
apply_demazure_product() (sage.categories.coxeter_groups.CoxeterGroups.ElementMethods method), 250
apply_multilinear_morphism() (sage.categories.modules_with_basis.ModulesWithBasis.TensorProducts.ElementMethods method), 655
apply_reflections() (sage.categories.complex_reflection_or_generalized_coxeter_groups.ComplexReflectionOrGeneralizedCoxeterGroups.ElementMethods method), 228
apply_simple_projection() (sage.categories.coxeter_groups.CoxeterGroups.ElementMethods method), 250
apply_simple_reflection() (sage.categories.complex_reflection_or_generalized_coxeter_groups.ComplexReflectionOrGeneralizedCoxeterGroups.ElementMethods method), 229
apply_simple_reflection_left() (sage.categories.complex_reflection_or_generalized_coxeter_groups.ComplexReflectionOrGeneralizedCoxeterGroups.ElementMethods method), 230
apply_simple_reflection_right() (sage.categories.complex_reflection_or_generalized_coxeter_groups.ComplexReflectionOrGeneralizedCoxeterGroups.ElementMethods method), 231
apply_simple_reflection_right() (sage.categories.hopf_algebras_with_basis.MyGroupAlgebra method), 875
as_finite_dimensional_algebra() (sage.catego-
Associative (sage.categories.magma.Magma.attribute), 587
Associative (sage.categories.magnetic_algebras.MagnaticAlgebras attribute), 603
Associative() (sage.categories.magma.Magma.SubcategoryMethods method), 594
AssociativeAlgebras (class in sage.categories.associative_algebras), 192
axiom() (in module sage.categories.category_with_axiom), 96
axiom_of_nested_class() (in module sage.categories.category_with_axiom), 97
AxiomContainer (class in sage.categories.category_with_axiom), 913
axioms() (sage.categories.category_with_axiom.CategoryWithAxiom method), 93
axioms() (sage.categories.category.Category method), 50

B

b_sharp() (sage.categories.loop_crystals.KirillovReshetikhinCrystals.ParentMethods method), 575
baker_campbell_hausdorff() (sage.categories.algebras.LieAlgebra.ParentMethods method), 555
Bars (class in sage.categories.category_with_axiom), 88
base() (sage.categories.category_types.CategoryOverBase method), 908
base() (sage.categories.homsets.HomsetsCategory method), 838
base() (sage.categories.associative_algebras.TensorProductsCategory method), 826
base() (sage.categories.algebras_with_basis.GradedPartitionModuleParentMethods method), 825
base_category() (sage.categories.category_with_axiom.CategoryWithAxiom method), 94
base_category() (sage.categories.functorial_construction.FunctorialConstructionCategory method), 821
base_category_class_and_axiom() (in module sage.categories.category_with_axiom), 97
base_change_matrix() (sage.categories.associative_algebras.FiniteComplexReflectionGroups.ParentMethods method), 361
base_field() (sage.categories.modular_abelian_varieties.ModularAbelianVarieties method), 615
base_field() (sage.categories.algebra_functor.AlgebraFunctor method), 832
base_ring() (sage.categories.associative_algebras.associative_algebras_with_basis.SubcategoryMethods method), 603
base_point() (sage.categories.category_with_axiom.CategoryWithAxiom method), 767
base_point_map() (sage.categories.simplicial_sets.SimplicialSets.Pointed.ParentMethods method), 768
base_ring() (sage.categories.algebra_functor.AlgebraFunctor method), 832
base_ring() (sage.categories.cartesian_product.CartesianProductsCategory method), 824
base_ring() (sage.categories.category_types.CategoryOverBaseRing method), 909
base_ring() (sage.categories.modules.Modules.Homsets method), 620
base_ring() (sage.categories.modules.Modules.SubcategoryMethods method), 625
base_scheme() (sage.categories.schemes.Schemes_over_base_scheme method), 717
base_set() (sage.categories.examples.with_realizations.SubsetAlgebra method), 904
base_space() (sage.categories.schemes.schemes_pointed_schemes.OverBase method), 801
basis() (sage.categories.examples.finite_dimensional_lie_algebras_with_basis.AbelianLieAlgebra method), 859
basis() (sage.categories.modules_with_module_bases_modules_with_basics.FilteredModulesWithBasis.ParentMethods method), 872
basis() (sage.categories.modules_with_module_bases_modules_with_basics.FilteredModulesWithBasis.ParentMethods method), 346
basis() (sage.categories.modules_with_module_bases_modules_with_basics.FilteredModulesWithBasis.ParentMethods method), 642
basis_matrix() (sage.categories.examples.finite_dimensional_lie_algebras_with_basis.AbelianLieAlgebra method), 860
basis_matrix() (sage.categories.examples.finite_dimensional_lie_algebras_with_basis.AbelianLieAlgebra method), 428
bch() (sage.categories.algebras_with_basis.LieAlgebras.ParentMethods method), 556
bhz_poset() (sage.categories.finite_coxeter_groups.FiniteCoxeterGroups.ParentMethods method), 377
Bialgebras (class in sage.categories.bialgebras), 193
Bialgebras.ElementMethods (class in sage.categories.bialgebras), 193
Bialgebras.Super (class in sage.categories.bialgebras), 193
BialgebrasWithBasis (class in sage.categories.bialgebras_with_basics), 194
BialgebrasWithBasis.ElementMethods (class
in sage.categories.bialgebras_with_basis), 194
BialgebrasWithBasis.ParentMethods (class in sage.categories.bialgebras_with_basis), 197
Bimodules (class in sage.categories.bimodules), 199
Bimodules.ElementMethods (class in sage.categories.bimodules), 199
Bimodules.ParentMethods (class in sage.categories.bimodules), 199
binary_factorizations() (sage.categories.lambda_bracket_algebras.LambdaBracketAlgebras.ElementMethods method), 251
birational_free_labelling() (sage.categories.finite_posets.FinitePosets.ParentMethods method), 462
birational_rowmotion() (sage.categories.finite_posets.FinitePosets.ParentMethods method), 466
birational_toggle() (sage.categories.finite_posets.FinitePosets.ParentMethods method), 468
birational_toggles() (sage.categories.finite_posets.FinitePosets.ParentMethods method), 470
BlackBoxConstructionFunctor (class in sage.categories.pushout), 130
Blahs (class in sage.categories.category_with_axiom), 89
Blahs.Categorical (class in sage.categories.category_with_axiom), 89
Blahs.Connected (class in sage.categories.category_with_axiom), 89
Blahs.FiniteDimensional (class in sage.categories.category_with_axiom), 89
Blahs.Flying (class in sage.categories.category_with_axiom), 89
Blahs.SubcategoryMethods (class in sage.categories.category_with_axiom), 90
Blahs.Unital (class in sage.categories.category_with_axiom), 90
Blahs.Unital.Blue (class in sage.categories.category_with_axiom), 90
Blue () (sage.categories.category_with_axiom.Blahs.SubcategoryMethods method), 90
Blue_extra_super_categories () (sage.categories.category_with_axiom.Blahs method), 89
bracket() (sage.categories.lambda_bracket_algebras.LambdaBracketAlgebras.ElementMethods method), 546
bracket() (sage.categories.lie_algebras.LieAlgebras.ElementMethods method), 552
bracket() (sage.categories.lie_algebras.LieAlgebras.ParentMethods method), 557
bracket() (sage.categories.rings.Rings.ParentMethods method), 707
bracket_on_basis() (sage.categories.examples.lie_algebras_with_basis.AbelianLieAlgebra method), 880
bracket_on_basis() (sage.categories.lie_algebras_with_basis.LieAlgebrasWithBasis.ParentMethods method), 565
braid_group_as_finitely_presented_group() (sage.categories.coxeter_groups.CoxeterGroups.ParentMethods method), 270
braid_orbit() (sage.categories.coxeter_groups.CoxeterGroups.ParentMethods method), 271
braid_orbit_iter() (sage.categories.coxeter_groups.CoxeterGroups.ParentMethods method), 272
braid_relations() (sage.categories.coxeter_groups.CoxeterGroups.ParentMethods method), 272
bruhat_cone() (sage.categories.weyl_groups.WeylGroups.ParentMethods method), 812
bruhat_graph() (sage.categories.coxeter_groups.CoxeterGroups.ParentMethods method), 272
bruhat_interval() (sage.categories.coxeter_groups.CoxeterGroups.ParentMethods method), 273
bruhat_interval_poset() (sage.categories.coxeter_groups.CoxeterGroups.ParentMethods method), 274
bruhat_le() (sage.categories.coxeter_groups.CoxeterGroups.ElementMethods method), 252
bruhat_lower_covers() (sage.categories.coxeter_groups.CoxeterGroups.ElementMethods method), 252
bruhat_lower_covers_coroots() (sage.categories.weyl_groups.WeylGroups.ElementMethods method), 806
bruhat_lower_covers_reflections() (sage.categories.coxeter_groups.CoxeterGroups.ElementMethods method), 253
bruhat_poset() (sage.categories.finite_coxeter_groups.FiniteCoxeterGroups.ElementMethods method), 377
bruhat_upper_covers() (sage.categories.coxeter_groups.CoxeterGroups.ElementMethods method), 253
bruhat_upper_covers() (sage.categories.finite_coxeter_groups.FiniteCoxeterGroups.ElementMethods method), 374
bruhat_upper_covers_coroots() (sage.categories.weyl_groups.WeylGroups.ElementMethods method), 806
bruhat_upper_covers_reflections() (sage.categories.coxeter_groups.CoxeterGroups.ElementMethods method), 254
Index

Category() (sage.categories.morphism.Morphism method), 124
Category_contains_method_by_parent_class (class in sage.categories.category_singleton), 910
category_for() (sage.categories.map.Map method), 110
category_from_categories() (sage.categories.covariant_functorial_construction.CovariantFunctorialConstruction method), 820
category_from_category() (sage.categories.covariant_functorial_construction.CovariantFunctorialConstruction method), 820
category_from_parents() (sage.categories.covariant_functorial_construction.CovariantFunctorialConstruction method), 821
category_graph() (in module sage.categories.category), 64
category_graph() (sage.categories.category.Category method), 51
Category_ideal (class in sage.categories.category_types), 907
Category_in_ambient (class in sage.categories.category_types), 907
Category_module (class in sage.categories.category_types), 908
category_of() (sage.categories.covariant_functorial_construction.FunctorialConstructionCategory class method), 821
Category_over_base (class in sage.categories.category_types), 908
Category_over_base_ring (class in sage.categories.category_types), 908
Category_realization_of_parent (class in sage.categories.realizations), 840
category_sample() (in module sage.categories.category), 65
Category_singleton (class in sage.categories.category_singleton), 910
category_sort_key() (in module sage.categories.category_cy_helper), 914
CategoryWithAxiom (class in sage.categories.category_with_axiom), 90
CategoryWithAxiom_over_base_ring (class in sage.categories.category_with_axiom), 95
CategoryWithAxiom_singleton (class in sage.categories.category_with_axiom), 95
CategoryWithParameters (class in sage.categories.category), 61
cayley_graph() (sage.categories.semisigroups.Semigroups.ParentMethods method), 720
cayley_graph_disabled() (sage.categories.finite_groups.FiniteGroups.ParentMethods method), 450
cayley_table() (sage.categories.groups.Groups.ParentMethods method), 522
cell_module() (sage.categories.finite_dimensional_algebras_with_basis.FiniteDimensionalAlgebrasWithBasis.Cellular.ParentMethods method), 389
cell_module_indices() (sage.categories.finite_dimensional_algebras_with_basis.FiniteDimensionalAlgebrasWithBasis.Cellular.ParentMethods method), 389
cell_poset() (sage.categories.finite_dimensional_algebras_with_basis.FiniteDimensionalAlgebrasWithBasis.Cellular.ParentMethods method), 390
cells() (sage.categories.cw_complexes.CWComplexes.ParentMethods method), 308
cells() (sage.categories.examples.cw_complexes.Surface method), 854
cells() (sage.categories.finite_dimensional_algebras_with_basis.FiniteDimensionalAlgebrasWithBasis.Cellular.ParentMethods method), 390
Cellular() (sage.categories.finite_dimensional_algebras_with_basis.FiniteDimensionalAlgebrasWithBasis.SubcategoryMethods method), 407
cellular_basis() (sage.categories.finite_dimensional_algebras_with_basis.FiniteDimensionalAlgebrasWithBasis.Cellular.ElementMethods method), 389
Cellular_involution() (sage.categories.finite_dimensional_algebras_with_basis.FiniteDimensionalAlgebrasWithBasis.SubcategoryMethods method), 389
center() (sage.categories.finite_dimensional_algebras_with_basis.FiniteDimensionalAlgebrasWithBasis.ParentMethods method), 396
center() (sage.categories.finite_dimensional_lie_algebras_with_basis.FiniteDimensionalAlgebrasWithBasis.ParentMethods method), 390
gebras_with_basis.FiniteDimensionalLieAlgebrasWithBasis.ParentMethods method), 413
center_basis() (sage.categories.finite_dimensional_algebras_with_basis.FiniteDimensionalAlgebrasWithBasis.ParentMethods method), 396
center_basis() (sage.categories.group_algebras.GroupAlgebras.ParentMethods method), 516
central_form() (sage.categories.group_algebras.GroupAlgebras.ElementMethods method), 514
central_orthogonal_idempotents() (sage.categories.finite_dimensional_semisimple_algebras_with_basis.FiniteDimensionalSemisimpleAlgebrasWithBasis.Commutative.ParentMethods method), 440
central_orthogonal_idempotents() (sage.categories.finite_dimensional_semisimple_algebras_with_basis.FiniteDimensionalSemisimpleAlgebrasWithBasis.ParentMethods method), 441
centralizer() (sage.categories.finite_dimensional_lie_algebras_with_basis.FiniteDimensionalLieAlgebrasWithBasis.ParentMethods method), 413
centralizer_basis() (sage.categories.finite_dimensional_lie_algebras_with_basis.FiniteDimensionalLieAlgebrasWithBasis.ParentMethods method), 414
classical_crystals.ElementMethods (class in sage.categories.classical_crystals), 200
ClassicalCrystals.ParentMethods (class in sage.categories.classical_crystals), 201
ClassicalCrystals.TensorProducts (class in sage.categories.classical_crystals), 203
classically_highest_weight_vectors() (sage.categories.rings.AlgebrasWithBasis.ParentMethods method), 581
Coalgebras (class in sage.categories.coalgebras), 204
Coalgebras.Cocommutative (class in sage.categories.coalgebras), 204
Coalgebras.DualObjects (class in sage.categories.coalgebras), 204
Coalgebras.ElementMethods (class in sage.categories.coalgebras), 204
Coalgebras.Filtered (class in sage.categories.coalgebras), 205
Coalgebras.ParentMethods (class in sage.categories.coalgebras), 205
Coalgebras.Realizations (class in sage.categories.coalgebras), 206
Coalgebras.Realizations.ParentMethods (class in sage.categories.coalgebras), 206
Coalgebras.SubcategoryMethods (class in sage.categories.coalgebras), 207
Coalgebras.Super (class in sage.categories.coalgebras), 207
Coalgebras.Super.SubcategoryMethods (class in sage.categories.coalgebras), 207
Coalgebras.Super.Supercocommutative (class in sage.categories.coalgebras), 207
Coalgebras.TensorProducts (class in sage.categories.coalgebras), 208
Coalgebras.TensorProducts.ElementMethods (class in sage.categories.coalgebras), 208
Coalgebras.TensorProducts.ParentMethods (class in sage.categories.coalgebras), 208
CoalgebrasWithBasis (class in sage.categories.coalgebras_with_basis), 209
CoalgebrasWithBasis.ElementMethods (class in sage.categories.coalgebras_with_basis), 209
CoalgebrasWithBasis.Filtered (class in sage.categories.coalgebras_with_basis), 210
CoalgebrasWithBasis.ParentMethods (class in sage.categories.coalgebras_with_basis), 210
CoalgebrasWithBasis.Super (class in sage.categories.coalgebras_with_basis), 211
<table>
<thead>
<tr>
<th>Function/Method</th>
<th>Class/Module</th>
</tr>
</thead>
<tbody>
<tr>
<td>Codegens()</td>
<td>(sage.categories.finite_complex_reflection_groups.FiniteComplexReflectionGroups.ParentMethods method), 362</td>
</tr>
<tr>
<td>codomain()</td>
<td>(sage.categories.functor.ElementMethods method), 216</td>
</tr>
<tr>
<td>codomain()</td>
<td>(sage.categories.cartesian_products.ElementMethods method), 215</td>
</tr>
<tr>
<td>codomain()</td>
<td>(sage.categories.action.Action method), 216</td>
</tr>
<tr>
<td>codomain()</td>
<td>(sage.categories.action.PrecomposedAction method), 215</td>
</tr>
<tr>
<td>codomain()</td>
<td>(sage.categories.action.InverseAction method), 216</td>
</tr>
<tr>
<td>coercion_reversed()</td>
<td>(sage.categories.pushout.ConstructionFunctor method), 216</td>
</tr>
<tr>
<td>coercion_reversed()</td>
<td>(sage.categories.pushout.SubspaceFunctor method), 216</td>
</tr>
<tr>
<td>cohomology()</td>
<td>(sage.categories.finite_dimesional_lie_algebras_with_basis.FiniteDimensionalLIEAlgebrasWithBasis.ParentMethods method), 215</td>
</tr>
<tr>
<td>common_base()</td>
<td>(sage.categories.pushout.ConstructionFunctor method), 216</td>
</tr>
<tr>
<td>common_base()</td>
<td>(sage.categories.pushout.MultivariateConstructionFunctor method), 216</td>
</tr>
<tr>
<td>Commutative</td>
<td>(sage.categories.algebras.Algebras_attributes), 216</td>
</tr>
<tr>
<td>Commutative</td>
<td>(sage.categories.division_rings.DivisionRings_attributes), 216</td>
</tr>
<tr>
<td>Commutative</td>
<td>(sage.categories.domains.Domains_attributes), 216</td>
</tr>
<tr>
<td>Commutative</td>
<td>(sage.categories.rings.Rings_attributes), 216</td>
</tr>
<tr>
<td>Commutative</td>
<td>(sage.categories.category_with_axiom.Blahs.SubcategoryMethods method), 90</td>
</tr>
<tr>
<td>Commutative</td>
<td>(sage.categories.magmas.Magmas.SubcategoryMethods method), 216</td>
</tr>
<tr>
<td>Commutative</td>
<td>(sage.categories.l_trivial_semigroups.LTrivialSemigroups method), 216</td>
</tr>
<tr>
<td>Commutative</td>
<td>(sage.categories.r_trivial_semigroups.RTrivialSemigroups method), 216</td>
</tr>
<tr>
<td>Commutative</td>
<td>(sage.categories.commutative_additive_groups), 216</td>
</tr>
<tr>
<td>Commutative</td>
<td>(sage.categories.commutative_additive_monoids), 216</td>
</tr>
<tr>
<td>Commutative</td>
<td>(sage.categories.commutative_additive_semigroups), 216</td>
</tr>
<tr>
<td>CommutativeAlgebraIdeals()</td>
<td>(sage.categories.commutative_algebra_ideals), 216</td>
</tr>
<tr>
<td>CommutativeAlgebras()</td>
<td>(sage.categories.commutative_algebras), 216</td>
</tr>
<tr>
<td>CommutativeAlgebras.TensorProducts()</td>
<td>(sage.categories.commutative_algebras), 216</td>
</tr>
<tr>
<td>CommutativeRingIdeals()</td>
<td>(sage.categories.commutative_ring_ideals), 216</td>
</tr>
<tr>
<td>CommutativeRings()</td>
<td>(sage.categories.commutative_rings), 216</td>
</tr>
<tr>
<td>CommutativeRings.CartesianProducts()</td>
<td>(sage.categories.commutative_rings), 216</td>
</tr>
<tr>
<td>CommutativeRings.ElementMethods()</td>
<td>(sage.categories.commutative_rings), 216</td>
</tr>
<tr>
<td>CommutativeRings.Finite()</td>
<td>(sage.categories.commutative_rings), 216</td>
</tr>
<tr>
<td>CommutativeRings.Finite.ParentMethods()</td>
<td>(sage.categories.commutative_rings), 216</td>
</tr>
<tr>
<td>CommutativeRings.ParentMethods()</td>
<td>(sage.categories.commutative_rings), 216</td>
</tr>
<tr>
<td>Commutes()</td>
<td>(sage.categories.pushout.CompletionFunctor method), 216</td>
</tr>
<tr>
<td>Compact()</td>
<td>(sage.categories.topological_spaces.TopologicalSpaces.SubcategoryMethods method), 216</td>
</tr>
<tr>
<td>Compact_extra_super_categories()</td>
<td>(sage.categories.cw_complexes.CWComplexes method), 216</td>
</tr>
<tr>
<td>Complete()</td>
<td>(sage.categories.metric_spaces.MetricSpaces.SubcategoryMethods method), 216</td>
</tr>
</tbody>
</table>
CompleteDiscreteValuationFields (class in sage.categories.complete_discrete_valuation), 221
CompleteDiscreteValuationFields.ElementMethods (class in sage.categories.complete_discrete_valuation), 221
CompleteDiscreteValuationFields.ElementMethods (class in sage.categories.complete_discrete_valuation), 221
CompleteDiscreteValuationRings (class in sage.categories.complete_discrete_valuation), 222
CompleteDiscreteValuationRings.ElementMethods (class in sage.categories.complete_discrete_valuation), 223
completion() (sage.categories.graded_algebras_with_basis.GradedAlgebrasWithBasis.ParentMethods method), 497
CompletionFunctor (class in sage.categories.pushout), 131
Complex() (sage.categories.manifolds.Manifolds.SubcategoryMethods method), 609
ComplexManifolds (class in sage.categories.manifolds), 606
ComplexReflectionGroups (class in sage.categories.complex_reflection_groups), 225
ComplexReflectionGroups.ParentMethods (class in sage.categories.complex_reflection_groups), 226
ComplexReflectionOrGeneralizedCoxeterGroups (class in sage.categories.complex_reflection_groups), 227
ComplexReflectionOrGeneralizedCoxeterGroups.ElementMethods (class in sage.categories.complex_reflection_groups), 228
ComplexReflectionOrGeneralizedCoxeterGroups.Irreducible (class in sage.categories.complex_reflection_groups), 232
ComplexReflectionOrGeneralizedCoxeterGroups.Irreducible.ParentMethods (class in sage.categories.complex_reflection_groups), 232
ComplexReflectionOrGeneralizedCoxeterGroups.SubcategoryMethods (class in sage.categories.complex_reflection_groups), 243
CompositeConstructionFunctor (class in sage.categories.pushout), 132
conjugacy_class() (sage.categories.groups.Groups.ParentMethods method), 521
conjugacy_classes() (sage.categories.finite_groups.FiniteGroups.ParentMethods method), 450
conjugacy_classes_representatives() (sage.categories.finite_groups.FiniteGroups.ParentMethods method), 450
Connected() (sage.categories.category_with_axiom.Blahs.SubcategoryMethods method), 90
Connected() (sage.categories.cell_complexes.CellComplexes.SubcategoryMethods method), 308
Connected() (sage.categories.filtered_modules.FiltratedModules.SubcategoryMethods method), 337
Connected() (sage.categories.manifolds.Manifolds.SubcategoryMethods method), 609
Connected() (sage.categories.topological_spaces.TopologicalSpaces.SubcategoryMethods method), 793
connected_components() (sage.categories.crystals.Crystals.ParentMethods method), 296
connected_components_generators() (sage.categories.crystals.Crystals.ParentMethods method), 296
connected_components_generators() (sage.categories.highest_weight_crystals.HighestWeightCrystals.ParentMethods method), 531
connectivity() (sage.categories.simplicial_sets.SimplicialSets.Pointed.ParentMethods method), 768
construction() (sage.categories.modules.TensorProducts.ParentMethods method), 626
construction() (sage.categories.sets_cat.Sets.ParentMethods method), 742
construction_tower() (in module sage.categories.pushout), 149
ConjugacyFunctor (class in sage.categories.pushout), 133
convolution_power_of_id() (sage.categories...
coxeter_matrix() (sage.categories.coxeter_groups.CoxeterGroups.ParentMethods method), 275
coxeter_matrix() (sage.categories.examples.finite_coxeter_groups.DihedralGroup method), 856
coxeter_matrix() (sage.categories.weyl_groups.WeylGroups.ParentMethods method), 813
coxeter_number() (sage.categories.finite_complex_reflection_groups.FiniteComplexReflectionGroups.Irreducible.ParentMethods method), 359
coxeter_number() (sage.categories.finite_complex_reflection_groups.FiniteComplexReflectionGroups.WellGenerated.Irreducible.ParentMethods method), 368
coxeter_poset() (sage.categories.finite_coxeter_groups.FiniteCoxeterGroups.ParentMethods method), 380
coxeter_sorting_word() (sage.categories.coxeter_groups.CoxeterGroups.ElementMethods method), 256
coxeter_type() (sage.categories.coxeter_groups.CoxeterGroups.ParentMethods method), 276
CoxeterGroupAlgebras (class in sage.categories.coxeter_group_algebras), 243
CoxeterGroupAlgebras.ParentMethods (class in sage.categories.coxeter_group_algebras), 243
CoxeterGroups (class in sage.categories.coxeter_groups), 246
CoxeterGroups.ElementMethods (class in sage.categories.coxeter_groups), 247
CoxeterGroups.ParentMethods (class in sage.categories.coxeter_groups), 270
crystal_morphism() (sage.categories.crystals.Crystals.ParentMethods method), 296
CrystalHomset (class in sage.categories.crystals), 283
CrystalMorphism (class in sage.categories.crystals), 286
CrystalMorphismByGenerators (class in sage.categories.crystals), 287
Crystals (class in sage.categories.crystals), 289
Crystals.ElementMethods (class in sage.categories.crystals), 289
Crystals.MorphismMethods (class in sage.categories.crystals), 295
Crystals.ParentMethods (class in sage.categories.crystals), 295
Crystals.SubcategoryMethods (class in sage.categories.crystals), 305
Crystals.TensorProducts (class in sage.categories.crystals), 306
CWComplexes (class in sage.categories.cw_complexes), 306
CWComplexes.Connected (class in sage.categories.cw_complexes), 307
CWComplexes.ElementMethods (class in sage.categories.cw_complexes), 307
CWComplexes.Finite (class in sage.categories.cw_complexes), 307
CWComplexes.FiniteDimensional (class in sage.categories.cw_complexes), 308
CWComplexes.Finite.ParentMethods (class in sage.categories.cw_complexes), 307
CWComplexes.ParentMethods (class in sage.categories.cw_complexes), 308
CWComplexes.SubcategoryMethods (class in sage.categories.cw_complexes), 308
Cycle (class in sage.categories.examples.graphs), 874
cycle_index() (sage.categories.finite_permutation_groups.FinitePermutationGroups.ParentMethods method), 458
Cycle.Element (class in sage.categories.examples.graphs), 874

D
default_super_categories() (sage.categories.covariant_functorial_construction.CovariantConstructionCategory class method), 818
default_super_categories() (sage.categories.covariant_functorial_construction.RegressiveCovariantConstructionCategory class method), 822
default_super_categories() (sage.categories.graded_modules.GradedModulesCategory class method), 506
default_super_categories() (sage.categories.homsets.HomsetsCategory class method), 838
default_super_categories() (sage.categories.isomorphic_objects.IsomorphicObjectsCategory class method), 835
default_super_categories() (sage.categories.metric_spaces.MetricSpacesCategory class method), 614
default_super_categories() (sage.categories.quotients.QuotientsCategory class method), 834
default_super_categories() (sage.categories.subobjects.SubobjectsCategory class method), 835
default_super_categories() (sage.categories.super_modules.SuperModulesCategory class method), 937
sage.categories.algebras_with_basis.FiniteDimensionalLieAlgebrasWithBasis.ParentMethods method), 417
derived_subalgebra() (sage.categories.finite_dimensional_lie_algebras_with_basis.FiniteDimensionalLieAlgebrasWithBasis.ParentMethods method), 418
descents() (sage.categories.coxeter_groups.CoxeterGroups.ElementMethods method), 257
Differentiable() (sage.categories.manifolds.Manifolds.SubcategoryMethods method), 609
differentiable() (sage.categories.vector_bundles.VectorBundles.SubcategoryMethods method), 800
digraph() (sage.categories.crystals.Crystals.ParentMethods method), 299
digraph() (sage.categories.higher_weight_crystals.HighestWeightCrystals.ParentMethods method), 531
digraph() (sage.categories.loop_crystals.LoopCrystals.ParentMethods method), 584
DihedralGroup (class in sage.categories.examples.finite_coxeter_groups.FiniteCoxeterGroups.ElementMethods method), 855
DihedralGroup.Element (class in sage.categories.examples.finite_coxeter_groups.FiniteCoxeterGroups.ElementMethods method), 855
dimension() (sage.categories.cw_complexes.CWComplexes.ElementMethods method), 307
dimension() (sage.categories.cw_complexes.CWComplexes.Finite.ParentMethods method), 307
dimension() (sage.categories.cw_complexes.CWComplexes.ParentMethods method), 308
dimension() (sage.categories.examples.cw_complexes.Surface.Element method), 854
dimension() (sage.categories.examples.graphs.Cycle.Element method), 874
dimension() (sage.categories.examples.manifolds.Plane method), 883
dimension() (sage.categories.example_graphs.Graphs.ParentMethods method), 512
dimension() (sage.categories.lie_algebras_with_basis.LieAlgebrasWithBasis.ParentMethods method), 565
dimension() (sage.categories.manifolds.Manifolds.ParentMethods method), 608
dimension() (sage.categories.modules_with_basis.ModulesWithBasis.ParentMethods method), 643
dimension() (sage.categories.simplicial_complexes.SimplicialComplexes.Finite.ParentMethods method), 763
dimension() (sage.categories.vector_spaces.VectorSpaces.ParentMethods method), 802
direct_sum() (sage.categories.crystals.Crystals.ParentMethods method), 301
directed_subset() (sage.categories.posets.Posets.ParentMethods method), 672
directed_subsets() (sage.categories.finite_posets.FinitePosets.ParentMethods method), 471
DiscreteValuationFields (class in sage.categories.discrete_valuation.Fields.ElementMethods method), 309
DiscreteValuationRings (class in sage.categories.discrete_valuation.Rings.ElementMethods method), 310
dist() (sage.categories.metric_spaces.MetricSpaces.ElementMethods method), 613
dist() (sage.categories.metric_spaces.MetricSpaces.ParentMethods method), 613
distinguished_reflection() (sage.categories.complex_reflection_or_generalized_coxeter_groups.ComplexReflectionOrGeneralizedCoxeterGroups.ElementMethods method), 233
distinguished_reflections() (sage.categories.complex_reflection_or_generalized_coxeter_groups.ComplexReflectionOrGeneralizedCoxeterGroups.ElementMethods method), 233
Distributive (sage.categories.magas_and_additive_magmas.MagmasAndAdditiveMagmas.attribute), 601
Distributive() (sage.categories.magas_and_additive_magmas.MagmasAndAdditiveMagmas.SubcategoryMethods method), 601
Distributive() (sage.categories.magas_and_additive_magmas.MagmasAndAdditiveMagmas.SubcategoryMethods method), 601
DistributiveMagmasAndAdditiveMagmas (class in sage.categories.distributive_magmas_and_additive_magmas.MagmasAndAdditiveMagmas.ElementMethods method), 312
DistributiveMagmasAndAdditiveMagmas.ElementMethods (class in sage.categories.distributive_magmas_and_additive_magmas.MagmasAndAdditiveMagmas.ElementMethods method), 312
DistributiveMagmasAndAdditiveMagmas.ElementMethods (class in sage.categories.distributive_magmas_and_additive_magmas.MagmasAndAdditiveMagmas.ElementMethods method), 312
DistributiveMagmasAndAdditiveMag-
Element (sage.categories.examples.semigroups_cython.LeftZeroSemigroup attribute), 893
Element (sage.categories.highest_weight_crystals.HighestWeightCrystalHomset attribute), 529
element_class (sage.categories.examples.sets_cat.PrimeNumbers attribute), 894
element_class (sage.categories.examples.sets_cat.PrimeNumbers_Facade attribute), 897
element_class() (sage.categories.category.Category method), 51
element_class_set_morphism() (sage.categories.homset.Homset method), 51
Elements (class in sage.categories.category_types), 909
elements_of_length() (sage.categories.coxeter_groups.CoxeterGroups.ParentMethods method), 276
ElementWrapper (sage.categories.examples.sets_cat.PrimeNumbers_Wrapper attribute), 899
EmptySetError, 732
End() (in module sage.categories.homset), 115
end() (in module sage.categories.homset), 122
Endset() (sage.categories.homsets.Homsets.SubcategoryMethods method), 838
Endsets() (sage.categories.objects.Objects.SubcategoryMethods method), 667
energy_function() (sage.categories.loop_crystals.KirillovReshetikhinCrystals.ElementMethods method), 573
Enumerated (sage.categories.examples.sets_cat.PrimeNumbers_Wrapper attribute), 899
Enumerated() (sage.categories.examples.sets_cat.PrimeNumbers_Facade attribute), 897
EnumeratedSets (class in sage.categories.enumerated_sets), 315
EnumeratedSets.CartesianProducts (class in sage.categories.enumerated_sets), 315
EnumeratedSets.CartesianProducts.ParentMethods (class in sage.categories.enumerated_sets), 316
EnumeratedSets.ElementMethods (class in sage.categories.enumerated_sets), 316
EnumeratedSets.ParentMethods (class in sage.categories.enumerated_sets), 316
Epsilon() (sage.categories.crystals.Crystals.ElementMethods method), 289
epsilon() (sage.categories.regular_crystals.RegularCrystals.ElementMethods method), 695
epsilon() (sage.categories.regular_supercrystals.RegularSuperCrystals.ElementMethods method), 701
EquivariantSubobjectConstructionFunctor (class in sage.categories.pushout), 136
euclidean_degree() (sage.categories.discrete_valuation.DiscreteValuationRings.ElementMethods method), 310
euclidean_degree() (sage.categories.euclidean_domains.EuclideanDomains.ElementMethods method), 322
euclidean_degree() (sage.categories.euclidean_domains.ElementMethods method), 324
EuclideanDomains (class in sage.categories.euclidean_domains), 321
EuclideanDomains.ElementMethods (class in sage.categories.euclidean_domains), 322
EuclideanDomains.ParentMethods (class in sage.categories.euclidean_domains), 323
even_component() (sage.categories.super_modules_with_basis.SuperModulesWithBasis.ElementMethods method), 785
Example (class in sage.categories.examples.finiteEnumeratedSets), 862
Example (in module sage.categories.examples.algebras_with_basis), 847
Example (in module sage.categories.examples.commutative_additive_monoids), 848
Example (in module sage.categories.examples.commutative_additive_semigroups), 849
Example (in module sage.categories.examples.complexes), 853
Example (in module sage.categories.examples.finiteCoxeterGroups), 857
Example (in module sage.categories.examples.finiteDimensionalAlgebrasWithBasis), 857
Example (in module sage.categories.examples.finiteDimensionalLieAlgebrasWithBasis), 862
Example (in module sage.categories.examples.finiteMonoids), 864
Example (in module sage.categories.examples.finiteSemigroups), 866
Example (in module sage.categories.examples.finiteWeylGroups), 868
Example (in module sage.categories.examples.gradedConnectedHopfAlgebrasWithBasis), 870
Example (in module sage.categories.examples.gradedModulesWithBasis), 871
Example (in module sage.categories.examples.graphs), 875
Example (in module sage.categories.examples.infiniteEnumeratedSets), 877
Example (in module sage.categories.examples.lieAlgebras), 878
Example (in module sage.categories.examples.lie_algebras_with_basis), 880
Example (in module sage.categories.examples.magmas), 881
Example (in module sage.categories.examples.manifolds), 882
Example (in module sage.categories.examples.monoids), 883
Example (in module sage.categories.examples.sets_with_grading), 899
example() (sage.categories.algebras_with_basis.AlgebrasWithBasis method), 192
example() (sage.categories.category.Category method), 52
example() (sage.categories.classical_crystals.ClassicalCrystals method), 203
example() (sage.categories.complex_reflection_groups.ComplexReflectionGroups method), 226
example() (sage.categories.crystals.Crystals method), 306
example() (sage.categories.facade_sets.FacadeSets method), 816
example() (sage.categories.finite_complex_reflection_groups.FiniteComplexReflectionGroups method), 373
example() (sage.categories.finite_complex_reflection_groups.FiniteComplexReflectionGroups.Irreducible method), 361
example() (sage.categories.finite_complex_reflection_groups.FiniteComplexReflectionGroups.WellGenerated method), 373
example() (sage.categories.finite_complex_reflection_groups.FiniteComplexReflectionGroups.WellGenerated.Irreducible method), 370
example() (sage.categories.finite_crystals.FiniteCrystals method), 387
example() (sage.categories.finite_dimensional_lie_algebras_with_basis.FiniteDimensionalLieAlgebrasWithBasis method), 429
example() (sage.categories.finiteEnumeratedSets.FiniteEnumeratedSets.IsomorphicObjects method), 445
example() (sage.categories.finiteGroups.FiniteGroups method), 451
example() (sage.categories.finite_permutation_groups.FinitePermutationGroups method), 461
example() (sage.categories.finitely_generated_semigroups.FinitelyGeneratedSemigroups method), 492
example() (sage.categories.graded_hopf_algebras_with_basis.GradedHopfAlgebrasWithBasis method), 503
example() (sage.categories.graded_hopf_algebras_with_basis.GradedHopfAlgebrasWithBasis.Connected method), 502
example() (sage.categories.group_algebras.GroupAlgebras method), 518
example() (sage.categories.groups.Groups method), 527
example() (sage.categories.highest_weight_crystals.HighestWeightCrystals method), 535
example() (sage.categories.hopf_algebras_with_basis.HopfAlgebrasWithBasis method), 541
example() (sage.categories.kac_moody_algebras.KacMoodyAlgebras method), 545
example() (sage.categories.lie_algebras_with_basis.LieAlgebrasWithBasis method), 566
example() (sage.categories.lie_algebras.LieAlgebras method), 563
example() (sage.categories.lie_conformal_algebras.LieConformalAlgebras method), 569
example() (sage.categories.loop_crystals.LoopCrystals method), 584
example() (sage.categories.magmas.Magmas.CartesianProducts method), 587
example() (sage.categories.posets.Posets method), 679
example() (sage.categories.quantum_group_representations.QuantumGroupRepresentations method), 693
example() (sage.categories.regular_crystals.RegularCrystals method), 700
example() (sage.categories.semisimples.Semisimples method), 729
example() (sage.categories.semisimples.Semisimples.Quotients method), 726
example() (sage.categories.semisimples.Semisimples.Subquotients method), 729
example() (sage.categories.sets_cat.Sets method), 758
example() (sage.categories.sets_cat.Sets.CartesianProducts method), 738
example() (sage.categories.sets_cat.Sets.WithRealizations method), 757
example() (sage.categories.super_lie_conformal_algebras.SuperLieConformalAlgebras method), 781
example() (sage.categories.vector_spaces.VectorSpaces.WithBasis.Filtered method), 803
example() (sage.categories.vector_spaces.VectorSpaces.WithBasis.Graded method), 804
exp() (sage.categories.lie_algebras.LieAlgebras.ElementMethods method), 552
expand() (sage.categories.pushout.AlgebraicExtensionFunctor method), 128
expand() (sage.categories.pushout.CompositeConstructionFunctor method), 133
expand() (sage.categories.pushout.ConstructionFunctor method), 133
expand() (sage.categories.pushout.CompositeConstructionFunctor method), 133
Example (CategoryFramework, Release 10.3
bras_with_basis.GradedHopfAlgebrasWithBasis example() (sage.categories.group_algebras.GroupAlgebras method), 518
tion_groups.FinitelyGeneratedSemigroups method) 461
tion_groups.FinitelyGeneratedSemigroups method) 461
tion_groups.FinitelyGeneratedSemigroups method) 492
Example (CategoryFramework, Release 10.3
bras_with_basis.GradedHopfAlgebrasWithBasis example() (sage.categories.group_algebras.GroupAlgebras method), 518
tion_groups.FinitelyGeneratedSemigroups method) 461
tion_groups.FinitelyGeneratedSemigroups method) 461
tion_groups.FinitelyGeneratedSemigroups method) 492
Example (CategoryFramework, Release 10.3
bras_with_basis.GradedHopfAlgebrasWithBasis example() (sage.categories.group_algebras.GroupAlgebras method), 518
tion_groups.FinitelyGeneratedSemigroups method) 461
tion_groups.FinitelyGeneratedSemigroups method) 461
tion_groups.FinitelyGeneratedSemigroups method) 492
Example (CategoryFramework, Release 10.3
bras_with_basis.GradedHopfAlgebrasWithBasis example() (sage.categories.group_algebras.GroupAlgebras method), 518
tion_groups.FinitelyGeneratedSemigroups method) 461
tion_groups.FinitelyGeneratedSemigroups method) 461
tion_groups.FinitelyGeneratedSemigroups method) 492
Example (CategoryFramework, Release 10.3
bras_with_basis.GradedHopfAlgebrasWithBasis example() (sage.categories.group_algebras.GroupAlgebras method), 518
tion_groups.FinitelyGeneratedSemigroups method) 461
tion_groups.FinitelyGeneratedSemigroups method) 461
tion_groups.FinitelyGeneratedSemigroups method) 492
Example (CategoryFramework, Release 10.3
bras_with_basis.GradedHopfAlgebrasWithBasis example() (sage.categories.group_algebras.GroupAlgebras method), 518
tion_groups.FinitelyGeneratedSemigroups method) 461
tion_groups.FinitelyGeneratedSemigroups method) 461
tion_groups.FinitelyGeneratedSemigroups method) 492
Example (CategoryFramework, Release 10.3
bras_with_basis.GradedHopfAlgebrasWithBasis example() (sage.categories.group_algebras.GroupAlgebras method), 518
tion_groups.FinitelyGeneratedSemigroups method) 461
extra_super_categories() (sage.categories.additive_semigroups.AdditiveSemigroups.CartesianProducts method), 178
extra_super_categories() (sage.categories.algebras_with_basis.AlgebrasWithBasis.CartesianProducts method), 189
extra_super_categories() (sage.categories.algebras_with_basis.AlgebrasWithBasis.TensorProducts method), 191
extra_super_categories() (sage.categories.algebras.Algebras.CartesianProducts method), 183
extra_super_categories() (sage.categories.algebras.Algebras.Algebras product method), 184
extra_super_categories() (sage.categories.algebras.Algebras.Algebras TensorProducts method), 186
extra_super_categories() (sage.categories.algebras.Algebras.Cone method), 188
extra_super_categories() (sage.categories.algebras.Algebras.lattice method), 190
extra_super_categories() (sage.categories.algebras.Algebras.pushout method), 192
extra_super_categories() (sage.categories.algebras.Algebras.tensor method), 193
extra_super_categories() (sage.categories.algebras_with_basis.AlgebrasWithBasis.CategoricalProducts method), 195
extra_super_categories() (sage.categories.algebras_with_basis.AlgebrasWithBasis.CategoricalProducts method), 196
extra_super_categories() (sage.categories.algebras_with_basis.AlgebrasWithBasis.CategoricalProducts method), 197
extra_super_categories() (sage.categories.algebras_with_basis.AlgebrasWithBasis.CategoricalProducts method), 198
extra_super_categories() (sage.categories.algebras_with_basis.AlgebrasWithBasis.CategoricalProducts method), 199
extra_super_categories() (sage.categories.algebras_with_basis.AlgebrasWithBasis.CategoricalProducts method), 200
extra_super_categories() (sage.categories.algebras_with_basis.AlgebrasWithBasis.CategoricalProducts method), 201
extra_super_categories() (sage.categories.algebras_with_basis.AlgebrasWithBasis.CategoricalProducts method), 202
extra_super_categories() (sage.categories.algebras_with_basis.AlgebrasWithBasis.CategoricalProducts method), 203
extra_super_categories() (sage.categories.algebras_with_basis.AlgebrasWithBasis.CategoricalProducts method), 204
extra_super_categories() (sage.categories.algebras_with_basis.AlgebrasWithBasis.CategoricalProducts method), 205
extra_super_categories() (sage.categories.algebras_with_basis.AlgebrasWithBasis.CategoricalProducts method), 206
extra_super_categories() (sage.categories.algebras_with_basis.AlgebrasWithBasis.CategoricalProducts method), 207
extra_super_categories() (sage.categories.algebras_with_basis.AlgebrasWithBasis.CategoricalProducts method), 208
extra_super_categories() (sage.categories.algebras_with_basis.AlgebrasWithBasis.CategoricalProducts method), 209
extra_super_categories() (sage.categories.algebras_with_basis.AlgebrasWithBasis.CategoricalProducts method), 210
extra_super_categories() (sage.categories.algebras_with_basis.AlgebrasWithBasis.CategoricalProducts method), 211
extra_super_categories() (sage.categories.algebras_with_basis.AlgebrasWithBasis.CategoricalProducts method), 212
extra_super_categories() (sage.categories.algebras_with_basis.AlgebrasWithBasis.CategoricalProducts method), 213
extra_super_categories() (sage.categories.algebras_with_basis.AlgebrasWithBasis.CategoricalProducts method), 214
extra_super_categories() (sage.categories.algebras_with_basis.AlgebrasWithBasis.CategoricalProducts method), 215
extra_super_categories() (sage.categories.algebras_with_basis.AlgebrasWithBasis.CategoricalProducts method), 216
extra_super_categories() (sage.categories.covariant_functorial_construction.FunctorialConstructionCategory method), 822
extra_super_categories() (sage.categories.crystals.Crystals.TensorProducts method), 306
extra_super_categories() (sage.categories.cw_complexes.CWComplexes.Finite module, 308
extra_super_categories() (sage.categories.distributive_magmas_and_additive_magmas.DistributiveMagmasAndAdditiveMagmas.CartesianProducts method), 312
extra_super_categories() (sage.categories.divi-
sion_rings.DivisionRings method), 313
extra_super_categories() (sage.categories.fields.Fields method), 328
extra_super_categories() (sage.categories.filtered_modules.FilteredModules method), 338
extra_super_categories() (sage.categories.finite_coxeter_groups.FiniteCoxeterGroups method), 387
extra_super_categories() (sage.categories.finite_crystals.FiniteCrystals method), 388
extra_super_categories() (sage.categories.finite_crystals.FiniteCrystals.TensorProducts method), 387
extra_super_categories() (sage.categories.finite_dimensional_algebras_with_basis.FiniteDimensionalAlgebrasWithBasis.Cellular.TensorProducts method), 392
extra_super_categories() (sage.categories.finite_dimensional_modules_with_basis.FiniteDimensionalModulesWithBasis.TensorProducts method), 438
extra_super_categories() (sage.categories.finite_enumerated_sets.FiniteEnumeratedSets.CartesianProducts method), 445
extra_super_categories() (sage.categories.finite_fields.FiniteFields method), 448
extra_super_categories() (sage.categories.finite_groups.FiniteGroups.Algebras method), 449
extra_super_categories() (sage.categories.finite_permutation_groups.FinitePermutationGroups method), 462
extra_super_categories() (sage.categories.finite_sets.FiniteSets.Algebras method), 485
extra_super_categories() (sage.categories.finite_sets.FiniteSets.Subquotients method), 485
extra_super_categories() (sage.categories.finitely_generated_semigroups.FinitelyGeneratdSemigroups method), 492
extra_super_categories() (sage.categories.generalized_coxeter_groups.GeneralizedCoxeterGroups method), 494
extra_super_categories() (sage.categories.graded_algebras_with_basis.GradedAlgebrasWithBasis.SignedTensorProducts method), 499
extra_super_categories() (sage.categories.graded_algebras.gradedAlgebras.SignedTensorProducts method), 496
extra_super_categories() (sage.categories.graded_coalgebras.gradedCoalgebras.SignedTensorProducts method), 500
extra_super_categories() (sage.categories.grade_ide_lie_algebras.GradedLieAlgebras.Stratified.FiniteDimensional method), 503
extra_super_categories() (sage.categories.graphs.Graphs.Connected method), 512
extra_super_categories() (sage.categories.group_algebras.GroupAlgebras method), 518
extra_super_categories() (sage.categories.groups.Groups.CartesianProducts method), 520
extra_super_categories() (sage.categories.hecke_modules.HeckeModules.Homsets method), 528
extra_super_categories() (sage.categories.highest_weight_crystals.HighestWeightCrystals.TensorProducts method), 535
extra_super_categories() (sage.categories.homsets.Homsets.Endset method), 837
extra_super_categories() (sage.categories.hopf_algebras_with_basis.HopfAlgebrasWithBasis.TensorProducts method), 541
extra_super_categories() (sage.categories.hopf_algebras.HopfAlgebras.TensorProducts method), 538
extra_super_categories() (sage.categories.j_trivial_semigroups.JTrivialSemigroups method), 545
extra_super_categories() (sage.categories.l_trivial_semigroups.LTrivialSemigroups method), 585
extra_super_categories() (sage.categories.lie_algebras.LieAlgebras.FiniteDimensional method), 554
extra_super_categories() (sage.categories.loop_crystals.KirillovReshetikhinCrystals.TensorProducts method), 582
extra_super_categories() (sage.categories.magmas_and_additive_magmas.MagmasAndAdditiveMagmas.CartesianProducts method), 601
extra_super_categories() (sage.categories.magmas.Magmas.Algebras method), 587
extra_super_categories() (sage.categories.magmas.Magmas.CartesianProducts method), 588
Index

extra_super_categories() (sage.categories.supercrystals.SuperCrystals.TensorProducts method), 791
extra_super_categories() (sage.categories.topological_spaces.TopologicalSpaces.CartesianProducts method), 792
extra_super_categories() (sage.categories.topological_spaces.TopologicalSpacesegment.CartesianProducts method), 793
extra_super_categories() (sage.categories.topological_spaces.TopologicalSpacesCompact.CartesianProducts method), 794
extra_super_categories() (sage.categories.topological_spaces.TopologicalSpacesConnected.CartesianProducts method), 795
extra_super_categories() (sage.categories.unital_algebras.UnitalAlgebras.CartesianProducts method), 796
extra_super_categories() (sage.categories.vector_spaces.VectorSpaces.CartesianProducts method), 801
extra_super_categories() (sage.categories.vector_spaces.VectorSpaces.CartesianProducts method), 802
extra_super_categories() (sage.categories.vector_spaces.VectorSpaces.FiniteDimensional.TensorProducts method), 802
extra_super_categories() (sage.categories.vector_spaces.VectorSpaces.TensorProducts method), 803
extra_super_categories() (sage.categories.vector_spaces.VectorSpaces.WithBasis.TensorProducts method), 807
extra_super_categories() (sage.categories.filtered_algebras_with BASIS.TensorProducts.ParentMethods method), 691
f_string() (sage.categories.crystals.Crystals.ElementMethods method), 291
Facade (sage.categories.sets_cat.Sets attribute), 739
Facade() (sage.categories.sets_cat.Sets.SubcategoryMethods method), 745
facade_for() (sage.categories.fasade_sets.FacadeSets.ParentMethods method), 815
FacadeSets (class in sage.categories.fasade_sets), 815
FacadeSets.ParentMethods (class in sage.categories.fasade_sets), 815
faces() (sage.categories.graphs.Graphs.ParentMethods method), 513
faces() (sage.categories.simplicial_complexes.SimplicialComplexes.ParentMethods method), 763
facets() (sage.categories.graphs.Graphs.ParentMethods method), 513
facets() (sage.categories.simplicial_complexes.SimplicialComplexes.ParentMethods method), 763
factor() (sage.categories.fields.Fields.ElementMethods method), 324
factor() (sage.categories.quotient_fields.QuotientFields.ElementMethods method), 681
Fields (class in sage.categories.fields), 324
Fields.ElementMethods (class in sage.categories.fields), 324
Fields.ParentMethods (class in sage.categories.fields), 327
Filtered (sage.categories.algebras_with_basis.AlgebrasWithBasis attribute), 189
Filtered (sage.categories.algebras.Algebras attribute), 184
Filtered (sage.categories.hopf_algebras_with_ba
sis.HopfAlgebrasWithBasis attribute), 540
Filtered (sage.categories.modules_with_ba
sises.ModulesWithBasis attribute), 641
Filtered (sage.categories.modules.Modules attribute), 617
Filtered() (sage.categories.modules.Modules.SubcategoryMethods method), 623
FilteredAlgebras (class in sage.categories.filter
Algebras, 329
FilteredAlgebras.ParentMethods (class in sage.categories.filtered_algebras), 329
FilteredAlgebrasWithBasis (class in sage.categories.filtered_algebras_with_basis), 329
FilteredAlgebrasWithBasis.ElementMethods (class in sage.categories.filtered_alge-
FiniteDimensional (sage.categories.graded_lie_algebras_with_basis.GradedLieAlgebrasWithBasis attribute), 504
FiniteDimensional (sage.categories.hopf_algebras_with_basis.HopfAlgebrasWithBasis attribute), 540
FiniteDimensional (sage.categories.modules_with_basis.ModulesWithBasis attribute), 641
FiniteDimensional (sage.categories.category_with_axiom.Blahs.SubcategoryMethods method), 90
FiniteDimensional (sage.categories.cw_complexes.CWComplexes.SubcategoryMethods method), 309
FiniteDimensional (sage.categories.manifolds.Manifolds.SubcategoryMethods method), 609
FiniteDimensional (sage.categories.modules.Modules.SubcategoryMethods method), 623
FiniteDimensionalAlgebrasWithBasis (class in sage.categories.finite_dimensional_algebras_with_basis), 388
FiniteDimensionalAlgebrasWithBasis.Cellular (class in sage.categories.finite_dimensional_algebras_with_basis), 388
FiniteDimensionalAlgebrasWithBasis.Cellular.ElementMethods (class in sage.categories.finite_dimensional_algebras_with_basis), 389
FiniteDimensionalAlgebrasWithBasis.Cellular.ParentMethods (class in sage.categories.finite_dimensional_algebras_with_basis), 389
FiniteDimensionalAlgebrasWithBasis.Cellular.TensorProducts (class in sage.categories.finite_dimensional_algebras_with_basis), 391
FiniteDimensionalAlgebrasWithBasis.Cellular.TensorProducts.ParentMethods (class in sage.categories.finite_dimensional_algebras_with_basis), 391
FiniteDimensionalAlgebrasWithBasis.ElementMethods (class in sage.categories.finite_dimensional_algebras_with_basis), 393
FiniteDimensionalAlgebrasWithBasis.ParentMethods (class in sage.categories.finite_dimensional_algebras_with_basis), 394
FiniteDimensionalAlgebrasWithBasis.SubcategoryMethods (class in sage.categories.finite_dimensional_algebras_with_basis), 407
FiniteDimensionalBialgebrasWithBasis() (in module sage.categories.finite_dimensional_bialgebras_with_basis), 407
FiniteDimensionalCoalgebrasWithBasis() (in module sage.categories.finite_dimensional_coalgebras_with_basis), 408
FiniteDimensionalGradedLieAlgebrasWithBasis (class in sage.categories.finite_dimensional_graded_lie_algebras_with_basis), 408
FiniteDimensionalGradedLieAlgebrasWithBasis.BasisWithBasis() (in module sage.categories.finite_dimensional_graded_lie_algebras_with_basis), 408
FiniteDimensionalGradedLieAlgebrasWithBasis.Cellular (class in sage.categories.finite_dimensional_graded_lie_algebras_with_basis), 409
FiniteDimensionalGradedLieAlgebrasWithBasis.ElementMethods (class in sage.categories.finite_dimensional_graded_lie_algebras_with_basis), 410
FiniteDimensionalGradedLieAlgebrasWithBasis.ParentMethods (class in sage.categories.finite_dimensional_graded_lie_algebras_with_basis), 410
FiniteDimensionalHopfAlgebrasWithBasis (class in sage.categories.finite_dimensional_hopf_algebras_with_basis), 410
FiniteDimensionalHopfAlgebrasWithBasis.ElementMethods (class in sage.categories.finite_dimensional_hopf_algebras_with_basis), 410
FiniteDimensionalLieAlgebrasWithBasis (class in sage.categories.finite_dimensional_lie_algebras_with_basis), 410
FiniteDimensionalLieAlgebrasWithBasis.ElementMethods (class in sage.categories.finite_dimensional_lie_algebras_with_basis), 410
FiniteDimensionalLieAlgebrasWithBasis.ParentMethods (class in sage.categories.finite_dimensional_lie_algebras_with_basis), 411
FiniteDimensionalLieAlgebrasWithBasis.Subobjects (class in sage.categories.finite_dimensional_lie_algebras_with_basis), 428
FiniteDimensionalLieAlgebrasWithBasis.Subobjects.ParentMethods (class in sage.categories.finite_dimensional_lie_algebras_with_basis), 428
FiniteDimensionalModulesWithBasis (class in sage.categories.finite_dimensional_modules_with_basis), 429
FiniteDimensionalModulesWithBasis.ElementMethods (class in sage.categories.finite_dimensional_modules_with_basis), 429
FiniteDimensionalModulesWithBasis.MorphismMethods (class in sage.categories.finite_dimensional_modules_with_basis), 430
FiniteDimensionalModulesWithBasis.ParentMethods (class in sage.categories.finite_dimensional_modules_with_basis), 432
FiniteDimensionalModulesWithBasis.TensorProducts (class in sage.categories.finite_dimensional_modules_with_basis), 438
FiniteDimensionalNilpotentLieAlgebrasWithBasis (class in sage.categories.finite_dimensional_nilpotent_lie_algebras_with_basis), 438
FiniteDimensionalNilpotentLieAlgebrasWithBasis.ParentMethods (class in sage.categories.finite_dimensional_nilpotent_lie_algebras_with_basis), 438
FiniteDimensionalSemisimpleAlgebrasWithBasis (class in sage.categories.finite_dimensional_semisimple_algebras_with_basis), 440
FiniteDimensionalSemisimpleAlgebrasWithBasis.Commutative (class in sage.categories.finite_dimensional_semisimple_algebras_with_basis), 440
FiniteDimensionalSemisimpleAlgebrasWithBasis.ParentMethods (class in sage.categories.finite_dimensional_semisimple_algebras_with_basis), 441
FiniteEnumeratedSets (class in sage.categories.finite Enumerated Sets), 442
FiniteEnumeratedSets.CartesianProducts (class in sage.categories.finiteEnumeratedSets), 442
FiniteEnumeratedSets.CartesianProducts.ParentMethods (class in sage.categories.finiteEnumeratedSets), 442
FiniteEnumeratedSets.IsomorphicObjects (class in sage.categories.finiteEnumeratedSets), 445
FiniteEnumeratedSets.IsomorphicObjects.ParentMethods (class in sage.categories.finiteEnumeratedSets), 445
FiniteEnumeratedSets.ParentMethods (class in sage.categories.finiteEnumeratedSets), 445
FiniteFields (class in sage.categories.finite_fields), 448
FiniteFields.ElementMethods (class in sage.categories.finite_fields), 448
FiniteFields.ParentMethods (class in sage.categories.finite_fields), 448
FiniteGroups (class in sage.categories.finite groups), 448
FiniteGroups.Algebras (class in sage.categories.finite_groups), 448
FiniteGroups.ElementMethods (class in sage.categories.finite groups), 449
FiniteGroups.ParentMethods (class in sage.categories.finite groups), 449
FiniteLatticePosets (class in sage.categories.finite lattice_posets), 451
FiniteLatticePosets.ParentMethods (class in sage.categories.finite lattice_posets), 451
FinitelyGenerated() (class in sage.categories.lambda_bracket_algebras.LambdaBracketAlgebras.SubcategoryMethods method), 548
FinitelyGenerated() (class in sage.categories.lambda_bracket_algebras.LambdaBracketAlgebras.SubcategoryMethods method), 548
FinitelyGeneratedAsLambdaBracketAlgebra (class in sage.categories.lambda_bracket_algebras.LambdaBracketAlgebras.SubcategoryMethods method), 548
FinitelyGeneratedAsLambdaBracketAlgebra (class in sage.categories.lambda_bracket_algebras.LambdaBracketAlgebras.SubcategoryMethods method), 548
FinitelyGeneratedAsMagma (class in sage.categories.lambda_bracket_algebras.LambdaBracketAlgebras.SubcategoryMethods method), 548
FinitelyGeneratedAsMagma (class in sage.categories.lambda_bracket_algebras.LambdaBracketAlgebras.SubcategoryMethods method), 548
FinitelyGeneratedLambdaBracketAlgebras (class in sage.categories.finitely generated lambda_bracket_algebras), 486
FinitelyGeneratedLambdaBracketAlgebras.Graded (class in sage.categories.finitely generated lambda_bracket_algebras), 486
FinitelyGeneratedLambdaBracketAlgebras.ParentMethods (class in sage.categories.finitely generated lambda_bracket_algebras), 486
FinitelyGeneratedLambdaBracketAlgebras.ParentMethods (class in sage.categories.finitely generated lambda_bracket_algebras), 486

Index 949
free()  (sage.categories.groups.Groups.Commutative
static method), 520
free()  (sage.categories.monoids.Monoids static method), 664
free()  (sage.categories.monoids.Monoids.Commutative
static method), 661
free_graded_module()  (sage.categories.graded_al-
gebras_with_basis.GradedAlgebrasWithBasis.
ParentMethods method), 497
free_module()  (sage.categories.rings.Rings.Parent-
Methods method), 708
FreeAlgebra  (class in sage.categories.examples.alge-
bras_with_basis), 847
FreeCommutativeAdditiveMonoid  (class in
sage.categories.examples.commutative_additive
monoids), 848
FreeCommutativeAdditiveMonoid.Element  (class
in sage.categories.examples.commutative_add-
tive_monoids), 849
FreeCommutativeAdditiveSemigroup  (class
in sage.categories.examples.commutative_addi-
tive_semigroups), 849
FreeCommutativeAdditiveSemigroup.Element  (class
in sage.categories.examples.commutative_addi-
tive_semigroups), 850
FreeMagma  (class in sage.categories.examples.magasms), 881
FreeMagma.Element  (class in sage.categories.examples
magasms), 881
FreeMonoid  (class in sage.categories.examples
monoids), 883
FreeMonoid.Element  (class in sage.categories.examples
monoids), 884
FreeSemigroup  (class in sage.categories.examples
semigroups), 887
FreeSemigroup.Element  (class in sage.cat-
egories.examples.semigroups), 887
from_base_ring()  (sage.categories.unital_al-
gebras.UnitalAlgebras.ParentMethods method), 798
from_base_ring()  (sage.categories.unital_al-
method), 798
from_base_ring_from_one_basis()  (sage.cat-
egories.unital_algebras.UnitalAlgebras.
WithBasis.ParentMethods method), 799
from_graded_conversion()  (sage.categories.fil-
tered_algebras_with_basis.FilteredAlge-
brasWithBasis.ParentMethods method), 330
from_graded_conversion()  (sage.categories.fil-
tered_modules_with_basis.FilteredModulesWith-
Basis.ParentMethods method), 347
from_reduced_word()  (sage.categories.complex_reflec-
tion_or_generalized_coxeter_groups.Com-
plexReflectionOrGeneralizedCoxeterGroups.Par-
entMethods method), 234
from_set()  (sage.categories.examples.with_real-
method), 902
from_vector()  (sage.categories.examples.finite_di-
mensioal_lie_algebras_with_basis.Abelian
LieAlgebraWithBasis.ParentMethods method), 860
from_vector()  (sage.categories.examples.finite_di-
mensioal_lie_algebras_with_basis.FiniteDimen-
sioalLieAlgebrasWithBasis.ParentMethods
method), 418
from_vector()  (sage.categories.finite_dimensional
modules_with_basics.FiniteDimensional
ModulesWithBasis.ParentMethods method), 436
full_super_categories()  (sage.categories.cate-
gory.Category method), 558
fully_commutative_elements()  (sage.cate-
gories.coxeter_groups.CoxeterGroups.Parent-
Methods method), 277
FunctionFields  (class in sage.categories.function
_fields), 492
FunctionFields.ElementMethods  (class in
sage.categories.function_fields), 492
FunctionFields.ParentMethods  (class in
sage.categories.function_fields), 492
Functor  (class in sage.categories.functor), 99
FunctorialConstructionCategory  (class in
sage.categories.covariant_functorial_construc-
tion), 821
fundamental_group()  (sage.categories.finit-
䁷e_complex_reflection_groups.FiniteCom-
plexReflectionGroups.WellGenerated.Irre-
ducible.ParentMethods method), 368
G  (sage.categories.action.Action attribute), 160
gcd()  (sage.categories.discrete_valuation.DiscreteValu-
ationRings.ElementMethods method), 310
gcd()  (sage.categories.euclidean_domains.EuclideanDo-
mains.ElementMethods method), 322
gcd()  (sage.categories.fields.Fields.ElementMethods
method), 324
gcd()  (sage.categories.quotient_fields.QuotientFields.
ElementMethods method), 682
Grading.ParentMethods method), 760
grading_set() (sage.categories.sets_with_grading.SetsWithGrading.ParentMethods method), 761
Grades (class in sage.categories.grades), 512
Graphs.Connected (class in sage.categories.graphs), 512
Groups (class in sage.categories.groups), 512
gssets (class in sage.categories.gsets), 493
gt () (sage.categories.posets.Posets.ParentMethods method), 672

H
has_descent() (sage.categories.coxeter_groups.CoxeterGroups.ElementMethods method), 258
has_full_support() (sage.categories.coxeter_groups.CoxeterGroups.ElementMethods method), 259
has_left_descent() (sage.categories.coxeter_groups.CoxeterGroups.ElementMethods method), 259
has_right_descent() (sage.categories.coxeter_groups.CoxeterGroups.ElementMethods method), 259
has_right_descent() (sage.categories.examples.finite_coxeter_groups.DihedralGroup.Element method), 856
has_right_descent() (sage.categories.examples.finite_weyl_groups.SymmetricGroup.Element method), 869
has_standard_involution() (sage.categories.algebras.Algebras.ParentMethods method), 184
HeckeModules (class in sage.categories.hecke_modules), 528
HeckeModules.Homsets (class in sage.categories.hecke_modules), 528
HeckeModules.Homsets.ParentMethods (class in sage.categories.hecke_modules), 528
HeckeModules.ParentMethods (class in sage.categories.hecke_modules), 528
highest_weight_vectors() (sage.categories.higherest_weight_crystals.HighestWeightCrystals.ParentMethods method), 532
highest_weight_vectors() (sage.categories.higherest_weight_crystals.HighestWeightCrystals.ParentMethods method), 532
highest_weight_vectors() (sage.categories.higherest_weight_crystals.HighestWeightCrystals.TensorProducts.ParentMethods method), 534
highest_weight_vectors_iterator() (sage.categories.highest_weight_crystals.HighestWeightCrystals.TensorProducts.ParentMethods method), 535
HighestWeightCrystalHomset (class in sage.categories.highest_weight_crystals), 529
HighestWeightCrystalMorphism (class in sage.categories.highest_weight_crystals), 529
HighestWeightCrystalOfTypeA (class in sage.categories.examples.crystals), 851
HighestWeightCrystalOfTypeA.Element (class in sage.categories.examples.crystals), 852
HighestWeightCrystals (class in sage.categories.highest_weight_crystals), 529
HomsetsCategory (class in sage.categories.homsets), 838
Homsets.Endset (class in sage.categories.homsets), 837
Homsets.Endset.ParentMethods (class in sage.categories.homsets), 837
HomsetsOf (class in sage.categories.homsets), 840
Homsets.ParentMethods (class in sage.categories.homsets), 837
Homsets.SubcategoryMethods (class in sage.categories.homsets), 838
HomsetWithSubcategory (class in sage.categories.homsets), 121
HopfAlgebras (class in sage.categories.hopf_algebras), 536
HopfAlgebras.DualCategory (class in sage.categories.hopf_algebras), 536
HopfAlgebras.DualCategory.ParentMethods (class in sage.categories.hopf_algebras), 536
HopfAlgebras.ElementMethods (class in sage.categories.hopf_algebras), 536
HopfAlgebras.Morphism (class in sage.categories.hopf_algebras), 536
HopfAlgebras.ParentMethods (class in sage.categories.hopf_algebras), 536
HopfAlgebras.Realizations (class in sage.categories.hopf_algebras), 536
HopfAlgebras.Realizations.ParentMethods (class in sage.categories.hopf_algebras), 536
HopfAlgebras.Super (class in sage.categories.hopf_algebras), 537
HopfAlgebras.Super.ElementMethods (class in sage.categories.hopf_algebras), 537
HopfAlgebras.TensorProducts (class in sage.categories.hopf_algebras), 537
HopfAlgebras.TensorProducts.ElementMethods (class in sage.categories.hopf_algebras), 537
HopfAlgebras.TensorProducts.ParentMethods (class in sage.categories.hopf_algebras), 537
HopfAlgebrasWithBasis (class in sage.categories.hopf_algebras_with_basis), 537
HopfAlgebrasWithBasis.ElementMethods (class in sage.categories.hopf_algebras_with_basis), 538
HopfAlgebrasWithBasis.ParentMethods (class in sage.categories.hopf_algebras_with_basis), 540
HopfAlgebrasWithBasis.ParentMethods (class in sage.categories.hopf_algebras_with_basis), 540
HopfAlgebrasWithBasis.TensorProducts (class in sage.categories.hopf_algebras_with_basis), 540
HopfAlgebrasWithBasis.TensorProducts (class in sage.categories.hopf_algebras_with_basis), 541

Index 955
IdentityFunctor (class in sage.categories.pushout), 138

IdentityFunctor() (in module sage.categories.pushout), 138

IdentityFunctor() (class in module sage.categories.pushout), 101

IdentityFunctor_generic (class in sage.categories.morphism), 102

IdentityMorphism (class in sage.categories.morphism), 123

im_gens() (sage.categories.crystals.CrystalMorphismByGenerators method), 288

image() (sage.categories.crystals.CrystalMorphismByGenerators method), 288

image() (sage.categories.examples.finite_dimensional_modules_with_basis.FiniteDimensionalModulesWithBasis.MorphismMethods method), 430

image() (sage.categories.sets_cat.Sets.MorphismMethods method), 740

IncompleteSubquotientSemigroup (class in sage.categories.examples.semigroups), 888

IncompleteSubquotientSemigroup.Element (class in sage.categories.examples.semigroups), 888

index() (sage.categories.lambda_bracket_algebras_with_basis.LambdaBracketAlgebrasWithBasis.ElementMethods method), 549

index_set() (sage.categories.complex_reflection_or_generalized_coxeter_groups.ComplexReflectionOrGeneralizedCoxeterGroups.ParentMethods method), 237

index_set() (sage.categories.coxeter_groups.CoxeterGroups.ParentMethods method), 277


index_set() (sage.categories.crystals.Crystals.ParentMethods method), 301

index_set() (sage.categories.examples.finite_coxeter_groups.DihedralGroup method), 856

index_set() (sage.categories.finite_weyl_groups.SymmetricGroup method), 869

index_set() (sage.categories.quantum_group_representations.QuantumGroupRepresentations.ParentMethods method), 687

IndexedPolynomialRing (class in sage.categories.examples.lie_algebras_with_basis), 880

indices() (sage.categories.examples.with_realizations.SubsetAlgebra method), 905

indices_key() (sage.categories.examples.with_realizations.SubsetAlgebra method), 905

induced_graded_map() (sage.categories.filtered_algebras_with_basis.FilteredAlgebrasWithBasis.ParentMethods method), 331

induced_graded_map() (sage.categories.filtered_modules_with_basis.FilteredModulesWith...
is_ideal() (sage.categories.finite_dimensional_lie_algebras_with_basis.FiniteDimensionalLieAlgebrasWithBasis.ParentMethods method), 420
is_ideal() (sage.categories.algebras.LieAlgebras.ParentMethods method), 559
is_idempotent() (sage.categories.examples.semigroups_cython.IdempotentSemigroups.Element method), 891
is_idempotent() (sage.categories.examples.semi_groups.LeftZeroSemigroup.Element method), 889
is_idempotent() (sage.categories.magmas.Magmas.ElementMethods method), 589
is_identity() (sage.categories.morphism.IdentityMorphismMethods method), 123
is_identity() (sage.categories.morphism.MorphismMethods method), 125
is_identity_decomposition_into_orthogonal_idempotents() (sage.categories.finite_dimensional_algebras_with_basis.FiniteDimensionalAlgebrasWithBasis.ParentMethods method), 397
is_injective() (sage.categories.crystals.CrystalMorphism method), 286
is_injective() (sage.categories.map.FormalCompositeMap method), 106
is_injective() (sage.categories.morphism.IdentityMorphismMethods method), 123
is_injective() (sage.categories.rings.Rings.MorphismMethods method), 706
is_injective() (sage.categories.sets_cat.Sets.MorphismMethods method), 740
is_integral_domain() (sage.categories.group_algebras.GroupAlgebras.ParentMethods method), 517
is_integral_domain() (sage.categories.integral_domains.IntegralDomains.ParentMethods method), 544
is_integrally_closed() (sage.categories.fields.Fields.ParentMethods method), 327
is_irreducible() (sage.categories.complex_reflection_or_generalized_coxeter_groups.ComplexReflectionOrGeneralizedCoxeterGroups.ParentMethods method), 237
is_isomorphism() (sage.categories.crystals.Crystals.MorphismMethods method), 295
is_isomorphism() (sage.categories.regular_crystals.RegularCrystals.MorphismMethods method), 697
is_lattice() (sage.categories.finite_posets.FinitePosets.ParentMethods method), 471
is_lattice_morphism() (sage.categories.finite_lattice_posets.FiniteLatticePosets.ParentMethods method), 452
is_left() (sage.categories.action.Action method), 160
is_lowest_weight() (sage.categories.crystals.Crystals.ElementMethods method), 292
is_Map() (in module sage.categories.map), 114
is_Morphism() (in module sage.categories.morphism), 126
is_nilpotent() (sage.categories.finite_dimensional_lie_algebras_with_basis.FiniteDimensionalLieAlgebrasWithBasis.ParentMethods method), 420
is_nilpotent() (sage.categories.finite_dimensional_nilpotent_lie_algebras_with_basis.FiniteDimensionalNilpotentLieAlgebrasWithBasis.ParentMethods method), 438
is_nilpotent() (sage.categories.lie_algebras.LieAlgebrasNilpotent.ParentMethods method), 555
is_nilpotent() (sage.categories.lie_algebras.LieAlgebras.ParentMethods method), 559
is_odd() (sage.categories.super_modules.SuperModules.ElementMethods method), 783
is_one() (sage.categories.monoids.Monoids.ElementMethods method), 662
is_order_filter() (sage.categories.posets.Posets.ParentMethods method), 676
is_order_ideal() (sage.categories.posets.Posets.ParentMethods method), 676
is_parent_of() (sage.categories.facade_sets.FacadeSets.ParentMethods method), 816
is_parent_of() (sage.categories.sets_cat.Sets.ParentMethods method), 743
is_perfect() (sage.categories.fields.Fields.ParentMethods method), 328
is_perfect() (sage.categories.loop_crystals.KirillovReshetikhinCrystals.ParentMethods method), 576
is_pieri_factor() (sage.categories.weyl_groups.WeylGroups.ElementMethods method), 807
is_pointed() (sage.categories.simplicial_sets.SimplicialSets.ParentMethods method), 765
is_poset_isomorphism() (sage.categories.finite_posets.FinitePosets.ParentMethods method), 472
is_poset_morphism() (sage.categories.finite_posets.FinitePosets.ParentMethods method), 473
is_prime() (sage.categories.examples.sets_cat.PrimeNumbers_Abstract.Element method), 895
is_primitive() (sage.categories.bialgebras.Bialgebras.ElementMethods method), 193
is_real() (sage.categories.finite_complex_reflection_groups.FiniteComplexReflectionGroups.ParentMethods method), 363
is_real() (sage.categories.finite_coxeter_groups.FiniteCoxeterGroups.ParentMethods method), 381
is_reducible() (sage.categories.complex_reflection_or_generalized_coxeter_groups.ComplexReflectionOrGeneralizedCoxeterGroups.ParentMethods method), 238
is_reflection() (sage.categories.complex_reflection_or_generalized_coxeter_groups.ComplexReflectionOrGeneralizedCoxeterGroups.ElementMethods method), 232
is_ring() (sage.categories.rings.Rings.ParentMethods method), 710
is_self_dual() (sage.categories.finite_posets.FinitePosets.ParentMethods method), 473
is_semisimple() (sage.categories.finite_dimensional_lie_algebras_with_basis.FiniteDimensionalLieAlgebrasWithBasis.ParentMethods method), 421
is_simply_connected() (sage.categories.simplicial_sets.SimplicialSets.Pointed.ParentMethods method), 772
is_solvable() (sage.categories.finite_dimensional_lie_algebras_with_basis.FiniteDimensionalLieAlgebrasWithBasis.ParentMethods method), 421
is_solvable() (sage.categories.lie_algebras.LieAlgebras.ParentMethods method), 560
is_strict() (sage.categories.crystals.Crystals.MorphismMethods method), 295
is_subcategory() (sage.categories.category.Category method), 55
is_subcategory() (sage.categories.category.JoinCategory method), 64
is_super_homogeneous() (sage.categories.super_modules_with_basis.SuperModulesWithBasis.ElementMethods method), 785
is_surjective() (sage.categories.crystals.Crystals.CompositeMap method), 107
is_surjective() (sage.categories.map.Map method), 112
is_surjective() (sage.categories.morphism.IdentityMorphism method), 124
is_unique_factorization_domain() (sage.categories.unique_factorization_domains.UniqueFactorizationDomains.ParentMethods method), 796
is_unit() (sage.categories.discretevaluation.DiscreteValuationRings.ElementMethods method), 310
is_unit() (sage.categories.fields.Fields.ElementMethods method), 326
is_unit() (sage.categories.rings.Rings.ElementMethods method), 705
is_well_generated() (sage.categories.finite_complex_reflection_groups.FiniteComplexReflectionGroups.ParentMethods method), 364
is_well_generated() (sage.categories.finite_complex_reflection_groups.FiniteComplexReflectionGroups.FiniteComplexReflectionGroups.WellGenerated.ParentMethods method), 372
is_zero() (sage.categories.modules_with_basis.ModulesWithBasis.ElementMethods method), 631
is_zero() (sage.categories.rings.Rings.ParentMethods method), 710
IsomorphicObjectOfFiniteEnumeratedSet (class in sage.categories.examples.finiteEnumeratedSets), 863
IsomorphicObjects() (sage.categories.sets_cat.Sets.SubcategoryMethods method), 748
IsomorphicObjectsCategory (class in sage.categories.isomorphic_objects), 835
isotypic_projective_modules() (sage.categories.finite_dimensional_algebras_with_basis.FiniteDimensionalAlgebrasWithBasis.ParentMethods method), 399
iterator_range() (sage.categories.enumerated_sets.EnumeratedSets.ParentMethods method), 317
iterator_range() (sage.categories.finiteEnumeratedSets.ParentMethods method), 446
J
j_classes() (sage.categories.finite_semigroups.FiniteSemigroups.ParentMethods method), 483
j_classes_of_idempotents() (sage.categories.finite_semigroups.FiniteSemigroups.ParentMethods method), 484
j_transversal_of_idempotents() (sage.categories.finite_semigroups.FiniteSemigroups.ParentMethods method), 484
join() (sage.categories.category.Category static method), 55
join() (sage.categories.lattice_posets.LatticePosets.ParentMethods method), 550
join() (in module sage.categories.category_cy_helper), 914
join_irreducibles() (sage.categories.finite_lattice_posets.FiniteLatticePosets.ParentMethods method), 453
join_irreducibles_poset() (sage.categories.finite_lattice_posets.FiniteLatticePosets.Parent-
last() (sage.categories.finite_enumerated_sets.FiniteEnumeratedSets.CartesianProducts.ParentMethods method), 443
last() (sage.categories.finite_enumerated_sets.FiniteEnumeratedSets.ParentMethods method), 446
latex() (sage.categories.crystals.Crystals.ParentMethods method), 302
latex_file() (sage.categories.crystals.Crystals.ParentMethods method), 302
LatticePosets (class in sage.categories.lattice_posets), 550
LatticePosets.ParentMethods (class in sage.categories.lattice_posets), 550
LaurentPolynomialFunctor (class in sage.categories.lattice_posets), 550
lcm() (sage.categories.discrete_valuation.DiscreteValuationRings.ElementMethods method), 310
lcm() (sage.categories.fields.Fields.ElementMethods method), 326
lcm() (sage.categories.quotient_fields.QuotientFields.ElementMethods method), 682
le() (sage.categories.examples.posets.FiniteSetsOrderedByInclusion method), 886
le() (sage.categories.examples.posets.PartiallyOrderedSets.ElementMethods method), 886
le() (sage.categories.posets.Posets.ParentMethods method), 676
leading_coefficient() (sage.categories.modules_with_basis.ModulesWithBasis.ElementMethods method), 632
leading_item() (sage.categories.modules_with_basis.ModulesWithBasis.ElementMethods method), 632
leading_monomial() (sage.categories.modules_with_basis.ModulesWithBasis.ElementMethods method), 633
leading_support() (sage.categories.modules_with_basis.ModulesWithBasis.ElementMethods method), 633
leading_term() (sage.categories.modules_with_basis.ModulesWithBasis.ElementMethods method), 634
left_base_ring() (sage.categories.bimodules.Bimodules.ElementMethods method), 199
left_domain() (sage.categories.action.Action method), 160
left_inversions_as_reflections() (sage.categories.coxeter_groups.CoxeterGroups.ElementMethods method), 263
left_pieri_factorizations() (sage.categories.weyl_groups.WeylGroups.ElementMethods method), 808
left_presecomposition (sage.categories.action.PresecomposedAction attribute), 162
LeftModules (class in sage.categories.left_modules), 551
LeftModules.ElementMethods (class in sage.categories.left_modules), 551
LeftModules.ParentMethods (class in sage.categories.left_modules), 551
LeftRegularBand (class in sage.categories.examples.finite_semigroups), 866
LeftRegularBand.Element (class in sage.categories.examples.finite_semigroups), 867
LeftZeroSemigroup (class in sage.categories.examples.semigroups), 888
LeftZeroSemigroup (class in sage.categories.examples.semigroups_cython), 892
LeftZeroSemigroup.Element (class in sage.categories.examples.semigroups), 888
LeftZeroSemigroup.Element (class in sage.categories.examples.semigroups_cython), 893
length() (sage.categories.coxeter_groups.CoxeterGroups.ElementMethods method), 263
length() (sage.categories.modules_with_basis.ModulesWithBasis.ElementMethods method), 634
level() (sage.categories.loop_crystals.KirillovReshetikhinCrystals.ParentMethods method), 577
Lie (sage.categories.groups.Groups attribute), 522
lie_algebra_generators() (sage.categories.examples.finite_dimensional_lie_algebras_with_basis.AbelianLieAlgebra method), 861
lie_algebra_generators() (sage.categories.examples.lie_algebras_with_basis.AbelianLieAlgebra method), 880
lie_algebra_generators() (sage.categories.examples.lie_algebras.LieAlgebraFromAssociative method), 879
lie_group() (sage.categories.finite_dimensional_nilpotent_lie_algebras_with_basis.FiniteDimensionalNilpotentLieAlgebrasWithBasis.ElementMethods method), 438
lie_group() (sage.categories.lie_algebras.LieAlgebraParent method), 560
LieAlgebraFromAssociative (class in sage.categories.examples.lie_algebras), 878
LieAlgebraFromAssociative.Element (class in sage.categories.examples.lie_algebras), 879
LieAlgebras (class in sage.categories.lie_algebras), 551
LieAlgebras.ElementMethods (class in sage.categories.lie_algebras), 552
LieAlgebras.FiniteDimensional (class in sage.categories.lie_algebras), 554
lower_covers() (sage.categories.posets.Posets.ParentMethods method), 677
lowest_weight_vectors() (sage.categories.highest_weight_crystals.HighestWeightCrystals.ParentMethods method), 532
lt() (sage.categories.posets.Posets.ParentMethods method), 677
LTrivial (sage.categories.semigroups.Semigroups.attribute), 720
LTrivial() (sage.categories.semigroups.Semigroups.SubcategoryMethods method), 727
LTrivialSemigroups (class in sage.categories.l_trivial_semigroups), 585
lusztig_involution() (sage.categories.classical_crystals.ClassicalCrystals.ElementMethods method), 200
lusztig_involution() (sage.categories.loop_crystals.KirillovReshetikhinCrystals.ElementMethods method), 573

M
m_cambrian_lattice() (sage.categories.finite_coxeter_groups.FiniteCoxeterGroups.ParentMethods method), 382
magma_generators() (sage.categories.examples.magmas.FiniteMagma method), 882
magma_generators() (sage.categories.finitely_generated_magmas.FinitelyGeneratedMagma.ParentMethods method), 489
magma_generators() (sage.categories.semigroups.Semigroups.SubcategoryMethods method), 723
Magmas (class in sage.categories.magmas), 586
Magmas.Algebras (class in sage.categories.magmas), 586
Magmas.Algebras.ParentMethods (class in sage.categories.magmas), 586
MagmasAndAdditiveMagmas (class in sage.categories.magmas_and_additive_magmas), 600
MagmasAndAdditiveMagmas.CartesianProducts (class in sage.categories.magmas_and_additive_magmas), 601
MagmasAndAdditiveMagmas.SubcategoryMethods (class in sage.categories.magmas_and_additive_magmas), 601
Magmas.CartesianProducts (class in sage.categories.magmas), 587
Magmas.CartesianProducts.ParentMethods (class in sage.categories.magmas), 587
Magmas.Commutative (class in sage.categories.magmas), 588
Magmas.Commutative.Algebras (class in sage.categories.magmas), 588
Magmas.Commutative.CartesianProducts (class in sage.categories.magmas), 588
Magmas.Commutative.ParentMethods (class in sage.categories.magmas), 589
Magmas.ElementMethods (class in sage.categories.magmas), 589
Magmas.JTrivial (class in sage.categories.magmas), 589
Magmas.ParentMethods (class in sage.categories.magmas), 589
Magmas.Realizations (class in sage.categories.magmas), 593
Magmas.Realizations.ParentMethods (class in sage.categories.magmas), 593
Magmas.SubcategoryMethods (class in sage.categories.magmas), 593
Magmas.Subquotients (class in sage.categories.magmas), 596
Magmas.Subquotients.ParentMethods (class in sage.categories.magmas), 597
Magmas.Unital (class in sage.categories.magmas), 597
Magmas.Unital.Algebras (class in sage.categories.magmas), 597
Magmas.Unital.CartesianProducts (class in sage.categories.magmas), 598
Magmas.Unital.CartesianProducts.ElementMethods (class in sage.categories.magmas), 598
Magmas.Unital.CartesianProducts.ParentMethods (class in sage.categories.magmas), 598
Magmas.Unital.ElementMethods (class in sage.categories.magmas), 598
Magmas.Unital.Inverse (class in sage.categories.magmas), 598
Magmas.Unital.Inverse.CartesianProducts (class in sage.categories.magmas), 598
Magmas.Unital.ParentMethods (class in sage.categories.magmas), 599
Magmas.Unital.Realizations (class in sage.categories.magmas), 599
Magmas.Unital.Realizations.ParentMethods (class in sage.categories.magmas), 599
Magmas.Unital.SubcategoryMethods (class in sage.categories.magmas), 600
MagmaticAlgebras (class in sage.categories.magmatic_algebras), 602
MagmaticAlgebras.ParentMethods (class in sage.categories.magmatic_algebras), 603
MagmaticAlgebras.WithBasis (class in sage.categories.magmatic_algebras), 603
MagmaticAlgebras.WithBasis.FiniteDi-
meet() (sage.categories.category.Category static method), 57
meet() (sage.categories.lattice_posets.LatticePosets.ParentMethods method), 550
meet_irreducibles() (sage.categories.finite_lattice_posets.FiniteLatticePosets.ParentMethods method), 453
meet_irreducibles_poset() (sage.categories.finite_lattice_posets.FiniteLatticePosets.ParentMethods method), 454
merge() (sage.categories.pushout.AlgebraicClosureFunctor method), 127
merge() (sage.categories.pushout.AlgebraicExtensionFunctor method), 129
merge() (sage.categories.pushout.CompletionFunctor method), 132
merge() (sage.categories.pushout.ConstructionFunctor method), 135
merge() (sage.categories.pushout.InfinitePolynomialFunctor method), 140
merge() (sage.categories.pushout.LaurentPolynomialFunctor method), 141
merge() (sage.categories.pushout.MatrixFunctor method), 142
merge() (sage.categories.pushout.MultipolynomialFunctor method), 143
merge() (sage.categories.pushout.PermutationGroupFunctor method), 144
merge() (sage.categories.pushout.PolynomialFunctor method), 145
merge() (sage.categories.pushout.QuotientFunctor method), 146
merge() (sage.categories.pushout.SubspaceFunctor method), 147
merge() (sage.categories.pushout.VectorFunctor method), 148
metapost() (sage.categories.crystals.Crystals.ParentMethods method), 302
Metric (sage.categories.sets_cat.Sets attribute), 740
metric() (sage.categories.metric_spaces.MetricSpaces.ParentMethods method), 431
metric() (sage.categories.metric_spaces.MetricSpaces.ParentMethods method), 431
Metric() (sage.categories.sets_cat.Sets.SubcategoryMethods method), 613
metric_function() (sage.categories.metric_spaces.MetricSpaces.ParentMethods method), 148
Metric() (sage.categories.sets_cat.Sets.SubcategoryMethods method), 613
MetricSpaces (class in sage.categories.metric_spaces), 611
MetricSpaces.CartesianProducts (class in sage.categories.metric_spaces), 611
MetricSpaces.CartesianProducts.Par-
entMethods (class in sage.categories.metric_spaces), 611
MetricSpacesCategory (class in sage.categories.metric_spaces), 614
MetricSpaces.Complete (class in sage.categories.metric_spaces), 612
MetricSpaces.Complete.CartesianProducts (class in sage.categories.metric_spaces), 612
MetricSpaces.ElementMethods (class in sage.categories.metric_spaces), 612
MetricSpaces.Homsets (class in sage.categories.metric_spaces), 613
MetricSpaces.Homsets.ElementMethods (class in sage.categories.metric_spaces), 613
MetricSpaces.ParentMethods (class in sage.categories.metric_spaces), 613
MetricSpaces.SubcategoryMethods (class in sage.categories.metric_spaces), 614
MetricSpaces.WithRealizations (class in sage.categories.metric_spaces), 614
MetricSpaces.WithRealizations.ParentMethods (class in sage.categories.metric_spaces), 614
milnor_fiber_poset() (sage.categories.finite_complex_reflection_groups.FiniteComplexReflectionGroups.WellGenerated.ParentMethods method), 372
min_demazure_product_greater() (sage.categories.coxeter_groups.CoxeterGroups.ElementMethods method), 264
ModularAbelianVarieties (class in sage.categories.modular_abelian_varieties), 615
ModularAbelianVarieties.Homsets (class in sage.categories.modular_abelian_varieties), 615
ModularAbelianVarieties.Homsets.Endset (class in sage.categories.modular_abelian_varieties), 615
module
sage.categories.action, 159
sage.categories.additive_groups, 162
sage.categories.additive_magmas, 164
sage.categories.additive_monoids, 175
sage.categories.additive_semigroups, 176
sage.categories.affine_weyl_groups, 178
sage.categories.algebra_functor, 827
sage.categories.algebra_ideals, 181
sage.categories.algebra_modules, 182
sage.categories.algebras, 183
sage.categories.algebras_with_basis, 187
sage.categories.all, 1
sage.categories.aperiodic_semigroups, 192
sage.categories.associative_algebras, 192
sage.categories.bialgebras, 193
sage.categories.bialgebras_with_basis, 194
sage.categories.bimodules, 199
sage.categories.cartesian_product, 823
sage.categories.category, 29
sage.categories.category_cy_helper, 913
sage.categories.category_singleton, 910
sage.categories.category_types, 907
sage.categories.category_with_axiom, 66
sage.categories.classical_crystals, 200
sage.categories.coalgebras, 204
sage.categories.coalgebras_with_basis, 209
sage.categories.coercion_methods, 915
sage.categories.commutative_additive_groups, 212
sage.categories.commutative_additive_monoids, 213
sage.categories.commutative_additive_semigroups, 213
sage.categories.commutative_algebra_ideals, 214
sage.categories.commutative_algebras, 215
sage.categories.commutative_ring_ideals, 215
sage.categories.commutative_rings, 216
sage.categories.complete_discrete_valuation, 221
sage.categories.complex_reflection_groups, 225
sage.categories.complex_reflection_or_generalized_coxeter_groups, 227
sage.categories.covariant Functorial_construction, 817
sage.categories.coxeter_group_construction, 243
Category Framework, Release 10.3

sage.categories.coxeter_groups, 246
sage.categories.crystals, 283
sage.categories.cw_complexes, 306
sage.categories.discrete_valuation, 309
sage.categories.distributive_mags_and_additive_mags, 312
sage.categories.division_rings, 313
sage.categories.domains, 314
sage.categories.dual, 827
sage.categories.enumerated_sets, 315
sage.categories.euclidean_domains, 321
sage.categories.examples.algebras_with_basis, 847
sage.categories.examples.commutative_additive_monoids, 848
sage.categories.examples.commutative_additive_semigroups, 849
sage.categories.examples.coxeter_groups, 851
sage.categories.examples.crystals, 851
sage.categories.examples.cw_complexes, 853
sage.categories.examples.facade_sets, 854
sage.categories.examples.finite_coxeter_groups, 855
sage.categories.examples.finite_dimensional_algebras_with_basis, 857
sage.categories.examples.finite_dimensional_lie_algebras_with_basis, 858
sage.categories.examples.finite enumerated_sets, 862
sage.categories.examples.finite_monoids, 864
sage.categories.examples.finite_semigroups, 866
sage.categories.examples.finite_weyl_groups, 868
sage.categories.examples.graded_connected_hopf_algebras_with_basis, 870
sage.categories.examples.graded_modules_with_basis, 871
sage.categories.examples.graphs, 874
sage.categories.examples.hopf_algebras_with_basis, 875
sage.categories.examples.infinite enumerated_sets, 877
sage.categories.examples.lie algebras, 878
sage.categories.examples.lie algebras_with_basis, 879
sage.categories.examples.magnas, 881
sage.categories.examples.manifolds, 882
sage.categories.examples.monoids, 883
sage.categories.examples.posets, 885
sage.categories.examples.semi groups, 887
sage.categories.examples.semi groups_cython, 891
sage.categories.examples.sets_cat, 893
sage.categories.examples.sets_with_grading, 899
sage.categories.examples.with_realizations, 900
sage.categories.facade_sets, 815
sage.categories.fields, 324
sage.categories.filtered_algebras, 329
sage.categories.filtered_algebras_with_basis, 329
sage.categories.filtered_modules, 337
sage.categories.filtered_modules_with_basis, 339
sage.categories.finite_complex_reflection_groups, 355
sage.categories.finite_coxeter_groups, 373
sage.categories.finite_crystals, 387
sage.categories.finite-dimensional_algebras_with_basis, 388
sage.categories.finite-dimensional_bialgebras_with_basis, 407
sage.categories.finite-dimensional_coalgebras_with_basis, 408
sage.categories.finite-dimensional_graded_lie_algebras_with_basis, 408
sage.categories.finite-dimensional_hopf_algebras_with_basis, 410
sage.categories.finite-dimensional_lie_algebras_with_basis, 410
sage.categories.finite-dimensional_modules_with_basis, 429

Index 967
monoid_generators() (sage.categories.finite_groups.FiniteGroups.ParentMethods method), 450
monoid_generators() (sage.categories.groups.Groups.ParentMethods method), 526
MonoidAlgebras() (in module sage.categories.monoids), 657
Monoids (class in sage.categories.monoids), 658
Monoids.Algebras (class in sage.categories.monoids), 658
Monoids.Algebras.ElementMethods (class in sage.categories.monoids), 658
Monoids.Algebras.ParentMethods (class in sage.categories.monoids), 658
Monoids.CartesianProducts (class in sage.categories.monoids), 660
Monoids.CartesianProducts.ElementMethods (class in sage.categories.monoids), 660
Monoids.CartesianProducts.ParentMethods (class in sage.categories.monoids), 660
Monoids.Cyclic (class in sage.categories.monoids), 661
Monoids.Commutative (class in sage.categories.monoids), 661
Monoids.ElementMethods (class in sage.categories.monoids), 662
Monoids.ParentMethods (class in sage.categories.monoids), 662
Monoids.Subquotients (class in sage.categories.monoids), 663
Monoids.Subquotients.ParentMethods (class in sage.categories.monoids), 663
Monoids.WithRealizations (class in sage.categories.monoids), 664
Monoids.WithRealizations.ParentMethods (class in sage.categories.monoids), 664
monomial() (sage.categories.modules_with_basis.ModulesWithBasis.ParentMethods method), 649
monomial_coefficients() (sage.categories.examples.finite_dimensional_abelian_lie_algebras_with_basis.AbelianLieAlgebra.Element method), 859
monomial_coefficients() (sage.categories.modules_with_basis ModulesWithBasis.ElementMethods method), 637
monomial_or_zero_if_none() (sage.categories.modules_with_basis.ModulesWithBasis.ParentMethods method), 649
monomials() (sage.categories.modules_with_basis.ModulesWithBasis.ElementMethods method), 637
Morphism (class in sage.categories.morphism), 124
Index 971

generators (sage.categories.finitely_generated_lambdaBracket algebras.FinitelyGeneratedLambdaBracketAlgebras.ParentMethods method), 487
gen() (sage.categories.finite_monoids.FiniteMonoids.ParentMethods method), 455
next() (sage.categories.enumerated_sets.EnumeratedSets.ParentMethods method), 318
next() (sage.categories.examples.infinite Enumerated Sets.NonNegativeIntegers method), 878
next() (sage.categories.examples.sets_cat.PrimeNumbers_Abstract method), 895
ngens() (sage.categories.finitely_generated_lambdaBracket algebras.FinitelyGeneratedLambdaBracketAlgebras.ParentMethods method), 487
Nilpotent (sage.categories.finite_dimensional_lie algebras_with_basis.FiniteDimensionalLieAlgebrasWithBasis.ParentMethods method), 411
Nilpotent() (sage.categories.lie algebras.LieAlgebras.SubcategoryMethods method), 563
noncrossing_partition_lattice() (sage.categories.finite_complex_reflection_groups.FiniteComplexReflectionGroups.Irreducible.ParentMethods method), 369
numerator() (sage.categories.complete_discrete_valuation.CompleteDiscreteValuationRings.ElementMethods method), 244
numerator() (sage.categories.quotient_fields.QuotientFields.ElementMethods method), 683

O
object() (sage.categories.category_types.Elements method), 909
Objects (class in sage.categories.objects), 667
Objects.ParentMethods (class in sage.categories.objects), 667
Objects.SubcategoryMethods (class in sage.categories.objects), 667
odd_component() (sage.categories.super_modules_with_basis.SuperModulesWithBasis.ElementMethods method), 786

on_basis() (sage.categories.modules_with_basis.ModulesWithBasis.MorphismMethods method), 641

on_left_matrix() (sage.categories.finite_dimensional_algebras_with_basis.FiniteDimensionalAlgebrasWithBasis.ElementMethods method), 393

one() (sage.categories.algebras_with_basis.AlgebrasWithBasis.CartesianProducts.ParentMethods method), 188

one() (sage.categories.algebras_with_basis.AlgebrasWithBasis.ParentMethods method), 190

one() (sage.categories.examples.finite_coxeter_groups.DihedralGroup method), 857

one() (sage.categories.examples.finite_dimensional_algebras_with_basis.KroneckerQuiverPathAlgebra method), 857

one() (sage.categories.examples.finite_monoids.IntegerModMonoid method), 869

one() (sage.categories.examples.finite_weyl_groups.SymmetricGroup method), 869

one() (sage.categories.examples.monomoids.Freemodule method), 884

one() (sage.categories.examples.with_realizations.SubsetAlgebra.Basis method), 902

one() (sage.categories.examples.with_realizations.SubsetAlgebra.Fundamental method), 903

one() (sage.categories.homset.Homset method), 121


one() (sage.categories.magma.Magmas.Unital.ParentMethods method), 599


one() (sage.categories.monomoids.Monomoids.Subquotients.ParentMethods method), 663

one() (sage.categories.monomoids.Monomoids.WithRealizations.ParentMethods method), 664


one_basis() (sage.categories.additive_magmas.AdditiveMagmas.AdditiveUnitalAlgebras.ParentMethods method), 165

one_basis() (sage.categories.algebras_with_basis.AlgebrasWithBasis.TensorProducts.ParentMethods method), 190

one_basis() (sage.categories.examples.algebras_with_basis.FiniteDimensionalAlgebrasWithBasis.FiniteDimensionalAlgebrasWithBasis.ElementMethods method), 847

one_basis() (sage.categories.examples.graded_connected_hopf_algebras_with_basis.GradedConnectedCombinatorialHopfAlgebraWithPrimitiveGenerator method), 871

one_basis() (sage.categories.examples.hopf_algebras_with_basis.MyGroupAlgebra method), 876

one_basis() (sage.categories.examples.lie_algebras_with_basis.IndexedPolynomialRing method), 880

one_basis() (sage.categories.examples.with_realizations.SubsetAlgebra.Fundamental method), 903

one_basis() (sage.categories.graded_algebras_with_basis.GradedAlgebrasWithBasis.SignedTensorProducts.ParentMethods method), 498

one_from_automorphism_group() (sage.categories.algebras_with_basis.GradedConnectedCombinatorialHopfAlgebraWithPrimitiveGenerator method), 871

one_from_automorphism_group() (sage.categories.algebras_with_basis.HopfAlgebrasWithBasis.FiniteDimensionalHopfAlgebras method), 799


one_from_automorphism_group() (sage.categories.groups.Groups.FiniteGroups.ParentMethods method), 520

one_from_automorphism_group() (sage.categories.with_realizations.SubsetAlgebra.Fundamental method), 903

op() (sage.categories.action.Action attribute), 160

operation() (sage.categories.action.Action method), 160

or_subcategory() (sage.categories.category.Category method), 58

order() (sage.categories.groups.Groups.CartesianProducts.ParentMethods method), 520

order() (sage.categories.sets.Sets.FiniteSets.ParentMethods method), 582

order_filter() (sage.categories.posets.Posets.ParentMethods method), 677


order_ideal() (sage.categories.posets.Posets.ParentMethods method), 677


order_ideal_toggle() (sage.categories.action.Action method), 160
Index 973

permutededron() (sage.categories.finite_coxeter_groups.FiniteCoxeterGroups.ParentMethods method), 382
PermutationGroupFunctor (class in sage.categories.pushout), 144
PermutationGroups (class in sage.categories.permutation_groups), 669
Phi() (sage.categories.crystals.Crystals.ElementMethods method), 289
phi() (sage.categories.crystals.Crystals.ElementMethods method), 292
phi() (sage.categories.regular_crystals.RegularCrystals.ElementMethods method), 695
phi() (sage.categories.regular_super crystals.RegularSuperCrystals.ElementMethods method), 702
phi_minus_epsilon() (sage.categories.crystals.Crystals.ElementMethods method), 292
pieri_factors() (sage.categories.weyl_groups.WeylGroups.ParentMethods method), 813
Plane (class in sage.categories.examples.manifolds), 882
plot() (sage.categories.crystals.Crystals.ParentMethods method), 303
plot3d() (sage.categories.crystals.Crystals.ParentMethods method), 303
poincare_birkhoff_witt_basis() (sage.categories.lie_algebras_with_basis.LieAlgebrasWithBasis.ParentMethods method), 566
Pointed() (sage.categories.simplicial_sets.SimplicialSets.SubcategoryMethods method), 775
PointedSets (class in sage.categories.pointed_sets), 670
PolyhedralSets (class in sage.categories.polyhedra), 670
PolynomialFunctor (class in sage.categories.pushout), 144
PoorManMap (class in sage.categories.poor_man_map), 915
Posets (class in sage.categories.posets), 670
Posets.ElementMethods (class in sage.categories.posets), 671
Posets.ParentMethods (class in sage.categories.posets), 672
PositiveIntegerMonoid (class in sage.categories.posets), 854
PositiveIntegersOrderedByDivisibilityFacade (class in sage.categories.examples.posets), 886
PositiveIntegersOrderedByDivisibilityFacade.Element_class (class in sage.categories.examples.posets), 886
post-compose() (sage.categories.map.Map method), 113
powers() (sage.categories.monoids.Monoids.ElementMethods method), 662
pre-compose() (sage.categories.map.Map method),
113
PrecomposedAction (class in sage.categories.action), 161
PrimeNumbers (class in sage.categories.examples.sets_cat), 893
PrimeNumbers_Abstract (class in sage.categories.examples.sets_cat), 894
PrimeNumbers_Abstract.Element (class in sage.categories.examples.sets_cat), 895
PrimeNumbers_Facade (class in sage.categories.examples.sets_cat), 895
PrimeNumbers_Inherits (class in sage.categories.examples.sets_cat), 897
PrimeNumbers_Inherits.Element (class in sage.categories.examples.sets_cat), 898
PrimeNumbers_Wrapper (class in sage.categories.examples.sets_cat), 899
PrincipalIdealDomains (class in sage.categories.principal_ideal_domains), 680
PrincipalIdealDomains.ElementMethods (class in sage.categories.principal_ideal_domains), 680
PrincipalIdealDomains.ParentMethods (class in sage.categories.principal_ideal_domains), 680
print_compare() (in module sage.categories.sets_cat), 758
prod() (sage.categories.commutative_algebras.CommutativeAlgebras.ParentMethods method), 403
prod() (sage.categories.commutative_algebras.CommutativeAlgebras.IntegerModMonoid method), 865
prod() (sage.categories.examples.algebras_with_basis.GradedConnectedCombinatorialHopfAlgebra method), 870
prod() (sage.categories.examples.algebras_with_basis.KroneckerQuiverPathAlgebra method), 875
prod() (sage.categories.examples.algebras_with_basis.MyGroupAlgebra method), 876
prod() (sage.categories.examples.algebras_with_basis.SpecialLinearGroup method), 877
prod() (sage.categories.examples.algebras_with_basis.WeylGroup method), 878
prod() (sage.categories.examples.algebras_with_basis.SymmetricGroup method), 879
prod() (sage.categories.examples.algebras_with_basis.SymmetricGroups.ParentMethods method), 880
prod() (sage.categories.examples.algebras_with_basis.SymmetricGroups.SignedTensorProducts.ParentMethods method), 881
prod() (sage.categories.examples.algebras_with_basis.Syme
product_on_basis() (sage.categories.magmatic_algebras.MagmaticAlgebras_with_basis.ParentMethods method), 605
product_space() (sage.categories.finite_dimensional_lie_algebras_with_basis.FiniteDimensionalLieAlgebrasWithBasis.ParentMethods method), 424
profile() (sage.categories.finite_permutation_groups.FinitePermutationGroups.ParentMethods method), 460
profile_polynomial() (sage.categories.finite_permutation_groups.FinitePermutationGroups.ParentMethods method), 460
profile_series() (sage.categories.finite_permutation_groups.FinitePermutationGroups.ParentMethods method), 461
projection() (sage.categories.filtered_algebras_with_basis.FilteredAlgebrasWithBasis.ParentMethods method), 336
projection() (sage.categories.filtered_modules_with_basis.FilteredModulesWithBasis.ParentMethods method), 353
pseudo_order() (sage.categories.finite_monoids.FiniteMonoids.ElementMethods method), 454
pushforward() (sage.categories.morphism.MorphismParentMethods method), 125
pushout() (in module sage.categories.pushout), 150
pushout() (sage.categories.pushout.ConstructionFunctor method), 136
pushout_lattice() (in module sage.categories.pushout), 156

Q

q() (sage.categories.quantum_group_representations.QuantumGroupRepresentations.QuantumGroupRepresentations.ParentMethods method), 687
q_dimension() (sage.categories.highest_weight_crystals.HighestWeightCrystals.ParentMethods method), 532
q_dimension() (sage.categories.loop_crystals.KirillovReshetikhinCrystals.ParentMethods method), 578
quantum_bruhat_graph() (sage.categories.weyl_groups.WeylGroups.ParentMethods method), 814
quantum_bruhat_successors() (sage.categories.weyl_groups.WeylGroups.ElementMethods method), 809
QuantumGroupRepresentations (class in sage.categories.quantum_group_representations), 687
QuantumGroupRepresentations.ParentMethods (class in sage.categories.quantum_group_representations), 687
QuantumGroupRepresentations.TensorProducts (class in sage.categories.quantum_group_representations), 688
QuantumGroupRepresentations.TensorProducts.ParentMethods (class in sage.categories.quantum_group_representations), 688
QuotientFields (class in sage.categories.quotient_fields), 681
QuotientFields.ElementMethods (class in sage.categories.quotient_fields), 681
QuotientFields.ParentMethods (class in sage.categories.quotient_fields), 686
QuotientFunctor (class in sage.categories.pushout), 145
QuotientOfLeftZeroSemigroup (class in sage.categories.examples.semigroups), 889
QuotientOfLeftZeroSemigroup.Element (class in sage.categories.examples.semigroups), 890
Quotients() (sage.categories.sets_cat.Sets.Subcategories_with_category, 749
QuotientsCategory (class in sage.categories.quotients), 834

R

r() (sage.categories.loop_crystals.KirillovReshetikhinCrystals.ParentMethods method), 578
R_matrix() (sage.categories.loop_crystals.KirillovReshetikhinCrystals.ParentMethods method), 574
radical() (sage.categories.finite_dimensional_algebras_with_basis.FiniteDimensionalAlgebrasWithBasis.ParentMethods method), 404
radical() (sage.categories.unique_factorization_domains.UniqueFactorizationDomains.ElementMethods method), 795
radical_basis() (sage.categories.finite_dimensional_algebras_with_basis.FiniteDimensionalAlgebrasWithBasis.ParentMethods method), 405
radical_basis() (sage.categories.finite_dimensional_semisimple_algebras_with_basis.FiniteDimensionalSemisimpleAlgebrasWithBasis.ParentMethods method), 441
radical_basis() (sage.categories.semisimple_algebras.SemisimpleAlgebras.ParentMethods method), 731
random_element() (sage.categories.enumerated_sets.EnumeratedSets.ParentMethods method), 319
random_element() (sage.categories.finite_enumerated_sets.FiniteEnumeratedSets.CartesianProducts.ParentMethods method), 446
random_element() (sage.categories.infinite_enumerated_sets.InfiniteEnumeratedSets.ParentMethods method), 543
random_element() (sage.categories.modules_with_basis.ModulesWithBasis.ParentMethods method), 650
random_element_of_length() (sage.categories.coxeter_groups.CoxeterGroups.ParentMethods method), 279
rank (sage.categories.pushout.AlgebraicClosureFunctor attributes), 127
rank (sage.categories.pushout.AlgebraicExtensionFunctor attributes), 130
rank (sage.categories.pushout.BlackBoxConstructionFunctor attributes), 131
rank (sage.categories.pushout.CompletionFunctor attributes), 132
rank (sage.categories.pushout.FractionField attributes), 138
rank (sage.categories.pushout.IdentityConstructionFunctor attributes), 138
rank (sage.categories.pushout.InfinitePolynomialFunctor attributes), 140
rank (sage.categories.pushout.LaurentPolynomialFunctor attributes), 141
rank (sage.categories.pushout.MatrixFunctor attributes), 142
rank (sage.categories.pushout.MultiPolynomialFunctor attributes), 143
rank (sage.categories.pushout.PermutationGroupFunctor attributes), 144
rank (sage.categories.pushout.PolynomialFunctor attributes), 145
rank (sage.categories.pushout.QuotientFunctor attributes), 146
rank (sage.categories.pushout.SubspaceFunctor attributes), 147
rank (sage.categories.pushout.VectorFunctor attributes), 149
rank() (sage.categories.complex_reflection_groups.ComplexReflectionGroups.ParentMethods method), 226
rank() (sage.categories.enumerated_sets.EnumeratedSets.ElementMethods method), 316
rank() (sage.categories.enumerated_sets.EnumeratedSets.ParentMethods method), 319
rank() (sage.categories.finite_complex_reflection_groups.FiniteComplexReflectionGroups.ParentMethods method), 366
rank() (sage.categories.finite_complex_reflection_groups.FiniteComplexReflectionGroups WellGenerated.Irreducible.ParentMethods method), 370
Realizations() (in module sage.categories.realizations), 841
Methods method, 457
right_base_ring() (sage.categories.bimodules.Bimodules method), 200
right_domain() (sage.categories.action.Action method), 160
right_precomposition (sage.categories.action.PrecomposedAction attribute), 162
RightModules (class in sage.categories.right_modules), 702
RightModules.ElementMethods (class in sage.categories.right_modules), 702
RightModules.ParentMethods (class in sage.categories.right_modules), 703
ring() (sage.categories.category_types.CategoryIdeal method), 907
RingIdeals (class in sage.categories.ring_ideals), 703
Rings (class in sage.categories.rings), 704
Rings.ElementMethods (class in sage.categories.rings), 704
Rings.MorphismMethods (class in sage.categories.rings), 705
Rings.ParentMethods (class in sage.categories.rings), 707
Rings.SubcategoryMethods (class in sage.categories.rings), 714
Rngs (class in sage.categories.rngs), 714
rowmotion() (sage.categories.finite_posets.FinitePosets.ParentMethods method), 478
rowmotion_orbit_iter() (sage.categories.finite_posets.FinitePosets.ParentMethods method), 479
rowmotion_orbits() (sage.categories.finite_posets.FinitePosets.ParentMethods method), 480
rowmotion_orbits_plots() (sage.categories.finite_posets.FinitePosets.ParentMethods method), 480
RTrivial (sage.categories.semi_groups.Semigroups attribute), 726
RTrivial() (sage.categories.semi_groups.Semigroups.SubcategoryMethods method), 728
RTrivial_extra_super_categories() (sage.categories.l_trivial_semigroups.LTrivialSemigroups method), 585
RTrivialSemigroups (class in sage.categories.r_trivial_semigroups), 715
s() (sage.categories.crystals.Crystals.ElementMethods method), 292
s() (sage.categories.loop_crystals.KirillovReshetikhinCrystals.ParentMethods method), 578
sage.categories.action
sage.categories.commutative_additive_groups module, 212
sage.categories.commutative_additive_monoids module, 213
sage.categories.commutative_additive_semigroups module, 213
sage.categories.commutative_algebra_ideals module, 214
sage.categories.commutative_algebras module, 215
sage.categories.commutative_ring_ideals module, 215
sage.categories.commutative_rings module, 216
sage.categories.complete_discrete_valuation module, 221
sage.categories.complex_reflection_groups module, 225
sage.categories.complex_reflection_or_generalized_coxeter_groups module, 227
sage.categories.covariant_functorial_construction module, 817
sage.categories.coxeter_group_algebras module, 243
sage.categories.coxeter_groups module, 246
sage.categories.crystals module, 283
sage.categories.cw_complexes module, 306
sage.categories.discrete_valuation module, 309
sage.categories.distributive_magmas_and_additive_magmas module, 312
sage.categories.division_rings module, 313
sage.categories.domains module, 314
sage.categories.dual module, 827
sage.categories.enumerated_sets module, 315
sage.categories.euclidean_domains module, 321
sage.categories.examples.algebras_with_basis module, 847
sage.categories.examples.commutative_additive_monoids module, 848
sage.categories.examples.commutative_additive_semigroups module, 849
sage.categories.examples.commutative_algebras module, 851
sage.categories.examples.commutative_ring_ideals module, 851
sage.categories.examples.commutative_rings module, 854
sage.categories.examples.coxeter_groups module, 855
sage.categories.examples.euclidean_domains module, 857
sage.categories.examples.finite_coxeter_groups module, 858
sage.categories.examples.finite_dimenional_algebras_with_basis module, 859
sage.categories.examples.finite_dimenional_lie_algebras_with_basis module, 860
sage.categories.examples.finite enumerated_sets module, 862
sage.categories.examples.finite_monoids module, 864
sage.categories.examples.finite_semigroups module, 866
sage.categories.examples.finite_weyl_groups module, 868
sage.categories.examples.graded_connected_hopf_algebras_with_basis module, 870
sage.categories.examples.graded_modules_with_basis module, 871
sage.categories.examples.graphs module, 874
sage.categories.examples.hopf_algebras_with_basis module, 875
sage.categories.examples.infinite enumerated_sets module, 877
<table>
<thead>
<tr>
<th>Module Name</th>
<th>Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>sage.categories.examples.lie_algebras</td>
<td>878</td>
</tr>
<tr>
<td>sage.categories.examples.lie_algebras_with_basis</td>
<td>879</td>
</tr>
<tr>
<td>sage.categories.examples.magmas</td>
<td>881</td>
</tr>
<tr>
<td>sage.categories.examples.manifolds</td>
<td>882</td>
</tr>
<tr>
<td>sage.categories.examples.monoids</td>
<td>883</td>
</tr>
<tr>
<td>sage.categories.examples.posets</td>
<td>885</td>
</tr>
<tr>
<td>sage.categories.examples.semigroups</td>
<td>887</td>
</tr>
<tr>
<td>sage.categories.examples.semigroups_cython</td>
<td>891</td>
</tr>
<tr>
<td>sage.categories.examples.sets_cat</td>
<td>893</td>
</tr>
<tr>
<td>sage.categories.examples.sets_with_grading</td>
<td>899</td>
</tr>
<tr>
<td>sage.categories.examples.with_realizations</td>
<td>900</td>
</tr>
<tr>
<td>sage.categories.facade_sets</td>
<td>815</td>
</tr>
<tr>
<td>sage.categories.fields</td>
<td>324</td>
</tr>
<tr>
<td>sage.categories.filtered_algebras</td>
<td>329</td>
</tr>
<tr>
<td>sage.categories.filtered_algebras_with_basis</td>
<td>329</td>
</tr>
<tr>
<td>sage.categories.filtered_modules</td>
<td>337</td>
</tr>
<tr>
<td>sage.categories.filtered_modules_with_basis</td>
<td>339</td>
</tr>
<tr>
<td>sage.categories.finite_complex_reflection_groups</td>
<td>355</td>
</tr>
<tr>
<td>sage.categories.finite_coxeter_groups</td>
<td>373</td>
</tr>
<tr>
<td>sage.categories.finite_crystals</td>
<td>387</td>
</tr>
<tr>
<td>sage.categories.finite_dimensional_algebras</td>
<td>388</td>
</tr>
<tr>
<td>sage.categories.finite_dimensional_algebras_with_basis</td>
<td>388</td>
</tr>
<tr>
<td>sage.categories.finite_dimensional_coalgebras</td>
<td>408</td>
</tr>
<tr>
<td>sage.categories.finite_dimensional_coalgebras_with_basis</td>
<td>408</td>
</tr>
<tr>
<td>sage.categories.finite_dimensional_graded_lie_algebras</td>
<td>408</td>
</tr>
<tr>
<td>sage.categories.finite_dimensional_graded_lie_algebras_with_basis</td>
<td>408</td>
</tr>
<tr>
<td>sage.categories.finite_dimensional_hopf_algebras</td>
<td>410</td>
</tr>
<tr>
<td>sage.categories.finite_dimensional_hopf_algebras_with_basis</td>
<td>410</td>
</tr>
<tr>
<td>sage.categories.finite_dimensional_lie_algebras</td>
<td>410</td>
</tr>
<tr>
<td>sage.categories.finite_dimensional_lie_algebras_with_basis</td>
<td>410</td>
</tr>
<tr>
<td>sage.categories.finite_dimensional_modules</td>
<td>429</td>
</tr>
<tr>
<td>sage.categories.finite_dimensional_modules_with_basis</td>
<td>429</td>
</tr>
<tr>
<td>sage.categories.finite_dimensional_nilpotent_lie_algebras</td>
<td>438</td>
</tr>
<tr>
<td>sage.categories.finite_dimensional_nilpotent_lie_algebras_with_basis</td>
<td>438</td>
</tr>
<tr>
<td>sage.categories.finite_dimensional_semisimple_algebras</td>
<td>440</td>
</tr>
<tr>
<td>sage.categories.finite_dimensional_semisimple_algebras_with_basis</td>
<td>440</td>
</tr>
<tr>
<td>sage.categories.finite_enumerated_sets</td>
<td>442</td>
</tr>
<tr>
<td>sage.categories.finite_fields</td>
<td>448</td>
</tr>
<tr>
<td>sage.categories.finite_groups</td>
<td>448</td>
</tr>
<tr>
<td>sage.categories.finite_lattice_posets</td>
<td>448</td>
</tr>
<tr>
<td>sage.categories.finite_monoids</td>
<td>451</td>
</tr>
<tr>
<td>sage.categories.finite_permutation_groups</td>
<td>454</td>
</tr>
<tr>
<td>sage.categories.finite_permutation_groups</td>
<td>458</td>
</tr>
<tr>
<td>sage.categories.finite_posets</td>
<td>462</td>
</tr>
<tr>
<td>sage.categories.finite_semigroups</td>
<td>483</td>
</tr>
<tr>
<td>sage.categories.finite_sets</td>
<td>484</td>
</tr>
<tr>
<td>sage.categories.finite_weyl_groups</td>
<td>486</td>
</tr>
<tr>
<td>sage.categories.finitely_generated(lambda bracket algebras)</td>
<td>486</td>
</tr>
<tr>
<td>sage.categories.finitely_generated(lie conformal algebras)</td>
<td>488</td>
</tr>
<tr>
<td>sage.categories.finitely_generated_magmas</td>
<td>489</td>
</tr>
<tr>
<td>Category</td>
<td>Module</td>
</tr>
<tr>
<td>----------------------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td><code>sage.categories.magmas</code></td>
<td>586</td>
</tr>
<tr>
<td><code>sage.categories.magma_and_additive_magmas</code></td>
<td>600</td>
</tr>
<tr>
<td><code>sage.categories.magmatics_algebras</code></td>
<td>602</td>
</tr>
<tr>
<td><code>sage.categories.manifolds</code></td>
<td>606</td>
</tr>
<tr>
<td><code>sage.categories.map</code></td>
<td>105</td>
</tr>
<tr>
<td><code>sage.categories.matrix_algebras</code></td>
<td>610</td>
</tr>
<tr>
<td><code>sage.categories.metric_spaces</code></td>
<td>611</td>
</tr>
<tr>
<td><code>sage.categories.modular_abelian_varieties</code></td>
<td>615</td>
</tr>
<tr>
<td><code>sage.categories.modules</code></td>
<td>616</td>
</tr>
<tr>
<td><code>sage.categories.modules_with_basis</code></td>
<td>628</td>
</tr>
<tr>
<td><code>sage.categories.monoid_algebras</code></td>
<td>657</td>
</tr>
<tr>
<td><code>sage.categories.monoids</code></td>
<td>658</td>
</tr>
<tr>
<td><code>sage.categories.morphism</code></td>
<td>123</td>
</tr>
<tr>
<td><code>sage.categories.number_fields</code></td>
<td>665</td>
</tr>
<tr>
<td><code>sage.categories.objects</code></td>
<td>667</td>
</tr>
<tr>
<td><code>sage.categories.partially_ordered_monoids</code></td>
<td>668</td>
</tr>
<tr>
<td><code>sage.categories.permutation_groups</code></td>
<td>669</td>
</tr>
<tr>
<td><code>sage.categories.pointed_sets</code></td>
<td>670</td>
</tr>
<tr>
<td><code>sage.categories.polyhedra</code></td>
<td>670</td>
</tr>
<tr>
<td><code>sage.categories.poor_man_map</code></td>
<td>915</td>
</tr>
<tr>
<td><code>sage.categories.posets</code></td>
<td>670</td>
</tr>
<tr>
<td><code>sage.categories.primer</code></td>
<td>3</td>
</tr>
<tr>
<td><code>sage.categories.principal_ideal_domains</code></td>
<td>680</td>
</tr>
<tr>
<td><code>sage.categories.pushout</code></td>
<td>127</td>
</tr>
<tr>
<td><code>sage.categories.quantum_group_representations</code></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Category</th>
<th>Module</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>sage.categories.quotient_fields</code></td>
<td>681</td>
</tr>
<tr>
<td><code>sage.categories.quotients</code></td>
<td>834</td>
</tr>
<tr>
<td><code>sage.categories.r_trivial_semigroups</code></td>
<td>714</td>
</tr>
<tr>
<td><code>sage.categories.realizations</code></td>
<td>840</td>
</tr>
<tr>
<td><code>sage.categories.regular_crystals</code></td>
<td>693</td>
</tr>
<tr>
<td><code>sage.categories.regular_supercrystals</code></td>
<td>701</td>
</tr>
<tr>
<td><code>sage.categories.right_modules</code></td>
<td>702</td>
</tr>
<tr>
<td><code>sage.categories.ring_ideals</code></td>
<td>703</td>
</tr>
<tr>
<td><code>sage.categories.rings</code></td>
<td>704</td>
</tr>
<tr>
<td><code>sage.categories.rngs</code></td>
<td>714</td>
</tr>
<tr>
<td><code>sage.categories.schemes</code></td>
<td>715</td>
</tr>
<tr>
<td><code>sage.categories.semisimple_algebras</code></td>
<td>730</td>
</tr>
<tr>
<td><code>sage.categories.semigroups</code></td>
<td>717</td>
</tr>
<tr>
<td><code>sage.categories.semirings</code></td>
<td>730</td>
</tr>
<tr>
<td><code>sage.categories.simplicial_algebras</code></td>
<td>730</td>
</tr>
<tr>
<td><code>sage.categories.shephard_groups</code></td>
<td>762</td>
</tr>
<tr>
<td><code>sage.categories.signed_tensor</code></td>
<td>826</td>
</tr>
<tr>
<td><code>sage.categories.subobjects</code></td>
<td>835</td>
</tr>
<tr>
<td><code>sage.categories.subquotients</code></td>
<td>834</td>
</tr>
<tr>
<td><code>sage.categories.super_algebras</code></td>
<td>776</td>
</tr>
<tr>
<td><code>sage.categories.ideal_super_algebras_with_basis</code></td>
<td>778</td>
</tr>
<tr>
<td><code>sage.categories.simplicial_complexes</code></td>
<td>762</td>
</tr>
<tr>
<td><code>sage.categories.simplicial_sets</code></td>
<td>764</td>
</tr>
<tr>
<td><code>sage.categories.subobjects</code></td>
<td>835</td>
</tr>
<tr>
<td><code>sage.categories.subquotients</code></td>
<td>834</td>
</tr>
<tr>
<td><code>sage.categories.super_algebras</code></td>
<td>776</td>
</tr>
<tr>
<td><code>sage.categories.super_algebras_with_basis</code></td>
<td>778</td>
</tr>
</tbody>
</table>
module, 780
sage.categories.super_Lie_confor-
mal_algebras
module, 780
sage.categories.super_modules
module, 782
sage.categories.super_modules_with_ba-
sis
module, 784
sage.categories.supercommutative_alge-
bras
module, 786
sage.categories.supercrystals
module, 787
sage.categories.tensor
module, 825
sage.categories.topological_spaces
module, 792
sage.categories.triangul-
lar_kac_moody_algebras
module, 793
sage.categories.tutorial
module, 103
sage.categories.unique_factoriza-
tion_domains
module, 795
sage.categories.unital_algebras
module, 797
sage.categories.vector_bundles
module, 800
sage.categories.vector_spaces
module, 801
sage.categories.weyl1_groups
module, 805
sage.categories.with_realizations
module, 842
scaling_factors() (sage.categories.crystals.Crystal-
Morphism method), 287
Schemes (class in sage.categories.schemes), 716
Schemes_over_base (class in sage.cate-
gories.schemes), 717
Section (class in sage.categories.map), 114
section() (sage.categories.map.FormalCompositeMap
method), 108
section() (sage.categories.map.Map method), 114
section() (sage.categories.morphism.IdentityMorphism
method), 124
semidirect_product() (sage.cate-
gories.groups.Groups.ParentMethods method), 526
semigroup_generators() (sage.categories.com-
plex_reflection_or_generalized_cox-
eter_groups.ComplexReflectionOrGeneral-
izedCoxeterGroups.ParentMethods method), 240
semigroup_generators() (sage.categories.ex-
amples.finite_monoids.IntegerModMonoid method), 865
semigroup_generators() (sage.categories.ex-
amples.finite_semigroups.LeftRegularBand
method), 868
semigroup_generators() (sage.categories.ex-
amples.semigroups.FreeSemigroup method), 887
semigroup_generators() (sage.categories.finite_groups.FiniteGroups.ParentMethods
method), 450
semigroup_generators() (sage.cate-
gories.finitely_generated_semigroups.FinitelyGeneratedSemigroups.ParentMethods method), 491
semigroup_generators() (sage.cate-
gories.monoids.Monoids.ParentMethods method), 662
semigroup_generators() (sage.categories.semi-
groups.Semigroups.ParentMethods method), 724
semigroup_generators() (sage.categories.semi-
groups.Semigroups.Semigroups.ParentMethods method), 725
Semigroups (class in sage.categories.seigroups), 717
Semigroups.Algebras (class in sage.categories.semi-
groups), 717
Semigroups.Algebras.ParentMethods (class in sage.categories.seigroups), 717
Semigroups.CartesianProducts (class in sage.categories.seigroups), 720
Semigroups.ElementMethods (class in sage.cate-
gories.seigroups), 720
Semigroups.ParentMethods (class in sage.cate-
gories.seigroups), 720
Semigroups.Quotients (class in sage.cate-
gories.seigroups), 725
Semigroups.Quotients.ParentMethods (class in sage.categories.seigroups), 725
Semigroups.SubcategoryMethods (class in sage.cate-
gories.seigroups), 726
Semigroups.Subquotients (class in sage.cate-
gories.seigroups), 728
Semirings (class in sage.categories.semirings), 730
Semisimple (sage.categories.algebras.Algebras at-	ttribute), 185
Semisimple() (sage.categories.algebras.Algebras.Sub-
categoryMethods method), 186
semisimple_quotient() (sage.categories.fi-
nite_dimensional_algebras_with_basis.Finite-
DimensionalAlgebrasWithBasis.ParentMethods
method), 406
Index 983
SemisimpleAlgebras (class in sage.categories.semisimple_algebras), 730
SemisimpleAlgebras.FiniteDimensional (class in sage.categories.semisimple_algebras), 731
SemisimpleAlgebras.ParentMethods (class in sage.categories.semisimple_algebras), 731
set_base_point () (sage.categories.simplexial_sets.SimplicialSets.ParentMethods method), 766
SetMorphism (class in sage.categories.morphism), 126
Sets (class in sage.categories.sets_cat), 732
Sets.Algebras (class in sage.categories.sets_cat), 734
Sets.Algebras.ParentMethods (class in sage.categories.sets_cat), 734
Sets.CartesianProducts (class in sage.categories.sets_cat), 735
Sets.CartesianProducts.ElementMethods (class in sage.categories.sets_cat), 735
Sets.CartesianProducts.ParentMethods (class in sage.categories.sets_cat), 736
Sets.ElementMethods (class in sage.categories.sets_cat), 738
Sets.Infinite (class in sage.categories.sets_cat), 739
Sets.Infinite.ParentMethods (class in sage.categories.sets_cat), 739
Sets.IsomorphicObjects (class in sage.categories.sets_cat), 739
Sets.IsomorphicObjects.ParentMethods (class in sage.categories.sets_cat), 740
Sets.MorphismMethods (class in sage.categories.sets_cat), 740
Sets.ParentMethods (class in sage.categories.sets_cat), 740
Sets.Quotients (class in sage.categories.sets_cat), 743
Sets.Quotients.ParentMethods (class in sage.categories.sets_cat), 744
Sets.Realizations (class in sage.categories.sets_cat), 744
Sets.Realizations.ParentMethods (class in sage.categories.sets_cat), 744
Sets.SubcategoryMethods (class in sage.categories.sets_cat), 744
Sets.Subobjects (class in sage.categories.sets_cat), 752
Sets.Subobjects.ParentMethods (class in sage.categories.sets_cat), 752
Sets.Subquotients (class in sage.categories.sets_cat), 752
Sets.Subquotients.ElementMethods (class in sage.categories.sets_cat), 753
Sets.Subquotients.ParentMethods (class in sage.categories.sets_cat), 753
SetsWithGrading (class in sage.categories.sets_with_grading), 759
SetsWithGrading.ParentMethods (class in sage.categories.sets_with_grading), 760
SetsWithPartialMaps (class in sage.categories.sets_with_partial_maps), 761
Sets.WithRealizations (class in sage.categories.sets_cat), 754
Sets.WithRealizations.ParentMethods (class in sage.categories.sets_cat), 754
Sets.WithRealizations.ParentMethods.Realizations (class in sage.categories.sets_cat), 754
shard_poset () (sage.categories.finite_coxeter_groups.FiniteCoxeterGroups.ParentMethods method), 762
ShephardGroups (class in sage.categories.simplicial_sets), 762
sign_representation() (sage.categories.simplicial_sets.SimplicialSets.ParentMethods method), 754
SignedTensorProductFunctor (class in sage.categories.signed_tensor), 826
SignedTensorProducts() (sage.categories.graded_algebras.GradedAlgebras.SubcategoryMethods method), 496
SignedTensorProducts() (sage.categories.graded_coalgebras.GradedCoalgebras.SubcategoryMethods method), 500
SignedTensorProducts() (sage.categories.signed_tensor.SignedTensorProductsCategory), 826
SignedTensorProductsCategory (class in sage.categories.signed_tensor), 826
simple_module_parameterization() (sage.categories.finite_dimensional_algebras_with_basis.FiniteDimensionalAlgebrasWithBasis.Cellular.ParentMethods method), 391
simple_projection() (sage.categories.coxeter_groups.CoxeterGroups.ParentMethods method), 280
simple_projections() (sage.categories.coxeter_groups.CoxeterGroups.ParentMethods method), 281
simple_reflection() (sage.categories.complex_reflection_or_generalized_coxeter_groups.ComplexReflectionOrGeneralizedCoxeterGroups.ParentMethods method), 241
simple_reflection() (sage.categories.examples.finite_weyl_groups.SymmetricGroup method), 870
simple_reflection_orders() (sage.categories.complex_reflection_or_generalized_coxeter_groups.ComplexReflectionOrGeneralized-
Index
super_categories()  (sage.categories.modules.Modules.Subcategories method), 624
super_categories()  (sage.categories.additive_magmas.AdditiveMagmas method), 175
super_categories()  (sage.categories.affine_weyl_groups.AffineWeylGroups method), 181
super_categories()  (sage.categories.algebra ideals.AlgebraIdeals method), 182
super_categories()  (sage.categories.algebra_modules.AlgebraModules method), 182
super_categories()  (sage.categories.bialgebras.Bialgebras method), 194
super_categories()  (sage.categories.bimodules.Bimodules method), 200
super_categories()  (sage.categories.category_types.Elements method), 909
super_categories()  (sage.categories.category_with_axiom.Bars method), 89
super_categories()  (sage.categories.category_with_axiom.Blahs method), 90
super_categories()  (sage.categories.category_with_axiom.CategoryWithAxiom method), 94
super_categories()  (sage.categories.category_with_axiom.TestObjects method), 96
super_categories()  (sage.categories.category_with_axiom.TestObjectsOverBaseRing method), 96
super_categories()  (sage.categories.category.Category method), 61
super_categories()  (sage.categories.category.JoinCategory method), 64
super_categories()  (sage.categories.classical_crystals.ClassicalCrystals method), 203
super_categories()  (sage.categories.coalgebras.Coalgebras method), 209
super_categories()  (sage.categories.commutative_algebra_ideals.CommutativeAlgebraIdeals method), 214
super_categories()  (sage.categories.commutative_ring_ideals.CommutativeRingIdeals method), 215
super_categories()  (sage.categories.complete_discretevaluation.CompleteDiscreteValuationFields method), 222
super_categories()  (sage.categories.complete_discretevaluation.CompleteDiscreteValuationRings method), 224
super_categories()  (sage.categories.complex_reflection_groups.ComplexReflectionGroups method), 226
super_categories()  (sage.categories.complex_reflection_or_generalized_coxeter_groups.ComplexReflectionOrGeneralizedCoxeterGroups method), 243
super_categories()  (sage.categories.covariant FunctorialConstruction FunctorialConstructionCategory method), 822
super_categories()  (sage.categories.coxeter_groups.CoxeterGroups method), 283
super_categories()  (sage.categories.crystals.Crystals method), 306
super_categories()  (sage.categories.crystals.discrete_valuation.DiscreteValuationFields method), 309
super_categories()  (sage.categories.crystals.discrete_valuation.DiscreteValuationRings method), 310
super_categories()  (sage.categories.domains.Domains method), 314
super_categories()  (sage.categories.enumerated_sets.EnumeratedSets method), 321
super_categories()  (sage.categories.euclidean_domains.EuclideanDomains method), 323
super_categories()  (sage.categories.examples.semigroups_cython.IdempotentSemigroups method), 891
super_categories()  (sage.categories.examples.with_realizations.SubsetAlgebra.Bases method), 902
super_categories()  (sage.categories.function_fields.FunctionFields method), 492
super_categories()  (sage.categories.g_sets.GSets method), 493
super_categories()  (sage.categories.gcd_domains.GcdDomains method), 494
super_categories()  (sage.categories.generalized_coxeter_groups.GeneralizedCoxeterGroups method), 495
super_categories()  (sage.categories.graded_hopf_algebras_with_basis.GradedHopfAlgebrasWithBasis method), 503
super_categories()  (sage.categories.groups.Group method), 513
super_categories()  (sage.categories.groupoid.Groupoid method), 519
super_categories()  (sage.categories.hecke_modules.HeckeModules method), 528
super_categories()  (sage.categories.highest_weight_crystals.HighestWeightCrystals method), 535
super_categories()  (sage.categories.homsets.Homsets method), 838
super_categories()  (sage.categories.homsets.HomsetsOf method), 840
super_categories()  (sage.categories.hopf_algebras.HopfAlgebras method), 841
super_categories()  (sage.categories.integer_relations.IntegerRelations method), 842
super_categories()  (sage.categories.linear_categories.LinearCategories method), 843
super_categories()  (sage.categories.manifolds_with_diff_forms.ManifoldsWithDiffForms method), 844
super_categories()  (sage.categories.morphism.Morphism method), 845
super_categories()  (sage.categories.number_fields.NumberFields method), 846
super_categories()  (sage.categories.order.Order method), 847
super_categories()  (sage.categories.principal_ideal_domains.PrincipalIdealDomains method), 848
super_categories()  (sage.categories.principal_ideal_rings.PrincipalIdealRings method), 849
super_categories()  (sage.categories.real_grading.RealGrading method), 850
super_categories()  (sage.categories.real_objects.RealObjects method), 851
super_categories()  (sage.categories.real_vector_spaces.RealVectorSpaces method), 852
super_categories()  (sage.categories.realizations.Realizations method), 853
super_categories()  (sage.categories.rings.Rings method), 854
super_categories()  (sage.categories.rings_with_basis.RingsWithBasis method), 855
super_categories()  (sage.categories.rings_with_covariant_functorial_construction.RingsWithCovariantFunctorialConstruction method), 856
super_categories()  (sage.categories.rings_with_coxeter_groups.RingsWithCoxeterGroups method), 857
super_categories()  (sage.categories.rings_with_enumerated_sets.RingsWithEnumeratedSets method), 858
super_categories()  (sage.categories.rings_with_grading.RingsWithGrading method), 859
super_categories()  (sage.categories.rings_with_homsets.RingsWithHomsets method), 860
super_categories()  (sage.categories.rings_with_realizations.RingsWithRealizations method), 861
super_categories()  (sage.categories.rings_with_vectors.RingsWithVectors method), 862
super_categories()  (sage.categories.structures.Structures method), 863
super_categories()  (sage.categories.tensor_objects.TensorObjects method), 864
super_categories()  (sage.categories.topological_spaces.TopologicalSpaces method), 865
super_categories()  (sage.categories.unique_factorization_domains.UniqueFactorizationDomains method), 866
super_categories()  (sage.categories.unique_factorization_rings.UniqueFactorizationRings method), 867
super_categories()  (sage.categories.unique_factorization_rings_with_basis.UniqueFactorizationRingsWithBasis method), 868
super_categories()  (sage.categories.unique_factorization_rings_with_coxeter_groups.UniqueFactorizationRingsWithCoxeterGroups method), 869
super_categories()  (sage.categories.unique_factorization_rings_with_enumerated_sets.UniqueFactorizationRingsWithEnumeratedSets method), 870
super_categories()  (sage.categories.unique_factorization_rings_with_grading.UniqueFactorizationRingsWithGrading method), 871
super_categories()  (sage.categories.unique_factorization_rings_with_homsets.UniqueFactorizationRingsWithHomsets method), 872
super_categories()  (sage.categories.unique_factorization_rings_with_realizations.UniqueFactorizationRingsWithRealizations method), 873
super_categories()  (sage.categories.unique_factorization_rings_with_vectors.UniqueFactorizationRingsWithVectors method), 874
super_categories()  (sage.categories.unique_factorization_rings_with_vectors.UnderlyingRingsWithVectors method), 875
super_categories()  (sage.categories.unital_domains.UnitalDomains method), 876
super_categories()  (sage.categories.unital_rings.UnitalRings method), 877
super_categories()  (sage.categories.unity.Unity method), 878
super_categories()  (sage.categories.unity_elements.UnityElements method), 879
super_categories()  (sage.categories.unity_elements_with_axiom.UnityElementsWithAxiom method), 880
super_categories()  (sage.categories.unity_elements_with_axiom.UnityElementsWithAxiomWithRealizations method), 881
super_categories()  (sage.categories.unity_elements_with_axiom_with_realizations.UnityElementsWithAxiomWithRealizations method), 882
super_categories()  (sage.categories.unity_elements_with_coxeter_groups.UnityElementsWithCoxeterGroups method), 883
super_categories()  (sage.categories.unity_elements_with_coxeter_groups.UnityElementsWithCoxeterGroupsWithRealizations method), 884
super_categories()  (sage.categories.unity_elements_with_enumerated_sets.UnityElementsWithEnumeratedSets method), 885
super_categories()  (sage.categories.unity_elements_with_enumerated_sets.UnityElementsWithEnumeratedSetsWithRealizations method), 886
super_categories()  (sage.categories.unity_elements_with_grading.UnityElementsWithGrading method), 887
super_categories()  (sage.categories.unity_elements_with_homsets.UnityElementsWithHomsets method), 888
super_categories()  (sage.categories.unity_elements_with_homsets.UnityElementsWithHomsetsWithRealizations method), 889
super_categories()  (sage.categories.unity_elements_with_realizations.UnityElementsWithRealizations method), 890
super_categories()  (sage.categories.unity_elements_with_vectors.UnityElementsWithVectors method), 891
super_categories()  (sage.categories.unity_elements_with_vectors.UnityElementsWithVectorsWithRealizations method), 892
super_categories()  (sage.categories.unity_elements_with_vectors.UnderlyingElementsWithVectors method), 893

<table>
<thead>
<tr>
<th>Category</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>bras.HopfAlgebras method</code></td>
<td>538</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.kac_moody_algebras.KacMoodyAlgebras method)</td>
<td>546</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.lambda_bracket_algebras.LambdaBracketAlgebras method)</td>
<td>548</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.lattice_posets.LatticePosets method)</td>
<td>551</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.left_modules.LeftModules method)</td>
<td>551</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.lie_algebras.LieAlgebras method)</td>
<td>563</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.lie_conformal_algebras.LieConformalAlgebras method)</td>
<td>569</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.lie_groups.LieGroups method)</td>
<td>573</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.loop_crystals.KirillovReshetikhinCrystals method)</td>
<td>583</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.loop_crystals.RegularLoopCrystals method)</td>
<td>584</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.loop_crystals.RegularSuperCrystals method)</td>
<td>585</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.magmas_and_additive_magmas.MagmasAndAdditiveMagmas method)</td>
<td>602</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.magmas.Magmas method)</td>
<td>600</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.magnific_algebras.MagmaticAlgebras method)</td>
<td>606</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.manifolds.ComplexManifolds method)</td>
<td>606</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.manifolds.Manifolds method)</td>
<td>610</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.matrix_algebras.MatrixAlgebras method)</td>
<td>610</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.modular_abelian_varieties.ModularAbelianVarieties method)</td>
<td>615</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.modules.Modules method)</td>
<td>627</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.number_fields.NumberFields method)</td>
<td>666</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.objects.Objects method)</td>
<td>668</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.partially_ordered_monoids.PartiallyOrderedMonoids method)</td>
<td>669</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.permutation_groups.PermutationGroups method)</td>
<td>669</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.pointed_sets.PointedSets method)</td>
<td>670</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.polyhedrals.PolyhedralSets method)</td>
<td>670</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.posets.Posets method)</td>
<td>679</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.principal_ideal_domains.PrincipalIdealDomains method)</td>
<td>680</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.quantum_group_representations.QuantumGroupRepresentations method)</td>
<td>693</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.quotient_fields.QuotientFields method)</td>
<td>686</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.regular_crystals.RegularCrystals method)</td>
<td>700</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.regular_supercrystals.RegularSuperCrystals method)</td>
<td>702</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.right_modules.RightModules method)</td>
<td>703</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.schemes.AbelianVarieties method)</td>
<td>716</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.schemes.Schemes method)</td>
<td>716</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.schemes.Schemes_over_base method)</td>
<td>717</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.schemes.schemes_with_grading.SetsWithGrading method)</td>
<td>731</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.sets_cat.Sets method)</td>
<td>758</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.sets_cat.Sets_with_realizations.ParentMethodsRealizations method)</td>
<td>754</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.simplicial_sets.SetsWithPartialMaps method)</td>
<td>762</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.simplicial_sets.SimplicialSets method)</td>
<td>775</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.simplicial_sets.SimplicialSets_SetsWithPartialMaps method)</td>
<td>783</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.standard_crystals.StandardCrystals method)</td>
<td>791</td>
</tr>
<tr>
<td><code>super_categories()</code></td>
<td></td>
</tr>
<tr>
<td>(sage.categories.triangular_kac_moody_algebras.TriangularKacMoodyAlgebras method)</td>
<td>795</td>
</tr>
</tbody>
</table>
super_categories() (sage.categories.unique_factorization_domains.UniqueFactorizationDomains method), 797
super_categories() (sage.categories.vector_bundles.VectorBundles method), 801
super_categories() (sage.categories.vector_spaces.VectorSpaces method), 805
super_categories() (sage.categories.weyl_groups.WeylGroups method), 815
SuperAlgebras (class in sage.categories.super_algebras), 776
SuperAlgebras.ParentMethods (class in sage.categories.super_algebras), 776
SuperAlgebras.SignedTensorProducts (class in sage.categories.super_algebras), 777
SuperAlgebras.SubcategoryMethods (class in sage.categories.super_algebras), 777
SuperAlgebrasWithBasis (class in sage.categories.super_algebras_with_basis), 778
SuperAlgebrasWithBasis.ElementMethods (class in sage.categories.super_algebras_with_basis), 778
SuperAlgebrasWithBasis.ParentMethods (class in sage.categories.super_algebras_with_basis), 779
SuperAlgebrasWithBasis.SignedTensorProducts (class in sage.categories.super_algebras_with_basis), 779
SuperAlgebrasWithBasis.ElementMethods (class in sage.categories.super_algebras_with_basis), 779
SuperAlgebrasWithBasis.ParentMethods (class in sage.categories.super_algebras_with_basis), 779
SuperAlgebrasWithBasis.SignedTensorProducts (class in sage.categories.super_algebras_with_basis), 779
Superalgebras (class in sage.categories.coalgebras.Coalgebras.Super.SubcategoryMethods method), 207
Supercommutative (sage.categories.super_algebras.SuperAlgebras attribute), 777
Supercommutative() (class in sage.categories.algebras.Algebras.SubcategoryMethods method), 186
Supercommutative() (sage.categories.algebras.Algebras.SuperSubcategoryMethods method), 777
SupercommutativeAlgebras (class in sage.categories.supercommutative_algebras), 786
SupercommutativeAlgebras.SignedTensorProducts (class in sage.categories.supercommutative_algebras), 787
SupercommutativeAlgebras.WithBasis (class in sage.categories.supercommutative_algebras), 787
SupercommutativeAlgebrasWithBasis.ParentMethods (class in sage.categories.supercommutative_algebras), 787
Supercommutator() (sage.categories.super_algebras_with_basis.SuperAlgebrasWithBasis.ElementMethods method), 778
SuperCrystals (class in sage.categories.supercrystals), 787
SuperCrystals.Finite (class in sage.categories.supercrystals), 787
SuperCrystals.Finite.ElementMethods (class in sage.categories.supercrystals), 787
SuperCrystals.Finite.ParentMethods (class in sage.categories.supercrystals), 788
SuperCrystals.ParentMethods (class in sage.categories.supercrystals), 791
SuperCrystals.TensorProducts (class in sage.categories.supercrystals), 791
SuperHopfAlgebrasWithBasis (class in sage.categories.super_hopf_algebras_with_basis), 780
SuperHopfAlgebrasWithBasis.ParentMethods (class in sage.categories.super_hopf_algebras_with_basis), 780
SuperLieConformalAlgebras (class in sage.categories.super_lie_conformal_algebras), 780
SuperLieConformalAlgebras.ElementMethods (class in sage.categories.super_lie_conformal_algebras), 781
SuperLieConformalAlgebras.Graded (class in sage.categories.super_lie_conformal_algebras), 781
SuperLieConformalAlgebras.ParentMethods (class in sage.categories.super_lie_conformal_algebras), 781
SuperModules (class in sage.categories.super_modules), 782
SuperModulesCategory (class in sage.categories.super Modules), 783
SuperModules.ElementMethods (class in sage.categories.super_modules), 782
SuperModules.ParentMethods (class in sage.categories.super_modules), 783
SuperModulesWithBasis (class in sage.categories.super_modules_with_basis), 784
SuperModulesWithBasis.ElementMethods (class in sage.categories.super_modules_with_basis), 785
SuperModulesWithBasis.ParentMethods (class in sage.categories.super_modules_with_basis), 786
support() (sage.categories.coxeter_groups.CoxeterGroups.ElementMethods method), 268
support() (sage.categories.modules_with_basis.ModulesWithBasis.ElementMethods method), 637
support_of_term() (sage.categories.modules_with_basis.ModulesWithBasis.ElementMethods method), 638
supsets() (sage.categories.examples.with_realizations.SubsetAlgebra method), 905
Surface (class in sage.categories.examples.cw_complexes), 853
Surface.Element (class in sage.categories.examples.cw_complexes), 853
symbol (sage.categories.cartesian_product.CartesianProductFunctor attribute), 824
symbol (sage.categories.dual.DualFunctor attribute), 827
symbol (sage.categories.tensor.TensorProductFunctor attribute), 825
SymmetricGroup (class in sage.categories.examples.finite_weyl_groups), 868
SymmetricGroup.Element (class in sage.categories.examples.finite_weyl_groups), 869
T () (sage.categories.lambda_bracket_algebras.LambdaBracketAlgebras.ElementMethods method), 546
tensor (in module sage.categories.tensor), 825
tensor () (sage.categories.crystals.Crystals.ElementMethods method), 293
tensor () (sage.categories.crystals.Crystals.ParentMethods method), 305
tensor () (sage.categories.modules_with_basis.ModulesWithBasis.ElementMethods method), 638
tensor () (sage.categories.tensor.TensorProducts.ParentMethods method), 654
tensor() (sage.categories.tensor.TensorProducts.ElementMethods method), 690
tensor() (sage.categories.tensor.TensorProducts.ParentMethods method), 627
tensor_square() (sage.categories.tensor.TensorProducts.ElementMethods method), 621
TensorProductFunctor (class in sage.categories.tensor), 825
TensorProducts () (sage.categories.crystals.Crystals.SubcategoryMethods method), 305
TensorProducts () (sage.categories.tensor.TensorProductsElementMethods method), 624
TensorProducts() (sage.categories.tensor.TensorProductsCategory method), 825
TensorProductsCategory (class in sage.categories.tensor), 825
term() (sage.categories.tensor.TensorProducts.ElementMethods method), 654
terms() (sage.categories.tensor.TensorProducts.ElementMethods method), 638
twisted_homology() (sage.categories.simplicial_sets.SimplicialSets.Pointed.ParentMethods method), 772
twisted_invariant_module() (sage.categories.finite_dimensional_modules_with_basis.FiniteDimensionalModulesWithBasis.ParentMethods method), 437
type_to_parent() (in module sage.categories.pushout), 157

U
uncamelcase() (in module sage.categories.category_with_axiom), 98
unicode_symbol (sage.categories.tensor.TensorProductFunctor attribute), 826
unicode_symbol (sage.categories.tensor.TensorProductFunctor attribute), 825
uniformizer() (sage.categories.discrete_valuation.DiscreteValuationRings.ParentMethods method), 311
UniqueFactorizationDomains (class in sage.categories.unique_factorization_domains), 795
UniqueFactorizationDomains.ElementMethods (class in sage.categories.unique_factorization_domains), 796
Unital (sage.categories.associative_algebras.AssociativeAlgebras attribute), 193
Unital (sage.categories.magmatic_algebras.MagmaticAlgebras attribute), 603
Unital (sage.categories.rings.Rings attribute), 714
Unital (sage.categories.semigroups.Semigroups attribute), 729
Unital (sage.categories.category_with_axiom.Blahs.SubcategoryMethods method), 90
Unital() (sage.categories.magmas.Magmas.SubcategoryMethods method), 596
Unital_extra_super_categories() (sage.categories.category_with_axiom.Bars method), 88
UnitalAlgebras (class in sage.categories.unital_algebras), 797
UnitalAlgebras.CartesianProducts (class in sage.categories.unital_algebras), 797
UnitalAlgebras.CartesianProducts.ParentMethods (class in sage.categories.unital_algebras), 797
UnitalAlgebras.ParentMethods (class in sage.categories.unital_algebras), 798
UnitalAlgebras.WithBasis (class in sage.categories.unital_algebras), 798
UnitalAlgebras.WithBasis.ParentMethods (class in sage.categories.unital_algebras), 798
universal_commulative_algebra() (sage.categories.finite_dimensional_lie_algebras_with_basis.FiniteDimensionalLieAlgebrasWithBasis.ParentMethods method), 427
universal_cover() (sage.categories.simplicial_sets.SimplicialSets.Pointed.ParentMethods method), 774
universal_cover_map() (sage.categories.simplicial_sets.SimplicialSets.Pointed.ParentMethods method), 775
universal_enveloping_algebra() (sage.categories.lie_algebras.LieAlgebras.ParentMethods method), 562
universal_polynomials() (sage.categories.finite_dimensional_lie_algebras_with_basis.FiniteDimensionalLieAlgebrasWithBasis.ParentMethods method), 427
unpickle_map() (in module sage.categories.map), 115
unrank() (sage.categories.enumerated_setsEnumeratedSets.ParentMethods method), 320
unrank_range() (sage.categories.enumerated_setsEnumeratedSets.ParentMethods method), 320
upper_covers() (sage.categories.coxeter_groups.CoxeterGroups.ElementMethods method), 268
upper_covers() (sage.categories.posets.Posets.ParentMethods method), 679

V
valuation() (sage.categories.complete discrete valuation.CompleteDiscreteValuationRings.Element-
WithBasis (sage.categories.coalgebras.Coalgebras attribute), 208
WithBasis (sage.categories.hopf_algebras.HopfAlgebras attribute), 538
WithBasis (sage.categories.lambdaBracketAlgebras.LambdaBracketAlgebras attribute), 548
WithBasis (sage.categories.lie_algebras.LieAlgebras attribute), 563
WithBasis (sage.categories.lie_conformal_algebras.LieConformalAlgebras attribute), 569
WithBasis (sage.categories.modules.Modules attribute), 627
WithBasis (sage.categories.semisimple_algebras.SemisimpleAlgebras.FiniteDimensional attribute), 731
WithBasis() (sage.categories.modules.Modules.SubcategoryMethods method), 624
WithRealizations() (in module sage.categories.with_realizations), 842
WithRealizations() (sage.categories.category.Category method), 43
wrapped_class (sage.categories.examples.finite_coxeter_groups.DihedralGroup.Element attribute), 856
wrapped_class (sage.categories.examples.finite_monoids.IntegerModMonoid.Element attribute), 865
wrapped_class (sage.categories.examples.finite_semigroups.LeftRegularBand.Element attribute), 867
wrapped_class (sage.categories.examples.magmas.FreeMagma.Element attribute), 881
wrapped_class (sage.categories.examples.monoids.FreeMonoid.Element attribute), 884
wrapped_class (sage.categories.examples.posets.FiniteSetsOrderedByInclusion.Element attribute), 885
wrapped_class (sage.categories.examples.semi_groups.FreeSemigroup.Element attribute), 887

X
xgcd() (sage.categories.fields.Fields.ElementMethods method), 326
xgcd() (sage.categories.quotient_fields.QuotientFields.ElementMethods method), 685

Z
zero() (sage.categories.additive_magmas.AdditiveMagmas.FiniteDimensional parent.Realizations, ParentMethods method), 168
zero() (sage.categories.additive_magmas.AdditiveMonoids.FiniteDimensional with_realizations, AdditiveUnital.Element attribute), 849
zero() (sage.categories.additive_monoids.FiniteCommutativeAdditiveMonoid.Element attribute), 861
zero() (sage.categories.algebras.Algebras.Element attribute), 861
zero() (sage.categories.categories.Category parent), 43
zero() (sage.categories.categories.Parent parent), 43
zeta_function() (sage.categories.number_fields.NumberFields.Element attribute), 665