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1.1 What is coercion all about?

The primary goal of coercion is to be able to transparently do arithmetic, comparisons, etc. between elements of distinct sets.

As a concrete example, when one writes $1 + 1/2$ one wants to perform arithmetic on the operands as rational numbers, despite the left being an integer. This makes sense given the obvious and natural inclusion of the integers into the rational numbers. The goal of the coercion system is to facilitate this (and more complicated arithmetic) without having to explicitly map everything over into the same domain, and at the same time being strict enough to not resolve ambiguity or accept nonsense. Here are some examples:

```sage
sage: 1 + 1/2
3/2
sage: R.<x,y> = ZZ[]
sage: R
Multivariate Polynomial Ring in x, y over Integer Ring
sage: parent(x)
Multivariate Polynomial Ring in x, y over Integer Ring
sage: parent(1/3)
Rational Field
sage: x+1/3
x + 1/3
sage: parent(x+1/3)
Multivariate Polynomial Ring in x, y over Rational Field
sage: GF(5)(1) + CC(I)
Traceback (most recent call last):
 ...
TypeError: unsupported operand parent(s) for +: 'Finite Field of size 5' and 'Complex Field with 53 bits of precision'
```
1.2 Parents and Elements

Parents are objects in concrete categories, and Elements are their members. Parents are first-class objects. Most things in Sage are either parents or have a parent. Typically whenever one sees the word Parent one can think Set. Here are some examples:

```sage
sage: parent(1)
Integer Ring
sage: parent(1) is ZZ
True
sage: ZZ
Integer Ring
sage: parent(1.5)
Real Field with 120 bits of precision
sage: parent(x)
Symbolic Ring
sage: x^sin(x)
x^sin(x)
sage: R.<t> = Qp(5)

sage: f = t^3-5; f
(1 + O(5^20))*t^3 + 4*5 + 4*5^2 + 4*5^3 + 4*5^4 + 4*5^5 + 4*5^6 + 4*5^7 + 4*5^8 + 4*5^9 + 4*5^10 + 4*5^11 + 4*5^12 + 4*5^13 + 4*5^14 + 4*5^15 + 4*5^16 + 4*5^17 + 4*5^18 + 4*5^19 + 4*5^20 + O(5^21)

sage: parent(f)
Univariate Polynomial Ring in t over 5-adic Field with capped relative precision 20

sage: f = EllipticCurve('37a').lseries().taylor_series(10); f
0.997997869801216 + 0.00140712894524925*z - 0.000498127610960097*z^2 + 0.0000215906522442876*z^3 - 0.0000086506522442708*z^4 + (3.20363155418421e-6)*z^5 + O(z^6) # 32-bit
0.997997869801216 + 0.0014071289452452*z - 0.000498127610960097*z^2 + 0.0000215906522442876*z^3 - 0.0000086506522442708*z^4 + (3.20363155418427e-6)*z^5 + O(z^6) # 64-bit

sage: parent(f)
Power Series Ring in z over Complex Field with 53 bits of precision
```

There is an important distinction between Parents and types:

```sage
sage: a = GF(5).random_element()
sage: b = GF(7).random_element()
sage: type(a)
<type 'sage.rings.finite_rings.integer_mod.IntegerMod_int'>
sage: type(b)
<type 'sage.rings.finite_rings.integer_mod.IntegerMod_int'>
sage: type(a) == type(b)
True
sage: parent(a)
Finite Field of size 5
sage: parent(a) == parent(b)
False
```

However, non-Sage objects do not really have parents, but we still want to be able to reason with them, so their type is used instead:
In fact, under the hood, a special kind of parent “The set of all Python objects of class T” is used in these cases.

Note that parents are not always as tight as possible.

### 1.3 Maps between Parents

Many parents come with maps to and from other parents.

Sage makes a distinction between being able to convert between various parents, and coerce between them. Conversion is explicit and tries to make sense of an object in the target domain if at all possible. It is invoked by calling:

```python
sage: ZZ(5)
5
sage: ZZ(10/5)
2
sage: QQ(10)
10
sage: parent(QQ(10))
Rational Field
sage: a = GF(5)(2); a
2
sage: parent(a)
Finite Field of size 5
sage: parent(ZZ(a))
Integer Ring
sage: GF(71)(1/5)
57
sage: ZZ(1/2)
Traceback (most recent call last):
...
TypeError: no conversion of this rational to integer
```

Conversions need not be canonical (they may for example involve a choice of lift) or even make sense mathematically (e.g. constructions of some kind).

```python
sage: ZZ("123")
123
sage: ZZ(GF(5)(14))
4
sage: ZZ[x](4,3,2,1)
x^3 + 2*x^2 + 3*x + 4
sage: a = Qp(5, 10)(1/3); a
2 + 3*5 + 5*2 + 3*5*3 + 5*4 + 3*5*5 + 5*6 + 3*5*7 + 5*8 + 3*5*9 + 0(5*10)
```

(continues on next page)
On the other hand, Sage has the notion of a **coercion**, which is a canonical morphism (occasionally up to a conventional choice made by developers) between parents. A coercion from one parent to another **must** be defined on the whole domain, and always succeeds. As it may be invoked implicitly, it should be obvious and natural (in both the mathematically rigorous and colloquial sense of the word). Up to inescapable rounding issues that arise with inexact representations, these coercion morphisms should all commute. In particular, if there are coercion maps $A \to B$ and $B \to A$, then their composites must be the identity maps.

Coercions can be discovered via the `Parent.has_coerce_map_from()` method, and if needed explicitly invoked with the `Parent.coerce()` method:

```python
sage: QQ.has_coerce_map_from(ZZ)
True
sage: QQ.has_coerce_map_from(RR)
False
sage: ZZ['x'].has_coerce_map_from(QQ)
False
sage: ZZ['x'].has_coerce_map_from(ZZ)
True
sage: ZZ['x'].coerce(5)
5
sage: ZZ['x'].coerce(5).parent()
Univariate Polynomial Ring in x over Integer Ring
sage: ZZ['x'].coerce(5/1)
Traceback (most recent call last):
...
TypeError: no canonical coercion from Rational Field to Univariate Polynomial Ring in x over Integer Ring
```
CHAPTER TWO

BASIC ARITHMETIC RULES

Suppose we want to add two element, a and b, whose parents are A and B respectively. When we type a+b then

1. If A is B, call a._add_(b)
2. If there is a coercion \( \phi : B \to A \), call a._add_(\( \phi \) (b))
3. If there is a coercion \( \phi : A \to B \), call \( \phi \) (a)._add_(b)
4. Look for Z such that there is a coercion \( \phi_A : A \to Z \) and \( \phi_B : B \to Z \), call \( \phi_A \) (a)._add_(\( \phi_B \) (b))

These rules are evaluated in order; therefore if there are coercions in both directions, then the parent of a._add_b is A – the parent of the left-hand operand is used in such cases.

The same rules are used for subtraction, multiplication, and division. This logic is embedded in a coercion model object, which can be obtained and queried.

```
sage: parent(1 + 1/2)
Rational Field
sage: cm = coercion_model; cm
<coercion_model.CoercionModel at ...>
```

```
sage: cm.explain(ZZ, QQ)
Coercion on left operand via
   Natural morphism:
      From: Integer Ring
      To:   Rational Field
Arithmetic performed after coercions.
Result lives in Rational Field
Rational Field
```

```
sage: cm.explain(ZZ['x','y'], QQ['x'])
Coercion on left operand via
   Coercion map:
      From: Multivariate Polynomial Ring in x, y over Integer Ring
      To:   Multivariate Polynomial Ring in x, y over Rational Field
Coercion on right operand via
   Coercion map:
      From: Univariate Polynomial Ring in x over Integer Ring
      To:   Multivariate Polynomial Ring in x, y over Rational Field
Arithmetic performed after coercions.
Result lives in Multivariate Polynomial Ring in x, y over Rational Field
Multivariate Polynomial Ring in x, y over Rational Field
```

The coercion model can be used directly for any binary operation (callable taking two arguments).
There are also actions in the sense that a field \( K \) acts on a module over \( K \), or a permutation group acts on a set. These are discovered between steps 1 and 2 above.

```sage
sage: cm.bin_op(77, 9, gcd)
1
```

Note that by trac ticket #14711 Sage's coercion system uses maps with weak references to the domain. Such maps should only be used internally, and so a copy should be used instead (unless one knows what one is doing):

```sage
sage: QQ.coerce_map_from(int)
Native morphism:
  From: Set of Python objects of class 'int'
  To:   Rational Field
sage: QQ2 = QQ^2
(continues on next page)
```
<table>
<thead>
<tr>
<th>Command</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>sage: (QQ2).get_action(QQ)</code></td>
<td>Right scalar multiplication by Rational Field on Vector space of dimension 2 over Rational Field</td>
</tr>
<tr>
<td><code>sage: QQ['x'].get_action(RR)</code></td>
<td>Right scalar multiplication by Real Field with 53 bits of precision on Univariate Polynomial Ring in x over Rational Field</td>
</tr>
</tbody>
</table>
3.1 Methods to implement

- Arithmetic on Elements: _add_, _sub_, _mul_, _div_

  This is where the binary arithmetic operators should be implemented. Unlike Python’s __add__, both operands are guaranteed to have the same Parent at this point.

- Coercion for Parents: _coerce_map_from_

  Given two parents R and S, R._coerce_map_from_(S) is called to determine if there is a coercion \( \phi : S \rightarrow R \). Note that the function is called on the potential codomain. To indicate that there is no coercion from S to R (self), return False or None. This is the default behavior. If there is a coercion, return True (in which case an morphism using R._element_constructor_ will be created) or an actual Morphism object with S as the domain and R as the codomain.

- Actions for Parents: _get_action_ or _rmul_, _lmul_, _act_on_, _acted_upon_

  Suppose one wants R to act on S. Some examples of this could be \( R = \mathbb{Q}, S = \mathbb{Q}[x] \) or \( R = \text{Gal}(S/\mathbb{Q}) \) where \( S \) is a number field. There are several ways to implement this:

  - If \( R \) is the base of \( S \) (as in the first example), simply implement _rmul_ and/or _lmul_ on the Elements of \( S \). In this case \( r \ast s \) gets handled as \( s._rmul_(r) \) and \( s \ast r \) as \( s._lmul_(r) \). The argument to _rmul_ and _lmul_ are guaranteed to be Elements of the base of \( S \) (with coercion happening beforehand if necessary).

  - If \( R \) acts on \( S \), one can define the methods _act_on_ on Elements of \( R \) or _acted_upon_ on Elements of \( S \). In this case \( r \ast s \) gets handled as \( r._act_on_(s, \text{True}) \) or \( s._acted_upon_(r, \text{False}) \) and \( s \ast r \) as \( r._act_on_(s, \text{False}) \) or \( s._acted_upon_(r, \text{True}) \). There is no constraint on the type or parents of objects passed to these methods; raise a TypeError or ValueError if the wrong kind of object is passed in to indicate the action is not appropriate here.

  - If either \( R \) acts on \( S \) or \( S \) acts on \( R \), one may implement R._get_action_ to return an actual Action object to be used. This is how non-multiplicative actions must be implemented, and is the most powerful and complete way to do things.

  It should be noted that for the first way to work, elements of \( S \) are required to be ModuleElements. This requirement is likely to be lifted in the future.

- Element conversion/construction for Parents: use _element_constructor_ not __call__

  The Parent.__call__() method dispatches to _element_constructor_. When someone writes \( R(x, \ldots) \), this is the method that eventually gets called in most cases. See the documentation on the __call__ method below.

  Parents may also call the self._populate_coercion_lists_ method in their __init__ functions to pass any callable for use instead of _element_constructor_. Provide a list of Parents with coercions to self (as an alternative
to implementing _coerce_map_from_, provide special construction methods (like \_integer\_ for \ZZ\_), etc. This also allows one to specify a single coercion embedding out of self (whereas the rest of the coercion functions all specify maps into self). There is extensive documentation in the docstring of the \_populate_coercion_lists_ method.

### 3.2 Example

Sometimes a simple example is worth a thousand words. Here is a minimal example of setting up a simple Ring that handles coercion. (It is easy to imagine much more sophisticated and powerful localizations, but that would obscure the main points being made here.)

```python
class Localization(Ring):
    def __init__(self, primes):
        """Localization of `\ZZ` away from primes."
        Ring.__init__(self, base=ZZ)
        self._primes = primes
        self._populate_coercion_lists_()

    def _repr_(self):
        """How to print self."
        return "%s localized at %s" % (self.base(), self._primes)

    def _element_constructor_(self, x):
        """Make sure x is a valid member of self, and return the constructed element."
        if isinstance(x, LocalizationElement):
            x = x._value
        else:
            x = QQ(x)
        for p, e in x.denominator().factor():
            if p not in self._primes:
                raise ValueError("Not integral at %s" % p)
        return LocalizationElement(self, x)

    def _coerce_map_from_(self, S):
        """The only things that coerce into this ring are:
        - the integer ring
        - other localizations away from fewer primes"
        if S is ZZ:
            return True
        elif isinstance(S, Localization):
            return all(p in self._primes for p in S._primes)
```

(continues on next page)
class LocalizationElement(RingElement):
    
    def __init__(self, parent, x):
        RingElement.__init__(self, parent)
        self._value = x

    # We're just printing out this way to make it easy to see what's going on in the examples.
    def __repr__(self):
        return "LocalElt(%s)" % self._value

    # Now define addition, subtraction, and multiplication of elements.
    # Note that left and right always have the same parent.
    def __add__(left, right):
        return LocalizationElement(left.parent(), left._value + right._value)
    def __sub__(left, right):
        return LocalizationElement(left.parent(), left._value - right._value)
    def __mul__(left, right):
        return LocalizationElement(left.parent(), left._value * right._value)

    # The basering was set to ZZ, so c is guaranteed to be in ZZ
    def __rmul__(self, c):
        return LocalizationElement(self.parent(), c * self._value)
    def __lmul__(self, c):
        return LocalizationElement(self.parent(), self._value * c)

That's all there is to it. Now we can test it out:

```
sage: R = Localization([2]); R
Integer Ring localized at [2]
sage: R(1)
LocalElt(1)
sage: R(1/2)
LocalElt(1/2)
sage: R(1/3)
Traceback (most recent call last):
... ValueError: Not integral at 3

sage: R.coerce(1)
LocalElt(1)
sage: R.coerce(1/4)
Traceback (click to the left for traceback)
... TypeError: no canonical coercion from Rational Field to Integer Ring localized at [2]
```
\begin{verbatim}
    sage: R(1/2) + R(3/4)
    LocalElt(5/4)
    sage: R(1/2) + 5
    LocalElt(11/2)
    sage: 5 + R(1/2)
    LocalElt(11/2)
    sage: R(1/2) + 1/7
    Traceback (most recent call last):
    ...TypeError: unsupported operand parent(s) for +: 'Integer Ring localized at [2]' and
               'Rational Field'
    sage: R(3/4) * 7
    LocalElt(21/4)
    sage: R.get_action(ZZ)
    Right scalar multiplication by Integer Ring on Integer Ring localized at [2]
    sage: cm = sage.structure.element.get_coercion_model()
    sage: cm.explain(R, ZZ, operator.add)
    Coercion on right operand via
    Conversion map:
      From: Integer Ring
      To:    Integer Ring localized at [2]
    Arithmetic performed after coercions.
    Result lives in Integer Ring localized at [2]
    Integer Ring localized at [2]
    sage: cm.explain(R, ZZ, operator.mul)
    Action discovered.
    Right scalar multiplication by Integer Ring on Integer Ring localized at [2]
    Result lives in Integer Ring localized at [2]
    Integer Ring localized at [2]
    sage: R6 = Localization([2,3]); R6
    Integer Ring localized at [2, 3]
    sage: R6(1/3) - R(1/2)
    LocalElt(-1/6)
    sage: parent(R6(1/3) - R(1/2))
    Integer Ring localized at [2, 3]
    sage: R.has_coerce_map_from(ZZ)
    True
    sage: R.coerce_map_from(ZZ)
    Conversion map:
      From: Integer Ring
      To:    Integer Ring localized at [2]
    sage: R6.coerce_map_from(R)
    Conversion map:
      From: Integer Ring localized at [2]
      To:    Integer Ring localized at [2, 3]
\end{verbatim}
3.3 Provided Methods

- **__call__**
  This provides a consistent interface for element construction. In particular, it makes sure that conversion always gives the same result as coercion, if a coercion exists. (This used to be violated for some Rings in Sage as the code for conversion and coercion got edited separately.) Let R be a Parent and assume the user types R(x), where x has parent X. Roughly speaking, the following occurs:
  1. If X is R, return x (*)
  2. If there is a coercion \( f : X \to R \), return \( f(x) \)
  3. If there is a coercion \( f : R \to X \), try to return \( f^{-1}(x) \)
  4. Return R._element_constructor_(x) (**)

  Keywords and extra arguments are passed on. The result of all this logic is cached.

  (*) Unless there is a “copy” keyword like R(x, copy=False)

  (**) Technically, a generic morphism is created from X to R, which may use magic methods like \_integer\_ or other data provided by \_populate_coercion_lists\_.

- **coerce**
  Coerces elements into self, raising a type error if there is no coercion map.

- **coerce_map_from, convert_map_from**
  Returns an actual Morphism object to coerce/convert from another Parent to self. Barring direct construction of elements of R, R.convert_map_from(S) will provide a callable Python object which is the fastest way to convert elements of S to elements of R. From Cython, it can be invoked via the cdef _call_ method.

- **has_coerce_map_from**
  Returns True or False depending on whether or not there is a coercion. R.has_coerce_map_from(S) is shorthand for R.coerce_map_from(S) is not None

- **get_action**
  This will unwind all the _get_action_, _rmul_, _lmul_, _act_on_, _acted_upon_, ... methods to provide an actual Action object, if one exists.
New parents are discovered using an algorithm in sage/category/pushout.py. The fundamental idea is that most Parents in Sage are constructed from simpler objects via various functors. These are accessed via the construction() method, which returns a (simpler) Parent along with a functor with which one can create self.

```python
sage: CC.construction()
(AlgebraicClosureFunctor, Real Field with 53 bits of precision)
sage: RR.construction()
(Completion[+Infinity, prec=53], Rational Field)
sage: QQ.construction()
(FractionField, Integer Ring)
sage: ZZ.construction()  # None
sage: Zp(5).construction()
(Completion[5, prec=20], Integer Ring)
sage: QQ.completion(5, 100, {})
5-adic Field with capped relative precision 100
sage: c, R = RR.construction()
sage: a = CC.construction()[0]
sage: a.commutes(c)
False
sage: RR == c(QQ)
True
sage: sage.categories.pushout.construction_tower(Frac(CDF['x']))
[(None, Fraction Field of Univariate Polynomial Ring in x over Complex Double Field),
(Poly[x], Complex Double Field),
(AlgebraicClosureFunctor, Real Double Field),
(Completion[+Infinity, prec=53], Rational Field),
(FractionField, Integer Ring)]
```

Given Parents R and S, such that there is no coercion either from R to S or from S to R, one can find a common Z with coercions $R \rightarrow Z$ and $S \rightarrow Z$ by considering the sequence of construction functors to get from a common ancestor to both R and S. We then use a heuristic algorithm to interleave these constructors in an attempt to arrive at a suitable Z (if one exists). For example:

```python
sage: ZZ['x'].construction()
(Poly[x], Integer Ring)
sage: QQ.construction()
(FractionField, Integer Ring)
```

(continues on next page)
The common ancestor is \( \mathbb{Z} \) and our options for \( \mathbb{Z} \) are \( \text{Frac}(\mathbb{Z}[x]) \) or \( \text{Frac}(\mathbb{Z})[x] \). In Sage we choose the later, treating the fraction field functor as binding “more tightly” than the polynomial functor, as most people agree that \( \mathbb{Q}[x] \) is the more natural choice. The same procedure is applied to more complicated Parents, returning a new Parent if one can be unambiguously determined.

```python
sage: sage.categories.pushout.pushout(Frac(ZZ['x', 'y', 'z']), QQ['z', 't'])
Univariate Polynomial Ring in t over Fraction Field of Multivariate Polynomial Ring in x, y, z over Rational Field
```
5.1 The coercion model

The coercion model manages how elements of one parent get related to elements of another. For example, the integer 2 can canonically be viewed as an element of the rational numbers. (The parent of a non-element is its Python type.)

```sage
sage: ZZ(2).parent()
Integer Ring
sage: QQ(2).parent()
Rational Field
```

The most prominent role of the coercion model is to make sense of binary operations between elements that have distinct parents. It does this by finding a parent where both elements make sense, and doing the operation there. For example:

```sage
sage: a = 1/2; a.parent()
Rational Field
sage: b = ZZ['x'].gen(); b.parent()
Univariate Polynomial Ring in x over Integer Ring
sage: a+b
x + 1/2
sage: (a+b).parent()
Univariate Polynomial Ring in x over Rational Field
```

If there is a coercion (see below) from one of the parents to the other, the operation is always performed in the codomain of that coercion. Otherwise a reasonable attempt to create a new parent with coercion maps from both original parents is made. The results of these discoveries are cached. On failure, a TypeError is always raised.

Some arithmetic operations (such as multiplication) can indicate an action rather than arithmetic in a common parent. For example:

```sage
sage: E = EllipticCurve('37a')
sage: P = E(0,0)
sage: 5*P
(1/4 : -5/8 : 1)
```

where there is action of \( \mathbb{Z} \) on the points of \( E \) given by the additive group law. Parents can specify how they act on or are acted upon by other parents.

There are two kinds of ways to get from one parent to another, coercions and conversions.

Coercions are canonical (possibly modulo a finite number of deterministic choices) morphisms, and the set of all coercions between all parents forms a commuting diagram (modulo possibly rounding issues). \( \mathbb{Z} \to \mathbb{Q} \) is an example.
of a coercion. These are invoked implicitly by the coercion model.

Conversions try to construct an element out of their input if at all possible. Examples include sections of coercions, creating an element from a string or list, etc. and may fail on some inputs of a given type while succeeding on others (i.e. they may not be defined on the whole domain). Conversions are always explicitly invoked, and never used by the coercion model to resolve binary operations.

For more information on how to specify coercions, conversions, and actions, see the documentation for Parent.

```python
class sage.structure.coerce.CoercionModel
    Bases: object

    See also sage.categories.pushout

    EXAMPLES:
```
```python
sage: f = ZZ['t','x'].0 + QQ['x'].0 + CyclotomicField(13).gen(); f
t + x + (zeta13)
sage: f.parent()
Multivariate Polynomial Ring in t, x over Cyclotomic Field of order 13 and degree 12
sage: ZZ['x','y'].0 + ~Frac(QQ['y']).0
(x*y + 1)/y
sage: MatrixSpace(ZZ['x'], 2, 2)(2) + ~Frac(QQ['x']).0
[(2*x + 1)/x 0]
[ 0 (2*x + 1)/x]
sage: f = ZZ['x,y,z'].0 + QQ['w,x,z,a'].0; f
w + x
sage: f.parent()
Multivariate Polynomial Ring in w, x, y, z, a over Rational Field
```
```python
```
AUTHOR:

• Robert Bradshaw

```python
analyse(xp, yp, op='mul')

Emulate the process of doing arithmetic between xp and yp, returning a list of steps and the parent that the result will live in. The explain function is easier to use, but if one wants access to the actual morphism and action objects (rather than their string representations) then this is the function to use.

EXAMPLES:
```
```python
sage: cm = sage.structure.element.get_coercion_model()
sage: GF7 = GF(7)
sage: steps, res = cm.analyse(GF7, ZZ)
sage: steps
['Coercion on right operand via', Natural morphism:
  From: Integer Ring
  To:   Finite Field of size 7, "Arithmetic performed after coercions.']
sage: res
Finite Field of size 7
sage: f = steps[1]; type(f)
<type 'sage.rings.finite_rings.integer_mod.Integer_to_IntegerMod'>
sage: f(100)
2
```
```
```
**bin_op**\((x, y, op)\)

Execute the operation op on x and y. It first looks for an action corresponding to op, and failing that, it tries to coerces x and y into a common parent and calls op on them.

If it cannot make sense of the operation, a TypeError is raised.

**INPUT:**

- x - the left operand
- y - the right operand
- op - a python function taking 2 arguments

**Note:** op is often an arithmetic operation, but need not be so.

**EXAMPLES:**

```
sage: cm = sage.structure.element.get_coercion_model()
sage: cm.bin_op(1/2, 5, operator.mul)
5/2
```

The operator can be any callable:

```
sage: R.<x> = ZZ['x']
sage: cm.bin_op(x^2-1, x+1, gcd)
x + 1
```

Actions are detected and performed:

```
sage: M = matrix(ZZ, 2, 2, range(4))
sage: V = vector(ZZ, [5,7])
sage: cm.bin_op(M, V, operator.mul)
(7, 31)
```

**canonical_coercion**\((x, y)\)

Given two elements x and y, with parents S and R respectively, find a common parent Z such that there are coercions \(f: S \rightarrow Z\) and \(g: R \rightarrow Z\) and return \(f(x), g(y)\) which will have the same parent.

Raises a type error if no such Z can be found.

**EXAMPLES:**

```
sage: cm = sage.structure.element.get_coercion_model()
sage: cm.canonical_coercion(mod(2, 10), 17)
(2, 7)
sage: x, y = cm.canonical_coercion(1/2, matrix(ZZ, 2, 2, range(4)))
sage: x
[1/2  0]
[   0 1/2]
sage: y
[ 0  1]
[2  3]
sage: parent(x) is parent(y)
True
```

There is some support for non-Sage datatypes as well:
We also make an exception for 0, even if \( \mathbb{Z} \) does not map in:

```python
sage: canonical_coercion(vector([1, 2, 3]), 0)
((1, 2, 3), (0, 0, 0))
sage: canonical_coercion(GF(5)(0), float(0))
(0, 0)
```

**coercion_maps** \((R, S)\)

Give two parents \( R \) and \( S \), return a pair of coercion maps \( f : R \to Z \) and \( g : S \to Z \), if such a \( Z \) can be found.

In the (common) case that \( R = Z \) or \( S = Z \) then \( None \) is returned for \( f \) or \( g \) respectively rather than constructing (and subsequently calling) the identity morphism.

If no suitable \( f, g \) can be found, a single \( None \) is returned. This result is cached.

**Note:** By trac ticket #14711, coerce maps should be copied when using them outside of the coercion system, because they may become defunct by garbage collection.

**EXAMPLES:**

```python
sage: cm = sage.structure.element.get_coercion_model()
sage: f, g = cm.coercion_maps(ZZ, QQ)
sage: print(copy(f))
Natural morphism:
  From: Integer Ring
  To:   Rational Field
sage: print(g)
None

sage: ZZx = ZZ['x']
sage: f, g = cm.coercion_maps(ZZx, QQ)
sage: print(f)
(map internal to coercion system -- copy before use)
Ring morphism:
```

(continues on next page)
From: Univariate Polynomial Ring in x over Integer Ring
To: Univariate Polynomial Ring in x over Rational Field

\texttt{sage: print(g)}

(map internal to coercion system -- copy before use)
Polynomial base injection morphism:
  From: Rational Field
  To: Univariate Polynomial Ring in x over Rational Field

\texttt{sage: K = GF(7)}
\texttt{sage: cm.coercion_maps(QQ, K) is None}
True

Note that to break symmetry, if there is a coercion map in both directions, the parent on the left is used:

\texttt{sage: V = QQ^3}
\texttt{sage: W = V.__class__(QQ, 3)}
\texttt{sage: V == W}
True
\texttt{sage: V is W}
False
\texttt{sage: cm = sage.structure.element.get_coercion_model()}
\texttt{sage: cm.coercion_maps(V, W)}
(\text{None}, (map internal to coercion system -- copy before use)
  Coercion map:
    From: Vector space of dimension 3 over Rational Field
    To: Vector space of dimension 3 over Rational Field)
\texttt{sage: cm.coercion_maps(W, V)}
(\text{None}, (map internal to coercion system -- copy before use)
  Coercion map:
    From: Vector space of dimension 3 over Rational Field
    To: Vector space of dimension 3 over Rational Field)
\texttt{sage: v = V([1,2,3])}
\texttt{sage: w = W([1,2,3])}
\texttt{sage: parent(v+w) is V}
True
\texttt{sage: parent(w+v) is W}
True

\texttt{common_parent(*args)}

Computes a common parent for all the inputs. It’s essentially an \(n\)-ary canonical coercion except it can operate on parents rather than just elements.

INPUT:

\* args – a set of elements and/or parents

OUTPUT:

A \texttt{Parent} into which each input should coerce, or raises a \texttt{TypeError} if no such \texttt{Parent} can be found.

EXAMPLES:

\texttt{sage: cm = sage.structure.element.get_coercion_model()}
\texttt{sage: cm.common_parent(ZZ, QQ)}
Rational Field
sage: cm.common_parent(ZZ, QQ, RR)
Real Field with 53 bits of precision
sage: ZZZ = ZZ[['T']]
sage: QQZ = QQ[['T']]
sage: cm.common_parent(ZZZ, QQZ, RDF)
Power Series Ring in T over Real Double Field
sage: cm.common_parent(4r, 5r)
<type 'int'>
sage: cm.common_parent(int, float, ZZ)
<type 'float'>
sage: real_fields = [RealField(prec) for prec in [10,20..100]]
sage: cm.common_parent(*real_fields)
Real Field with 10 bits of precision

There are some cases where the ordering does matter, but if a parent can be found it is always the same:

sage: QQxy = QQ[['x,y']]
sage: QQyz = QQ[['y,z']]
sage: cm.common_parent(QQxy, QQyz) == cm.common_parent(QQyz, QQxy)
True
sage: QQzt = QQ[['z,t']]
sage: cm.common_parent(QQxy, QQyz, QQzt)
Multivariate Polynomial Ring in x, y, z, t over Rational Field
sage: cm.common_parent(QQxy, QQzt, QQyz)
Traceback (most recent call last):
...TypeError: no common canonical parent for objects with parents: 'Multivariate Polynomial Ring in x, y over Rational Field' and 'Multivariate Polynomial Ring in z, t over Rational Field'

discover_action(R, S, op, r=None, s=None)

INPUT:
• R - the left Parent (or type)
• S - the right Parent (or type)
• op - the operand, typically an element of the operator module
• r - (optional) element of R
• s - (optional) element of S.

OUTPUT:
• An action A such that s op r is given by A(s,r).

The steps taken are illustrated below.

EXAMPLES:

sage: P.<x> = ZZ[['x']]
sage: P.get_action(ZZ)
Right scalar multiplication by Integer Ring on Univariate Polynomial Ring in x
over Integer Ring
sage: ZZ.get_action(P) is None

True
\begin{verbatim}
sage: cm = sage.structure.element.get_coercion_model()
\end{verbatim}

If \(R\) or \(S\) is a Parent, ask it for an action by/on \(R\):
\begin{verbatim}
sage: cm.discover_action(ZZ, P, operator.mul)
Left scalar multiplication by Integer Ring on Univariate Polynomial Ring in \(x\)
\(\rightarrow\) over Integer Ring
\end{verbatim}

If \(R\) or \(S\) a type, recursively call get_action with the Sage versions of \(R\) and/or \(S\):
\begin{verbatim}
sage: cm.discover_action(P, int, operator.mul)
Right scalar multiplication by Integer Ring on Univariate Polynomial Ring in \(x\)
\(\rightarrow\) over Integer Ring
with precomposition on right by Native morphism:
  From: Set of Python objects of class 'int'
  To: Integer Ring
\end{verbatim}

If \(\text{op}\) is division, look for action on right by inverse:
\begin{verbatim}
sage: cm.discover_action(P, ZZ, operator.truediv)
Right inverse action by Rational Field on Univariate Polynomial Ring in \(x\) over
\(\rightarrow\) Integer Ring
with precomposition on right by Natural morphism:
  From: Integer Ring
  To: Rational Field
\end{verbatim}

Check that trac ticket \#17740 is fixed:
\begin{verbatim}
sage: R = GF(5)['x']
sage: cm.discover_action(R, ZZ, operator.truediv)
Right inverse action by Finite Field of size 5 on Univariate Polynomial Ring in \(x\)
\(\rightarrow\) over Finite Field of size 5
with precomposition on right by Natural morphism:
  From: Integer Ring
  To: Finite Field of size 5
sage: cm.bin_op(R.gen(), 7, operator.truediv).parent()
Univariate Polynomial Ring in \(x\) over Finite Field of size 5
\end{verbatim}

Check that trac ticket \#18221 is fixed:
\begin{verbatim}
sage: F.<x> = FreeAlgebra(QQ)
sage: x / 2
1/2*x
sage: cm.discover_action(F, ZZ, operator.truediv)
Right inverse action by Rational Field on Free Algebra on 1 generators (\(x\))
\(\rightarrow\) over Rational Field
with precomposition on right by Natural morphism:
  From: Integer Ring
  To: Rational Field
\end{verbatim}

\texttt{discover coercion}(\(R, S\))
This actually implements the finding of coercion maps as described in the \texttt{coercion maps} method.

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EXAMPLES:

```python
sage: cm = sage.structure.element.get_coercion_model()
```

If R is S, then two identity morphisms suffice:

```python
sage: cm.discover_coercion(SR, SR)
(None, None)
```

If there is a coercion map either direction, use that:

```python
sage: cm.discover_coercion(ZZ, QQ)
((map internal to coercion system -- copy before use)
Natural morphism:
  From: Integer Ring
  To:  Rational Field, None)
```

```python
sage: cm.discover_coercion(RR, QQ)
(None, (map internal to coercion system -- copy before use)
Generic map:
  From: Rational Field
  To:  Real Field with 53 bits of precision)
```

Otherwise, try and compute an appropriate cover:

```python
sage: ZZxy = ZZ['x,y']
sage: cm.discover_coercion(ZZxy, RDF)
((map internal to coercion system -- copy before use)
Call morphism:
  From: Multivariate Polynomial Ring in x, y over Integer Ring
  To:  Multivariate Polynomial Ring in x, y over Real Double Field,
        (map internal to coercion system -- copy before use)
Polynomial base injection morphism:
  From: Real Double Field
  To:  Multivariate Polynomial Ring in x, y over Real Double Field)
```

Sometimes there is a reasonable “cover,” but no canonical coercion:

```python
sage: sage.categories.pushout.pushout(QQ, QQ^3)
Vector space of dimension 3 over Rational Field
sage: print(cm.discover_coercion(QQ, QQ^3))
None
```

`division_parent(P)`

Deduces where the result of division in P lies by calculating the inverse of `P.one()` or `P.an_element()`.

The result is cached.

EXAMPLES:

```python
sage: cm = sage.structure.element.get_coercion_model()
sage: cm.division_parent(ZZ)
Rational Field
sage: cm.division_parent(QQ)
Rational Field
sage: ZZx = ZZ['x']
```

(continues on next page)
sage: cm.division_parent(ZZx)
Fraction Field of Univariate Polynomial Ring in x over Integer Ring
sage: K = GF(41)
sage: cm.division_parent(K)
Finite Field of size 41
sage: Zmod100 = Integers(100)
sage: cm.division_parent(Zmod100)
Ring of integers modulo 100
sage: S5 = SymmetricGroup(5)
sage: cm.division_parent(S5)
Symmetric group of order 5! as a permutation group

exception_stack()

Returns the list of exceptions that were caught in the course of executing the last binary operation. Useful for diagnosis when user-defined maps or actions raise exceptions that are caught in the course of coercion detection.

If all went well, this should be the empty list. If things aren’t happening as you expect, this is a good place to check. See also coercion_traceback().

EXAMPLES:

sage: cm = sage.structure.element.get_coercion_model()
sage: cm.record_exceptions()
sage: 1/2 + 2
5/2
sage: cm.exception_stack()
[]
sage: 1/2 + GF(3)(2)
Traceback (most recent call last):
  ...TypeError: unsupported operand parent(s) for +: 'Rational Field' and 'Finite Field of size 3'

Now see what the actual problem was:

sage: import traceback
sage: cm.exception_stack()
['Traceback (most recent call last):...','Traceback (most recent call last):...']
sage: print(cm.exception_stack()[-1])
Traceback (most recent call last):
  ...TypeError: no common canonical parent for objects with parents: 'Rational Field' and 'Finite Field of size 3'

This is typically accessed via the coercion_traceback() function.

sage: coercion_traceback()
Traceback (most recent call last):
  ...TypeError: no common canonical parent for objects with parents: 'Rational Field' and 'Finite Field of size 3'
The SageMath function `explain` can be used to understand what coercions will happen for an arithmetic operation between `xp` and `yp` (which may be either elements or parents). If the parent of the result can be determined then it will be returned.

**Examples:**

```python
sage: cm = sage.structure.element.get_coercion_model()

sage: cm.explain(ZZ, ZZ)
Identical parents, arithmetic performed immediately.
Result lives in Integer Ring
Integer Ring

sage: cm.explain(QQ, int)
Coercion on right operand via
   Native morphism:
      From: Set of Python objects of class 'int'
      To:    Rational Field
Arithmetic performed after coercions.
Result lives in Rational Field
Rational Field

sage: R = ZZ['x']

sage: cm.explain(R, QQ)
Action discovered.
   Right scalar multiplication by Rational Field on Univariate Polynomial Ring
   \rightarrow in x over Integer Ring
Result lives in Univariate Polynomial Ring in x over Rational Field
Univariate Polynomial Ring in x over Rational Field

sage: cm.explain(ZZ['x'], QQ, operator.add)
Coercion on left operand via
   Ring morphism:
      From: Univariate Polynomial Ring in x over Integer Ring
      To:    Univariate Polynomial Ring in x over Rational Field
Defn: Induced from base ring by
   Natural morphism:
      From: Integer Ring
      To:    Rational Field
Coercion on right operand via
   Polynomial base injection morphism:
      From: Rational Field
      To:    Univariate Polynomial Ring in x over Rational Field
Arithmetic performed after coercions.
Result lives in Univariate Polynomial Ring in x over Rational Field
Univariate Polynomial Ring in x over Rational Field
```

Sometimes with non-sage types there is not enough information to deduce what will actually happen:

```python
sage: R100 = RealField(100)

sage: cm.explain(R100, float, operator.add)
Right operand is numeric, will attempt coercion in both directions.
Unknown result parent.
```
Special care is taken to deal with division:

\[
\text{sage: cm.explain(ZZ, ZZ, operator.truediv)}
\]
Identical parents, arithmetic performed immediately.
Result lives in Rational Field
Rational Field

\[
\text{sage: ZZx = ZZ['x']}
\]
\[
\text{sage: QQx = QQ['x']}
\]
\[
\text{sage: cm.explain(ZZx, QQx, operator.truediv)}
\]
Coercion on left operand via
Ring morphism:
  From: Univariate Polynomial Ring in x over Integer Ring
  To:  Univariate Polynomial Ring in x over Rational Field
  Defn: Induced from base ring by
          Natural morphism:
            From: Integer Ring
            To:  Rational Field
Arithmetic performed after coercions.
Result lives in Fraction Field of Univariate Polynomial Ring in x over Rational Field

\[
\text{sage: cm.explain(int, ZZ, operator.truediv)}
\]
Coercion on left operand via
Native morphism:
  From: Set of Python objects of class 'int'
  To:  Integer Ring
Arithmetic performed after coercions.
Result lives in Rational Field
Rational Field

\[
\text{sage: cm.explain(ZZx, ZZ, operator.truediv)}
\]
Action discovered.
  Right inverse action by Rational Field on Univariate Polynomial Ring in x over Integer Ring
  with precomposition on right by Natural morphism:
    From: Integer Ring
    To:  Rational Field
Result lives in Univariate Polynomial Ring in x over Rational Field
Univariate Polynomial Ring in x over Rational Field

**Note:** This function is accurate only in so far as \text{analyse()} is kept in sync with the \text{bin_op()} and

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`canonical_coercion()` which are kept separate for maximal efficiency.

**get_action**

`get_action(R, S, op='mul', r=None, s=None)`  
Get the action of R on S or S on R associated to the operation op.

**EXAMPLES:**

```python
sage: cm = sage.structure.element.get_coercion_model()
sage: ZZx = ZZ['x']
sage: cm.get_action(ZZx, ZZ, operator.mul)
Right scalar multiplication by Integer Ring on Univariate Polynomial Ring in x → over Integer Ring
sage: cm.get_action(ZZx, QQ, operator.mul)
Right scalar multiplication by Rational Field on Univariate Polynomial Ring in x → over Integer Ring
sage: QQx = QQ['x']
sage: cm.get_action(QQx, int, operator.mul)
Right scalar multiplication by Integer Ring on Univariate Polynomial Ring in x → over Rational Field
with precomposition on right by Native morphism:
  From: Set of Python objects of class 'int'
  To: Integer Ring
sage: A = cm.get_action(QQx, ZZ, operator.truediv); A
Right inverse action by Rational Field on Univariate Polynomial Ring in x over Rational Field
with precomposition on right by Natural morphism:
  From: Integer Ring
  To: Rational Field
sage: x = QQx.gen()
sage: A(x+10, 5)
1/5*x + 2
```

**get_cache()**

This returns the current cache of coercion maps and actions, primarily useful for debugging and introspection.

**EXAMPLES:**

```python
sage: cm = sage.structure.element.get_coercion_model()
sage: cm.canonical_coercion(1,2/3)
(1, 2/3)
sage: maps, actions = cm.get_cache()
```

Now let us see what happens when we do a binary operations with an integer and a rational:

```python
sage: left_morphism_ref, right_morphism_ref = maps[ZZ, QQ]
```

Note that by trac ticket #14058 the coercion model only stores a weak reference to the coercion maps in this case:

```python
sage: left_morphism_ref
<weakref at ...; to 'sage.rings.rational.Z_to_Q' at ...>
```

Moreover, the weakly referenced coercion map uses only a weak reference to the codomain:
To get an actual valid map, we simply copy the weakly referenced coercion map:

```python
sage: print(copy(left_morphism_ref()))
Natural morphism:
  From: Integer Ring
  To: Rational Field
```

We can see that it coerces the left operand from an integer to a rational, and doesn’t do anything to the right.

Now for some actions:

```python
sage: R.<x> = ZZ['x']
sage: 1/2 * x
1/2*x
sage: maps, actions = cm.get_cache()
sage: act = actions[QQ, R, operator.mul]; act
Left scalar multiplication by Rational Field on Univariate Polynomial Ring in x over Integer Ring
sage: act.actor()
Rational Field
sage: act.domain()
Univariate Polynomial Ring in x over Integer Ring
sage: act.codomain()
Univariate Polynomial Ring in x over Rational Field
sage: act(1/5, x+10)
1/5*x + 2
```

**record_exceptions**(value=True)

Enables (or disables) recording of the exceptions suppressed during arithmetic.

Each time that record_exceptions is called (either enabling or disabling the record), the exception_stack is cleared.

**reset_cache**()

Clear the coercion cache.

This should have no impact on the result of arithmetic operations, as the exact same coercions and actions will be re-discovered when needed.

It may be useful for debugging, and may also free some memory.

**EXAMPLES:**

```python
sage: cm = sage.structure.element.get_coercion_model()
sage: len(cm.get_cache()[0])  # random
42
sage: cm.reset_cache()
sage: cm.get_cache()
({}, {})
```
richcmp\((x, y, op)\)
Given two arbitrary objects \(x\) and \(y\), coerce them to a common parent and compare them using rich comparison operator \(op\).

EXAMPLES:
```python
sage: from sage.structure.element import get_coercion_model
sage: from sage.structure.richcmp import op_LT, op_LE, op_EQ, op_NE, op_GT, op_GE
sage: richcmp = get_coercion_model().richcmp
sage: richcmp(None, None, op_EQ)
True
sage: richcmp(None, 1, op_LT)
True
sage: richcmp("hello", None, op_LE)
False
sage: richcmp(-1, 1, op_GE)
False
sage: richcmp(int(1), float(2), op_GE)
False
```

If there is no coercion, we only support == and !=:
```python
sage: x = QQ.one(); y = GF(2).one()
sage: richcmp(x, y, op_EQ)
False
sage: richcmp(x, y, op_NE)
True
sage: richcmp(x, y, op_GT)
Traceback (most recent call last):
  ...TypeError: unsupported operand parent(s) for >: 'Rational Field' and 'Finite Field of size 2'
```

We support non-Sage types with the usual Python convention:
```python
sage: class AlwaysEqual(object):
    ....:    def __eq__(self, other):
    ....:        return True
sage: x = AlwaysEqual()
sage: x == 1
True
```

verify_action\((action, R, S, op, fix=True)\)
Verify that \(action\) takes an element of \(R\) on the left and \(S\) on the right, raising an error if not.

This is used for consistency checking in the coercion model.

EXAMPLES:
```python
sage: R.<x> = ZZ['x']
sage: cm = sage.structure.element.get_coercion_model()
sage: cm.verify_action(R.get_action(QQ), R, QQ, operator.mul)
```
Right scalar multiplication by Rational Field on Univariate Polynomial Ring in x over Integer Ring

```
sage: cm.verify_action(R.get_action(QQ), RDF, R, operator.mul)
Traceback (most recent call last):
...
RuntimeError: There is a BUG in the coercion model:
  Action found for R <built-in function mul> S does not have the correct domains
    R = Real Double Field
    S = Univariate Polynomial Ring in x over Integer Ring
    (should be Univariate Polynomial Ring in x over Integer Ring, Rational Field)
    action = Right scalar multiplication by Rational Field on Univariate Polynomial Ring in x over Integer Ring (type 'sage.structure.coerce_actions.RightModuleAction')
```

**verify_coercion_maps(R, S, homs, fix=False)**

Make sure this is a valid pair of homomorphisms from R and S to a common parent. This function is used to protect the user against buggy parents.

**EXAMPLES:**

```
sage: cm = sage.structure.element.get_coercion_model()
sage: homs = QQ.coerce_map_from(ZZ), None
sage: cm.verify_coercion_maps(ZZ, QQ, homs) == homs
True
sage: homs = QQ.coerce_map_from(ZZ), RR.coerce_map_from(QQ)
sage: cm.verify_coercion_maps(ZZ, QQ, homs) == homs
Traceback (most recent call last):
...
RuntimeError: ('BUG in coercion model, codomains must be identical', Natural morphism:
  From: Integer Ring
  To:  Rational Field, Generic map:
  From: Rational Field
  To:  Real Field with 53 bits of precision)
```

**sage.structure.coerce.is_mpmath_type(t)**

Check whether the type t is a type whose name starts with either mpmath. or sage.libs.mpmath.

**EXAMPLES:**

```
sage: from sage.structure.coerce import is_mpmath_type
sage: is_mpmath_type(int)
False
sage: import mpmath
sage: is_mpmath_type(mpmath.mpc(2))
False
sage: is_mpmath_type(type(mpmath.mpc(2)))
True
sage: is_mpmath_type(type(mpmath.mpf(2)))
True
```

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sage.structure.coerce.is_numpy_type(t)
Return True if and only if \( t \) is a type whose name starts with `numpy`.

EXAMPLES:

```python
sage: from sage.structure.coerce import is_numpy_type
sage: import numpy
sage: is_numpy_type(numpy.int16)
True
sage: is_numpy_type(numpy.floating)
True
sage: is_numpy_type(numpy.ndarray)
True
sage: is_numpy_type(numpy.matrix)
True
sage: is_numpy_type(int)
False
sage: is_numpy_type(Integer)
False
sage: is_numpy_type(Sudoku)
False
sage: is_numpy_type(None)
False
```

sage.structure.coerce.parent_is_integers(P)
Check whether the type or parent represents the ring of integers.

EXAMPLES:

```python
sage: from sage.structure.coerce import parent_is_integers
sage: parent_is_integers(int)
True
sage: parent_is_integers(float)
False
sage: parent_is_integers(bool)
True
sage: parent_is_integers(dict)
False
sage: import numpy
sage: parent_is_integers(numpy.int16)
True
sage: parent_is_integers(numpy.uint64)
True
sage: parent_is_integers(float)
False
sage: import gmpy2
sage: parent_is_integers(gmpy2.mpz)
True
sage: parent_is_integers(gmpy2.mpq)
False
```

Ensure (trac ticket #27893) is fixed:
sage: K.<f> = QQ[]
sage: gmpy2.mpz(2) * f
2*f

sage.structure.coerce.parent_is_numerical(P)
Test if elements of the parent or type P can be numerically evaluated as complex numbers (in a canonical way).

EXAMPLES:

```
sage: from sage.structure.coerce import parent_is_numerical
sage: import gmpy2, numpy
sage: [parent_is_numerical(R) for R in [RR, CC, QQ, QuadraticField(-1), ...: int, complex, gmpy2.mpc, numpy.complexfloating]]
[True, True, True, True, True, True, True, True]
sage: [parent_is_numerical(R) for R in [SR, QQ['x'], QQ[['x']], str]]
[False, False, False, False]
sage: [parent_is_numerical(R) for R in [RIF, RBF, CIF, CBF]]
[False, False, False, False]
```

sage.structure.coerce.parent_is_real_numerical(P)
Test if elements of the parent or type P can be numerically evaluated as real numbers (in a canonical way).

EXAMPLES:

```
sage: from sage.structure.coerce import parent_is_real_numerical
sage: import gmpy2
sage: [parent_is_real_numerical(R) for R in [RR, QQ, ZZ, RLF, ...: QuadraticField(2), int, float, gmpy2.mpq, numpy.integer]]
[True, True, True, True, True, True, True, True, True]
sage: [parent_is_real_numerical(R) for R in [CC, QuadraticField(-1), ...: complex, gmpy2.mpc, numpy.complexfloating]]
[False, False, False, False, False]
sage: [parent_is_real_numerical(R) for R in [SR, QQ['x'], QQ[['x']], str]]
[False, False, False, False]
sage: [parent_is_real_numerical(R) for R in [RIF, RBF, CIF, CBF]]
[False, False, False, False]
```

sage.structure.coerce.py_scalar_parent(py_type)
Returns the Sage equivalent of the given python type, if one exists. If there is no equivalent, return None.

EXAMPLES:

```
sage: from sage.structure.coerce import py_scalar_parent
sage: py_scalar_parent(int)
Integer Ring
sage: py_scalar_parent(float)
Real Double Field
sage: py_scalar_parent(complex)
Complex Double Field
sage: py_scalar_parent(bool)
Integer Ring
sage: py_scalar_parent(dict),
(None,
sage: import fractions
```

(continues on next page)
sage: py_scalar_parent(fractions.Fraction)
Rational Field

sage: import numpy
sage: py_scalar_parent(numpy.int16)
Integer Ring
sage: py_scalar_parent(numpy.int32)
Integer Ring
sage: py_scalar_parent(numpy.uint64)
Integer Ring

sage: py_scalar_parent(float)
Real Double Field
sage: py_scalar_parent(numpy.double)
Real Double Field

sage: py_scalar_parent(complex)
Complex Double Field

sage: import gmpy2
sage: py_scalar_parent(gmpy2.mpz)
Integer Ring
sage: py_scalar_parent(gmpy2.mpq)
Rational Field
sage: py_scalar_parent(gmpy2.mpfr)
Real Double Field
sage: py_scalar_parent(gmpy2.mpc)
Complex Double Field

sage.structure.coerce.py_scalar_to_element(x)
Convert x to a Sage Element if possible.

If x was already an Element or if there is no obvious conversion possible, just return x itself.

EXAMPLES:

sage: from sage.structure.coerce import py_scalar_to_element
sage: x = py_scalar_to_element(42)
sage: x, parent(x)
(42, Integer Ring)
sage: x = py_scalar_to_element(int(42))
sage: x, parent(x)
(42, Integer Ring)
sage: x = py_scalar_to_element(float(42))
sage: x, parent(x)
(42.0, Real Double Field)
sage: x = py_scalar_to_element(complex(42))
sage: x, parent(x)
(42.0, Complex Double Field)
sage: py_scalar_to_element('hello')
'hello'

sage: from fractions import Fraction
sage: f = Fraction(int(2^100), int(3^100))
sage: py_scalar_to_element(f)
1267650600228229401496703205376/515377520732011331036461129765621272702107522001

Note that bools are converted to 0 or 1:
sage: py_scalar_to_element(False), py_scalar_to_element(True)
(0, 1)

Test gmpy2’s types:
sage: import gmpy2
sage: x = py_scalar_to_element(gmpy2.mpz(42))
sage: x, parent(x)
(42, Integer Ring)
sage: x = py_scalar_to_element(gmpy2.mpq('3/4'))
sage: x, parent(x)
(3/4, Rational Field)
sage: x = py_scalar_to_element(gmpy2.mpfr(42.57))
sage: x, parent(x)
(42.57, Real Double Field)
sage: x = py_scalar_to_element(gmpy2.mpc(int(42), int(42)))
sage: x, parent(x)
(42.0 + 42.0*I, Complex Double Field)

Test compatibility with py_scalar_parent():
sage: from sage.structure.coerce import py_scalar_parent
sage: elt = [True, int(42), float(42), complex(42)]
sage: for x in elt:
    ....:     assert py_scalar_parent(type(x)) == py_scalar_to_element(x).parent()

sage: elt = [numpy.int8('-12'), numpy.uint8('143'),
    ....:     numpy.int16('-33'), numpy.uint16('122'),
    ....:     numpy.int32('-19'), numpy.uint32('44'),
    ....:     numpy.int64('-3'), numpy.uint64('552'),
    ....:     numpy.float16('-1.23'), numpy.float32('-2.22'),
    ....:     numpy.float64('-3.412'), numpy.complex64(1.2+I),
    ....:     numpy.complex128(-2+I)]

sage: for x in elt:
    ....:     assert py_scalar_parent(type(x)) == py_scalar_to_element(x).parent()

sage: elt = [gmpy2.mpz(42), gmpy2.mpq('3/4'),
    ....:     gmpy2.mpfr(42.57), gmpy2.mpc(int(42), int(42))]

sage: for x in elt:
    ....:     assert py_scalar_parent(type(x)) == py_scalar_to_element(x).parent()
5.2 Coerce actions

class sage.structure.coerce_actions.ActOnAction
    Bases: sage.structure.coerce_actions.GenericAction
    Class for actions defined via the _act_on_ method.

class sage.structure.coerce_actions.ActedUponAction
    Bases: sage.structure.coerce_actions.GenericAction
    Class for actions defined via the _acted_upon_ method.

class sage.structure.coerce_actions.GenericAction
    Bases: sage.categories.action.Action
    codomain()
        Returns the “codomain” of this action, i.e. the Parent in which the result elements live. Typically, this
        should be the same as the acted upon set.

        EXAMPLES:
        Note that coerce actions should only be used inside of the coercion model. For this test, we need to strongly
        reference the domains, for otherwise they could be garbage collected, giving rise to random errors (see trac
        ticket #18157).

        sage: M = MatrixSpace(ZZ,2)
        sage: A = sage.structure.coerce_actions.ActedUponAction(M, Cusps, True)
        sage: A.codomain()
        Set P^1(QQ) of all cusps
        sage: S3 = SymmetricGroup(3)
        sage: QQxyz = QQ['x,y,z']
        sage: A = sage.structure.coerce_actions.ActOnAction(S3, QQxyz, False)
        sage: A.codomain()
        Multivariate Polynomial Ring in x, y, z over Rational Field

class sage.structure.coerce_actions.IntegerAction
    Bases: sage.categories.action.Action
    Abstract base class representing some action by integers on something. Here, “integer” is defined loosely in the
    “duck typing” sense.

    INPUT:
    • Z – a type or parent representing integers

    For the other arguments, see Action.

    Note: This class is used internally in Sage’s coercion model. Outside of the coercion model, special precautions
    are needed to prevent domains of the action from being garbage collected.

class sage.structure.coerce_actions.IntegerMulAction
    Bases: sage.structure.coerce_actions.IntegerAction
    Implement the action \( n \cdot a = a + a + \ldots + a \) via repeated doubling.

    Both addition and negation must be defined on the set \( M \).

    INPUT:
• \( Z \) – a type or parent representing integers
• \( M \) – a ZZ-module
• \( m \) – (optional) an element of \( M \)

EXAMPLES:

```python
sage: from sage.structure.coerce_actions import IntegerMulAction
sage: R.<x> = QQ['x']

sage: act = IntegerMulAction(ZZ, R)
sage: act(5, x)
5*x
sage: act(0, x)
0
sage: act(-3, x-1)
-3*x + 3
```

```python
class sage.structure.coerce_actions.IntegerPowAction
Bases: sage.structure.coerce_actions.IntegerAction

The right action \( a ^ n = a * a * ... * a \) where \( n \) is an integer.

The action is implemented using the \_pow_int method on elements.

INPUT:

• \( Z \) – a type or parent representing integers
• \( M \) – a parent whose elements implement \_pow_int
• \( m \) – (optional) an element of \( M \)

EXAMPLES:

```python
sage: from sage.structure.coerce_actions import IntegerPowAction
sage: R.<x> = LaurentSeriesRing(QQ)

sage: act = IntegerPowAction(ZZ, R)

sage: act(x, 5)
x^5
sage: act(x, -2)
x^-2
sage: act(x, int(5))
x^5
```

```python
class sage.structure.coerce_actions.LeftModuleAction
Bases: sage.structure.coerce_actions.ModuleAction

class sage.structure.coerce_actions.ModuleAction
Bases: sage.categories.action.Action

Module action.

See also:

This is an abstract class, one must actually instantiate a \texttt{LeftModuleAction} or a \texttt{RightModuleAction}.

INPUT:

• \( G \) – the actor, an instance of \texttt{Parent}.
• \( S \) – the object that is acted upon.

5.2. Coerce actions
• $g$ – optional, an element of $G$.
• $a$ – optional, an element of $S$.
• check – if True (default), then there will be no consistency tests performed on sample elements.

NOTE:
By default, the sample elements of $S$ and $G$ are obtained from $\text{an_element()}$, which relies on the implementation of an $\_\text{an_element()}$ method. This is not always available. But usually, the action is only needed when one already has two elements. Hence, by trac ticket #14249, the coercion model will pass these two elements to the $\text{ModuleAction}$ constructor.

The actual action is implemented by the $\_\text{rmul\_}$ or $\_\text{lmul\_}$ function on its elements. We must, however, be very particular about what we feed into these functions, because they operate under the assumption that the inputs lie exactly in the base ring and may segfault otherwise. Thus we handle all possible base extensions manually here.

codomain()
The codomain of self, which may or may not be equal to the domain.

EXAMPLES:
Note that coerce actions should only be used inside of the coercion model. For this test, we need to strongly reference the domains, for otherwise they could be garbage collected, giving rise to random errors (see trac ticket #18157).

```
sage: from sage.structure.coerce_actions import LeftModuleAction
sage: ZZxyz = ZZ['x,y,z']
sage: A = LeftModuleAction(QQ, ZZxyz)
sage: A.codomain()
Multivariate Polynomial Ring in x, y, z over Rational Field
```

domain()
The domain of self, which is the module that is being acted on.

EXAMPLES:
Note that coerce actions should only be used inside of the coercion model. For this test, we need to strongly reference the domains, for otherwise they could be garbage collected, giving rise to random errors (see trac ticket #18157).

```
sage: from sage.structure.coerce_actions import LeftModuleAction
sage: ZZxyz = ZZ['x,y,z']
sage: A = LeftModuleAction(QQ, ZZxyz)
sage: A.domain()
Multivariate Polynomial Ring in x, y, z over Integer Ring
```

class sage.structure.coerce_actions.PyScalarAction
Bases: sage.categories.action.Action

class sage.structure.coerce_actions.RightModuleAction
Bases: sage.structure.coerce_actions.ModuleAction

sage.structure.coerce_actions.detect_element_action($X$, $Y$, $X\_on\_left$, $X\_el=None$, $Y\_el=None$)
Return an action of $X$ on $Y$ as defined by elements of $X$, if any.

EXAMPLES:
Note that coerce actions should only be used inside of the coercion model. For this test, we need to strongly reference the domains, for otherwise they could be garbage collected, giving rise to random errors (see trac
ticket #18157).

```python
sage: from sage.structure.coerce_actions import detect_element_action
sage: ZZx = ZZ['x']
sage: M = MatrixSpace(ZZ, 2)
sage: detect_element_action(ZZx, ZZ, False)
Left scalar multiplication by Integer Ring on Univariate Polynomial Ring in x over Integer Ring
sage: detect_element_action(ZZx, QQ, True)
Right scalar multiplication by Rational Field on Univariate Polynomial Ring in x over Integer Ring
sage: detect_element_action(Cusps, M, False)
Left action by Full MatrixSpace of 2 by 2 dense matrices over Integer Ring on Set P^\rightarrow 1(QQ) of all cusps
sage: detect_element_action(Cusps, M, True), (None,)
sage: detect_element_action(ZZ, QQ, True), (None,)
```

### 5.3 Coerce maps

```python
class sage.structure.coerce_maps.CCallableConvertMap_class
Bases: sage.categories.map.Map
class sage.structure.coerce_maps.CallableConvertMap
Bases: sage.categories.map.Map
```

This lets one easily create maps from any callable object.
This is especially useful to create maps from bound methods.

**EXAMPLES:**

```python
sage: from sage.structure.coerce_maps import CallableConvertMap
sage: def foo(P, x):
    return x/2
sage: f = CallableConvertMap(ZZ, QQ, foo)
sage: f(3)
3/2
sage: f
Conversion via foo map:
    From: Integer Ring
    To:  Rational Field
```

Create a homomorphism from \( \mathbb{R} \) to \( \mathbb{R}^+ \) viewed as additive groups.

```python
sage: f = CallableConvertMap(RR, RR, exp, parent_as_first_arg=False)
sage: f(0)
1.00000000000000
sage: f(1)
2.71828182845905
sage: f(-3)
0.0497870683678639
```
class sage.structure.coerce_maps.DefaultConvertMap
    Bases: sage.categories.map.Map

    This morphism simply calls the codomain’s element_constructor method, passing in the codomain as the first argument.

    EXAMPLES:

    sage: QQ[['x']].coerce_map_from(QQ)
    Coercion map:
    From: Rational Field
    To:   Power Series Ring in x over Rational Field

class sage.structure.coerce_maps.DefaultConvertMap_unique
    Bases: sage.structure.coerce_maps.DefaultConvertMap

    This morphism simply defers action to the codomain’s element_constructor method, WITHOUT passing in the codomain as the first argument.

    This is used for creating elements that don’t take a parent as the first argument to their __init__ method, for example, Integers, Rationals, Algebraic Reals... all have a unique parent. It is also used when the element_constructor is a bound method (whose self argument is assumed to be bound to the codomain).

class sage.structure.coerce_maps.ListMorphism
    Bases: sage.categories.map.Map

class sage.structure.coerce_maps.NamedConvertMap
    Bases: sage.categories.map.Map

    This is used for creating elements via the _xxx_ methods.

    For example, many elements implement an _integer_ method to convert to ZZ, or a _rational_ method to convert to QQ.

    method_name

class sage.structure.coerce_maps.TryMap
    Bases: sage.categories.map.Map

sage.structure.coerce_maps.test_CCallableConvertMap(domain, name=None)

For testing CCallableConvertMap_class.

5.4 Coercion via construction functors

class sage.categories.pushout.AlgebraicClosureFunctor
    Bases: sage.categories.pushout.ConstructionFunctor

    Algebraic Closure.

    EXAMPLES:

    sage: F = CDF.construction()[0]
sage: F(QQ)
    Algebraic Field
sage: F(RR)
    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 \(\mathbb{R}^2\). Therefore, we do not merge with algebraic extension.

**class** sage.categories.pushout.AlgebraicExtensionFunctor(polys, names, embeddings, structures,
cyclotomic=None, prec=None,
implementations=None, residue=None,
latex_names=None, **kwds)**

Bases: sage.categories.pushout.ConstructionFunctor

Algebraic extension (univariate polynomial ring modulo principal ideal).

**EXAMPLES:**

```python
sage: K.<a> = NumberField(x^3+x^2+1)
sage: F = K.construction()[0]
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:

```python
sage: F(CC)
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)
Univariate Quotient Polynomial Ring in a over Real Field with 53 bits of precision →with modulus a^3 + a^2 + 1.00000000000000
```

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)
Order in Number Field in a with defining polynomial x^3 + x^2 + 1
```

This also holds for non-absolute number fields:

```python
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 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: 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
```

(continues on next page)
sage: F(ZZ)
Maximal Order in Cyclotomic Field of order 8 and degree 4

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: 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: k = GF(3^2, prefix='z'); a = k.gen()
sage: l = GF(3^3, prefix='z'); b = l.gen()
sage: a + b  # indirect doctest
z6^5 + 2*z6^4 + 2*z6^3 + z6^2 + 2*z6 + 1
```

Note that embeddings are compatible in lattices of such finite fields:

```
sage: m = GF(3^5, prefix='z'); c = m.gen()
sage: (a+b)+c == a+(b+c)  # indirect doctest
True
```

Coercion is also available for number fields:

```
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+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
```

In the previous example, the number field L becomes the pushout of M1 and M2 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:

```
sage: K.<a> = NumberField(x^3-2, embedding=CDF(1/2*I*2^(1/3)*sqrt(3) - 1/2*2^(1/3)))
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)
Traceback (most recent call last):
```

(continues on next page)
CoercionException: ('Ambiguous Base Extension', Number Field in a with defining polynomial \(x^3 - 2\) with \(a = -0.62996052494743657 + 1.0911236359717227^\text{?}\)I,\
Number Field in b with defining polynomial \(x^6 - 2\) with \(b = 1.122462048309373^\text{?}\))

class sage.categories.pushout.BlackBoxConstructionFunctor(box)
Bases: sage.categories.pushout.ConstructionFunctor

Construction functor obtained from any callable object.

EXAMPLES:

```python
sage: from sage.categories.pushout import BlackBoxConstructionFunctor
sage: FG = BlackBoxConstructionFunctor(gap)
sage: FS = BlackBoxConstructionFunctor(singular)
sage: FG
BlackBoxConstructionFunctor
sage: FG(ZZ)
Integers
sage: FG(ZZ).parent()
Gap
sage: FS(QQ['t'])
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
False
sage: FG == loads(dumps(FG))
True
```

class sage.categories.pushout.CompletionFunctor(p, prec, extras=None)
Bases: sage.categories.pushout.ConstructionFunctor

Completion of a ring with respect to a given prime (including infinity).

EXAMPLES:

```python
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]
sage: F3(GF(3)['x'])
Power Series Ring in x over Finite Field of size 3

commutes(other)
Completion commutes with fraction fields.

EXAMPLES:

    sage: F1 = Zp(5).construction()[0]
sage: F2 = QQ.construction()[0]
sage: F1.commutes(F2)
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:

    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
sage: (R3(1) + R4(1)).parent()
Real Field with 30 bits of precision

class sage.categories.pushout.CompositeConstructionFunctor(*args)
Bases: sage.categories.pushout.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:

    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: F == loads(dumps(F))
True
sage: F == CompositeConstructionFunctor(*F.all)
True
sage: F(GF(2)["t"])  
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)

```python
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: sage.categories.functor.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
ZZ['x'] and QQ are obtained from ZZ 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 QQ and ZZ['x'], and
thus a common parent in which p and q can be added, is QQ['x'], since the construction functor with a lower
rank is applied first.
```

```python
sage: F1, R = QQ.construction()
sage: F1
FractionField
sage: R
Integer Ring
sage: F2, R = (ZZ['x']).construction()
sage: F2
Poly[x]
sage: R
Integer Ring
sage: F3 = F2.pushout(F1)
sage: F3
```

(continues on next page)
When composing two construction functors, they are sometimes merged into one, as is the case in the Quotient construction:

```python
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:

```python
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
    Of size 5
    Defn: a |--> a + b
    b |--> a - b
sage: F(f)(F(A)(x)*a)
(a + b)*x
```

\texttt{common\_base}(other\_functor, self\_bases, other\_bases)

This function is called by \texttt{pushout()} when no common parent is found in the construction tower.

\textbf{Note:} The main use is for multivariate construction functors, which use this function to implement recursion for \texttt{pushout()}.

\textbf{INPUT:}

5.4. Coercion via construction functors
• **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.e. **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: FP = F*P
sage: FP.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:**

```python
sage: F = QQ.construction()[0]
sage: P = ZZ['t'].construction()[0]
sage: F.merge(F)
FractionField
sage: F.merge(P)
Poly[t]
sage: P.merge(F)
```

**pushout(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.

**class** sage.categories.pushout.FractionField

**Bases:** sage.categories.pushout.ConstructionFunctor

Construction functor for fraction fields.

**EXAMPLES:**

```python
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
```

**class** sage.categories.pushout.IdentityConstructionFunctor

**Bases:** sage.categories.pushout.ConstructionFunctor
A construction functor that is the identity functor.

```python
class sage.categories.pushout.InfinitePolynomialFunctor(gens, order, implementation):
    Bases: sage.categories.pushout.ConstructionFunctor

    A Construction Functor 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 \(v_1, \ldots, v_n\) 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:
```

```python
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)
sage: A.construction()[0]*B.construction()[0]
InfPoly{[a,b], "lex", "dense"}(MPoly[x,y](...))
```

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:

```python
sage: A.<a,b> = InfinitePolynomialRing(ZZ['t'])
sage: A.construction()[0]*PolynomialRing(QQ,names=['x','y','a_3','a_1']).construction()[0]
Traceback (most recent call last):
  ... CoercionException: Incompatible term orders lex, degrevlex
```

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:

```python
sage: A.<a,b> = InfinitePolynomialRing(QQ,names=['x','y','a_3','a_1'], order='lex')
sage: A.construction()[0]*PolynomialRing(QQ,names=['x','y','a_3','a_1'], order='lex')
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 \(b_+\):

```python
Since the construction functors are actually used to construct infinite polynomial rings, the following result is no surprise:

```python
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:

```python
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:

```python
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
```

```python
expand()
```

Decompose the functor $F$ into sub-functors, whose product returns $F$.

**EXAMPLES:**

```python
sage: F = InfinitePolynomialRing(QQ, ['x','y'],order='degrevlex')
    .construction()[0]; F
InfPoly{[x,y], "degrevlex", "dense"}
sage: F.expand()
[InfPoly{[y], "degrevlex", "dense"}, InfPoly{[x], "degrevlex", "dense"}]
```

```python
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:

```python
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]
```

class `sage.categories.pushout.LaurentPolynomialFunctor`(`var`, `multi_variate=False`)

Bases: `sage.categories.pushout.ConstructionFunctor`

Construction functor for Laurent polynomial rings.

EXAMPLES:

```python
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)
Univariate Laurent Polynomial Ring in t over Univariate Laurent Polynomial Ring in␣˓→x over Integer Ring
sage: P.<x,y> = ZZ[]
sage: f = P.hom([x+2*y,3*x-y],P)
sage: F(f)
Ring endomorphism of Univariate Laurent Polynomial Ring in t over Multivariate␣˓→Polynomial Ring in x, y over Integer Ring
Defn: Induced from base ring by
   Ring endomorphism of Multivariate Polynomial Ring in x, y over Integer Ring
      Defn: x |--> x + 2*y
         y |--> 3*x - y
sage: F(f)(x*F(P).gen()^-2+y*F(P).gen()^3)
(x + 2*y)*t^-2 + (3*x - y)*t^3
```

`merge(other)`

Two Laurent polynomial construction functors merge if the variable names coincide. The result is multivariate if one of the arguments is multivariate.

EXAMPLES:

```python
sage: from sage.categories.pushout import LaurentPolynomialFunctor
sage: F1 = LaurentPolynomialFunctor('t')
sage: F2 = LaurentPolynomialFunctor('t', multi_variate=True)
```

(continues on next page)
```python
sage: F1.merge(F2)
LaurentPolynomialFunctor
sage: F1.merge(F2)(LaurentPolynomialRing(GF(2),'a'))
Multivariate Laurent Polynomial Ring in a, t over Finite Field of size 2
sage: F1.merge(F1)(LaurentPolynomialRing(GF(2),'a'))
Univariate Laurent Polynomial Ring in a over Finite Field of size 2
```

```python
class sage.categories.pushout.MatrixFunctor(nrows, ncols, is_sparse=False)
Bases: sage.categories.pushout.ConstructionFunctor

A construction functor for matrices over rings.

EXAMPLES:

```python
sage: MS = MatrixSpace(ZZ,2, 3)
sage: F = MS.construction()[0]; F
MatrixFunctor
sage: MS = MatrixSpace(ZZ,2)
sage: F = MS.construction()[0]; F
MatrixFunctor
sage: P.<x,y> = QQ[]
sage: R = F(P); R
Full MatrixSpace of 2 by 2 dense matrices over Multivariate Polynomial Ring in x, y over Rational Field
sage: f = P.hom([x+y,x-y],P); F(f)
Ring endomorphism 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]
```

```python
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:

```python
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)
sage: F1.merge(F3)
MatrixFunctor
sage: F13 = F1.merge(F3)
sage: F13.is_sparse
False
```
```
sage: F1.is_sparse
False
sage: F3.is_sparse
True
sage: F3.merge(F3).is_sparse
True

class sage.categories.pushout.MultiPolynomialFunctor(var, term_order)
Bases: sage.categories.pushout.ConstructionFunctor

A constructor for multivariate polynomial rings.

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[]
sage: x+t
dx + t
sage: parent(x+t)
Multivariate Polynomial Ring in x, y, z, t over Rational Field
sage: T.<y,s> = QQ[]
sage: x + s
Traceback (most recent call last):

```python
sage: R = PolynomialRing(ZZ, 'x', 500)
sage: S = PolynomialRing(GF(5), 'x', 200)
sage: R.gen(0) + S.gen(0)
2*x0
```

**merge**(other)

Merge self with another construction functor, or return None.

```python
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]
```

**class** sage.categories.pushout.MultivariateConstructionFunctor

Bases: sage.categories.pushout.ConstructionFunctor

An abstract base class for functors that take multiple inputs (e.g. Cartesian products).

**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.

**class** sage.categories.pushout.PermutationGroupFunctor(gens, domain)

Bases: sage.categories.pushout.ConstructionFunctor

**EXAMPLES:**

```python
sage: from sage.categories.pushout import PermutationGroupFunctor
sage: PF = PermutationGroupFunctor([PermutationGroupElement([[1,2]])], [1,2]); PF
PermutationGroupFunctor([1,2])
```

**gens()**

**EXAMPLES:**
merge(other)
Merge self with another construction functor, or return None.

EXAMPLES:

```python
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)]
```

class sage.categories.pushout.PolynomialFunctor(var, multi_variate=False, sparse=False)
Bases: sage.categories.pushout.ConstructionFunctor

Construction functor for univariate polynomial rings.

EXAMPLES:

```python
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 trac ticket #9944, the construction functor distinguishes sparse and dense polynomial rings. Before, the following example failed:

```python
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().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:

```python
sage: P = ZZ['x'].construction()[0]
sage: Q = ZZ['y','x'].construction()[0]
sage: P.merge(Q)
sage: P.merge(P) is P
True
```

class sage.categories.pushout.QuotientFunctor(I, names=None, as_field=False, domain=None, codomain=None, **kwds)

Bases: sage.categories.pushout.ConstructionFunctor

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:

```python
sage: P.<x,y> = ZZ[]
sage: Q = P.quo([(x^2+y^2)^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
\langle x^2 + y^2 \rangle
sage: F(QQ['x','y']) == QQ['x','y'].quo([(x^2+y^2)^2]*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'])
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:

```python
sage: P.<x> = QQ[]
sage: Q1 = P.quo([(x^2+1)^2*(x^2-3)])
sage: Q2 = P.quo([(x^2+1)^2*(x^2-3)])
```

(continues on next page)
```python
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 trac ticket #8800:

```python
sage: pushout(GF(5), Integers(5))
Finite Field of size 5
```

### sage.categories.pushout.SubspaceFunctor(basis)

**Bases:** sage.categories.pushout.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:**

```python
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]
```

**merge**(other)

Two Subspace Functors are merged into a construction functor of the sum of two subspaces.

**EXAMPLES:**

```python
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: 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]
```

(continues on next page)
class sage.categories.pushout.VectorFunctor(n, is_sparse=False, inner_product_matrix=None)
Bases: sage.categories.pushout.ConstructionFunctor

A construction functor for free modules over commutative rings.

EXAMPLES:

```python
sage: F = (ZZ^3).construction()[0]
sage: F
VectorFunctor
sage: F(GF(2)['t'])
Ambient free module of rank 3 over the principal ideal domain Univariate Polynomial\Ring in t over Finite Field of size 2 (using GF2X)
```

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
sage: P.<t> = ZZ[]
sage: M2 = FreeModule(P,3)
sage: M1([1,1/2,1/3]) + M2([t,t^2+t,3])  # indirect doctest
(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)))
sage: M1([1,1/2,1/3]) + M2([t,t^2+t,3])
(t + 1, t^2 + t + 1/2, 10/3)
sage: (M1([1,1/2,1/3]) + M3([t,t^2+t,3])).parent().inner_product_matrix()
[0 1 2]
[3 4 5]
[6 7 8]
```

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: M4 = FreeModule(QQ,3, inner_product_matrix = Matrix(3,3,1))
sage: M4 == M1
True
sage: M4.inner_product_matrix() == M1.inner_product_matrix()
True
sage: M4([1,1/2,1/3]) + M3([t,t^2+t,3])  # indirect doctest
Traceback (most recent call last):
  ...
TypeError: unsupported operand parent(s) for +: 'Ambient quadratic space of dimension 3 over Rational Field'
Inner product matrix:
\[
\begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}
\]
and 'Ambient free quadratic module of rank 3 over the integral domain Univariate Polynomial Ring in t over Integer Ring

Inner product matrix:
\[
\begin{bmatrix}
0 & 1 & 2 \\
3 & 4 & 5 \\
6 & 7 & 8
\end{bmatrix}
\]

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:

```python
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)]
```

```python
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 y over 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 $\text{Frac}(\text{Poly}_x(\mathbb{Z}))$, which give us $\text{Frac}(\text{Poly}_x(\text{Complete}_7(\text{Frac}(\mathbb{Z}))))$:

```
    sage: from sage.categories.pushout import pushout
    sage: pushout(Qp(7), Frac(ZZ['x']))
    Fraction Field of Univariate Polynomial Ring in x over 7-adic Field with capped˓→relative precision 20
    sage: pushout(Zp(7), Frac(QQ['x']))
    Fraction Field of Univariate Polynomial Ring in x over 7-adic Field with capped˓→relative precision 20
    sage: pushout(Zp(7)['x'], Frac(QQ['x']))
    Fraction Field of Univariate Polynomial Ring in x over 7-adic Field with capped˓→relative precision 20
```

Note we get the same thing with

```
    sage: pushout(Zp(7), Frac(QQ['x']))
    Fraction Field of Univariate Polynomial Ring in x over 7-adic Field with capped˓→relative precision 20
    sage: pushout(Zp(7)['x'], Frac(QQ['x']))
    Fraction Field of Univariate Polynomial Ring in x over 7-adic Field with capped˓→relative precision 20
```

Note that polynomial variable ordering must be unambiguously determined.

```
    sage: pushout(ZZ['x,y,z'], QQ['w,z,t'])
    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)
```

(continues on next page)
Some other examples:

```
sage: pushout(Zp(7)[['y']], Frac(QQ['t'])[['x,y,z']])
Multivariate Polynomial Ring in x, y, z over Fraction Field of Univariate Polynomial Ring in t over 7-adic Field with capped relative precision 20
sage: pushout(ZZ[['x,y,z']], Frac(ZZ[['x']'])[['y']])
Multivariate Polynomial Ring in y, z over Fraction Field of Univariate Polynomial Ring in x over Integer Ring
sage: pushout(MatrixSpace(RDF, 2, 2), Frac(ZZ[['x']]))
Full MatrixSpace of 2 by 2 dense matrices over Fraction Field of Univariate Polynomial Ring in x over Real Double Field
sage: pushout(ZZ, MatrixSpace(ZZ[['x']], 3, 3))
Full MatrixSpace of 3 by 3 dense matrices over Power Series Ring in x over Integer Ring
sage: pushout(QQ[['x,y']], ZZ[['x']])
Univariate Polynomial Ring in y over Power Series Ring in x over Rational Field
sage: pushout(Frac(ZZ[['x']]), QQ[['x']])
Laurent 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:

```
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: 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
```

Some more tests with `coercion_reversed = True`:

```
sage: from sage.categories.pushout import ConstructionFunctor
sage: class EvenPolynomialRing(type(QQ[['x']])):
    ....:     def __init__(self, base, var):
    ....:         super(EvenPolynomialRing, self).__init__(base, var)
    ....:         self.register_embedding(base[var])
    ....:     def __repr__(self):
    ....:         return "Even Power " + super(EvenPolynomialRing, self).__repr__()
```

(continues on next page)
....:    def construction(self):
....:        return EvenPolynomialFunctor(), self.base()[self.variable_name()]
....:    def _coerce_map_from_(self, R):
....:        return self.base().has_coerce_map_from(R)
sage: 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
sage: pushout(EvenPolynomialRing(QQ, 'x'), EvenPolynomialRing(QQ, 'x'))
Even Power Univariate Polynomial Ring in x over Rational Field
sage: pushout(EvenPolynomialRing(QQ, 'x'), EvenPolynomialRing(RR, 'x'))
Even Power Univariate Polynomial Ring in x over Real Field with 53 bits of precision
sage: pushout(EvenPolynomialRing(QQ, 'x')^2, RR^2)
Ambient free module of rank 2 over the principal ideal domain Even Power Univariate
→Polynomial Ring in x over Real Field with 53 bits of precision
sage: pushout(EvenPolynomialRing(QQ, 'x')^2, RR['x']^2)
Ambient free module of rank 2 over the principal ideal domain 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

$$\sum_{i=0}^{j} c_i X^{e_i}$$

with $c_i \in C$ and $e_i \in E$. We define

```
sage: class GPolynomialRing(Parent):
....:     def __init__(self, coefficients, var, exponents):
....:         self.coefficients = coefficients
....:         self.var = var
....:         self.exponents = exponents
....:         super(GPolynomialRing, self).__init__(category=Rings())
```

(continues on next page)
....: 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

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:

sage: 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)]
sage: GP_ZZ(QQ)
Generalized Polynomial Ring in X^(Integer Ring) over Rational Field

Since the construction

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:

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(ZZ['b,c']))
Generalized Polynomial Ring in X^(Integer Ring) over Multivariate Polynomial Ring in a, b over Integer Ring
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 Rational Field
sage: pushout(GP_ZZ(ZZ['a,b']), GP_ZZZ(ZZ['c,d']))
(continues on next page)
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: GP_ZZt = GPolynomialFunctor('X', ZZ['t'])
sage: pushout(GP_ZZt(ZZ), GP_QQ(ZZ))
Generalized Polynomial Ring in X^(Univariate Polynomial Ring in t over Rational Field) over Integer Ring

sage: pushout(GP_ZZ(ZZ), GP_QQ(QQ))
Generalized Polynomial Ring in X^(Rational Field) over Rational Field
sage: pushout(GP_QZ(QQ), GP_QQ(ZZ))
Generalized Polynomial Ring in X^(Rational Field) over Rational Field
sage: pushout(GP_ZZt(QQ), GP_QQ(ZZ))
Generalized Polynomial Ring in X^(Univariate Polynomial Ring in t over Rational Field) over Rational Field
sage: pushout(GP_ZZt(ZZ['a,b']), GP_QQ(ZZ['c,d']))
Traceback (most recent call last):
...
CoercionException: ('Ambiguous Base Extension', ...)
sage: pushout(GP_ZZt(ZZ['a,b']), GP_QQ(ZZ['b,c']))
Generalized Polynomial Ring in X^(Univariate Polynomial Ring in t over Rational Field) over Multivariate Polynomial Ring in a, b, c over Integer Ring
```

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 Univariate Polynomial Ring in t over Rational Field)
```

(continues on next page)
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(CartesianProductPoly, self).__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
....:             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 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'])),
    CartesianProductPoly((ZZ['b,c']['x'], SR['z'])))
The Cartesian product of
(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
(Univariate Polynomial Ring in x over
Multivariate Polynomial Ring in a, b over Integer Ring,
Univariate 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:
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- 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:

```
sage: from sage.categories.pushout import pushout_lattice
sage: A, B = pushout_lattice(Qp(7), Frac(ZZ['x']))
sage: A.codomain()
Fraction Field of Univariate Polynomial Ring in x over 7-adic Field with capped relative precision 20
sage: A.codomain() is B.codomain()
True
sage: A, B = pushout_lattice(ZZ, MatrixSpace(ZZ[['x']], 3, 3))
sage: B
Identity endomorphism of Full MatrixSpace of 3 by 3 dense matrices over Power Series Ring in x over Integer Ring
```

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

### 5.5 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 $G \times S \rightarrow S$ is a functor from $G$ to Sets.

```python
Warning: An Action object only keeps a weak reference to the underlying set which is acted upon. This decision was made in trac ticket #715 in order to allow garbage collection within the coercion framework (this is where actions are mainly used) and avoid memory leaks.

sage: from sage.categories.action import Action
sage: class P: pass
sage: A = Action(P(),P())
sage: import gc
sage: _ = gc.collect()
```

To avoid garbage collection of the underlying set, it is sufficient to create a strong reference to it before the action is created.

```python
sage: _ = gc.collect()
sage: from sage.categories.action import Action
sage: class P: pass
sage: q = P()
```

```python
sage: A = Action(P(),q)
sage: gc.collect()
0
sage: A
Left action by `<__main__.P ... at ...>` on `<__main__.P ... at ...>
```

**AUTHOR:**

• Robert Bradshaw: initial version

**class** `sage.categories.action.Action`

**Bases:** `sage.categories.functor.Functor`

The action of $G$ on $S$.

**INPUT:**
• $G$ – a parent or Python type
• $S$ – a parent or Python type
• $\text{is\_left}$ – (boolean, default: True) whether elements of $G$ are on the left
• $\text{op}$ – (default: None) operation. This is not used by $\text{Action}$ itself, but other classes may use it

$G$ action$(g, x)$

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:**

```
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: sage.categories.morphism.Morphism

The endomorphism defined by the action of one element.

**EXAMPLES:**

```
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: sage.categories.action.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 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 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
Traceback (most recent call last):
  ... TypeError: no inverse defined for Left action by Integer Ring on '<... list>'
```

codomain()

class sage.categories.action.PrecomposedAction
Bases: sage.categories.action.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 trac ticket #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
```
```
sage: _ = gc.collect()
```
```
sage: E = ModularSymbols(11).2
```
```
sage: v = E.manin_symbol_rep()
```
```
```python
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
```

```python
codomain()
domain()
left_precomposition
  The left map to precompose with, or None if there is no left precomposition map.
right_precomposition
  The right map to precompose with, or None if there is no right precomposition map.
```

## 5.6 Containers for storing coercion data

This module provides `TripleDict` and `MonoDict`. These are structures similar to `WeakKeyDictionary` in Python’s `weakref` module, and are optimized for lookup speed. The keys for `TripleDict` consist of triples `(k1,k2,k3)` and are looked up by identity rather than equality. The keys are stored by weakrefs if possible. If any one of the components `k1`, `k2`, `k3` gets garbage collected, then the entry is removed from the `TripleDict`.

Key components that do not allow for weakrefs are stored via a normal refcounted reference. That means that any entry stored using a triple `(k1,k2,k3)` so that none of the `k1,k2,k3` allows a weak reference behaves as an entry in a normal dictionary: Its existence in `TripleDict` prevents it from being garbage collected.

That container currently is used to store coercion and conversion maps between two parents (trac ticket #715) and to store homsets of pairs of objects of a category (trac ticket #11521). In both cases, it is essential that the parent structures remain garbage collectable, it is essential that the data access is faster than with a usual `WeakKeyDictionary`, and we enforce the "unique parent condition" in Sage (parent structures should be identical if they are equal).

`MonoDict` behaves similarly, but it takes a single item as a key. It is used for caching the parents which allow a coercion map into a fixed other parent (trac ticket #12313).

By trac ticket #14159, `MonoDict` and `TripleDict` can be optionally used with weak references on the values.

Note that this kind of dictionary is also used for caching actions and coerce maps. In previous versions of Sage, the cache was by strong references and resulted in a memory leak in the following example. However, this leak was fixed by trac ticket #715, using weak references:

```python
sage: K.<t> = GF(2^55)
sage: for i in range(50):
    ...:    a = K.random_element()
    ...:    E = EllipticCurve(j=a)
    ...:    P = E.random_point()
    ...:    Q = 2*P
sage: L = [Partitions(n) for n in range(200)]
# purge strong cache in...
CachedRepresentation
sage: import gc
sage: n = gc.collect()
```

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class sage.structure.coerce_dict.MonoDict
   Bases: object

   This is a hashtable specifically designed for (read) speed in the coercion model.
   It differs from a python WeakKeyDictionary in the following important ways:
   • Comparison is done using the ‘is’ rather than ‘==’ operator.
   • Only weak references to the keys are stored if at all possible. Keys that do not allow for weak
     references are stored with a normal refcounted reference.
   • The callback of the weak references is safe against recursion, see below.

   There are special cdef set/get methods for faster access. It is bare-bones in the sense that not all
   dictionary methods are implemented.

   IMPLEMENTATION:
   It is implemented as a hash table with open addressing, similar to python’s dict.

   INPUT:
   • data – optional iterable defining initial data, as dict or iterable of (key, value) pairs.
   • weak_values – optional bool (default False). If it is true, weak references to the values in this
     dictionary will be used, when possible.

   EXAMPLES:

   sage: from sage.structure.coerce_dict import MonoDict
   sage: L = MonoDict()
   sage: a = 'a'; b = 'ab'; c = '-15'
   sage: L[a] = 1
   sage: L[b] = 2
   sage: L[c] = 3

   The key is expected to be a unique object. Hence, the item stored for c cannot be obtained by providing
   another equal string:

   sage: L[a]
   1
   sage: L[b]
   2
   sage: L[c]
   3
   sage: L['-15']
   Traceback (most recent call last):
   ... KeyError: '-15'

   Not all features of Python dictionaries are available, but iteration over the dictionary items is possible:
Note that `MW` also accepts values that do not allow for weak references:

```python
sage: MW[k] = int(5)
sage: MW[k]
5
```

The following demonstrates that :class:`MonoDict` is safer than :class:`~weakref.WeakKeyDictionary` against recursions created by nested callbacks; compare :trac:`15069` (the mechanism used now is different, though):

```python
sage: M = MonoDict()
sage: class A: pass
sage: a = A()
sage: prev = a
sage: for i in range(1000):
    ....:    newA = A()
    ....:    M[prev] = newA
    ....:    prev = newA
sage: len(M)
1000
sage: del a
sage: len(M)
0
```

The corresponding example with a Python :class:`weakref.WeakKeyDictionary` would result in a too deep recursion during deletion of the dictionary items:

```python
sage: import weakref
sage: M = weakref.WeakKeyDictionary()
sage: a = A()
sage: prev = a
sage: for i in range(1000):
    ....:    newA = A()
    ....:    M[prev] = newA
```

(continues on next page)
....: prev = newA
sage: len(M)
1000
sage: del a  # py2 -- does not appear to be an issue on Python 3
Exception RuntimeError: 'maximum recursion depth exceeded...
˓→remove at ...> ignored
sage: len(M) > Ø # py2
True

Check that also in the presence of circular references, :class:`MonoDict`
gets properly collected:

sage: import gc
sage: def count_type(T):
....: return len([c for c in gc.get_objects() if isinstance(c,T)])
sage: _ = gc.collect()
sage: N = count_type(MonoDict)
sage: for i in range(100):
....: V = [MonoDict(\"id\":j+100*i) for j in range(100)]
....: n= len(V)
....: for i in range(n): V[i][V[(i+1)%n]=(i+1)%n
....: del V
....: _ = gc.collect()
....: assert count_type(MonoDict) == N
sage: count_type(MonoDict) == N
True

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**copy()**

Return a copy of this :class:`MonoDict` as Python dict.

**EXAMPLES:**

```python
sage: from sage.structure.coerce_dict import MonoDict
sage: L = MonoDict()
sage: L[1] = 42
sage: L.copy()
{1: 42}
```

**items()**

Iterate over the (key, value) pairs of this :class:`MonoDict`.

**EXAMPLES:**

```python
sage: from sage.structure.coerce_dict import MonoDict
sage: L = MonoDict()
sage: L[1] = None
```
```python
sage: L.items()
<generator object at ...>
sage: sorted(L.items())
[(1, None), (2, True)]
```

```python
class sage.structure.coerce_dict.MonoDictEraser
Bases: object

Erase items from a MonoDict when a weak reference becomes invalid.

This is of internal use only. Instances of this class will be passed as a callback function when creating a weak reference.

EXAMPLES:

```python
sage: from sage.structure.coerce_dict import MonoDict
sage: class A:
...:     pass
sage: a = A()
sage: M = MonoDict()
sage: M[a] = 1
sage: len(M)
1
sage: del a
sage: import gc
sage: n = gc.collect()
sage: len(M)  # indirect doctest
0
```

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```python
class sage.structure.coerce_dict.ObjectWrapper
Bases: object

A simple fast wrapper around a Python object. This is like a 1-element tuple except that it does not keep a reference to the wrapped object.

```python
class sage.structure.coerce_dict.TripleDict
Bases: object

This is a hashtable specifically designed for (read) speed in the coercion model.

It differs from a python dict in the following important ways:

• All keys must be sequence of exactly three elements. All sequence types (tuple, list, etc.) map to the same item.

• Any of the three key components that support weak-refs are stored via a weakref. If any of these components gets garbage collected then the entire entry is removed. In that sense, this structure behaves like a nested WeakKeyDictionary.

• Comparison is done using the ‘is’ rather than ‘==’ operator.

There are special cdef set/get methods for faster access. It is bare-bones in the sense that not all dictionary methods are implemented.

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INPUT:

- data – optional iterable defining initial data, as dict or iterable of (key, value) pairs.
- weak_values – optional bool (default False). If it is true, weak references to the values in this dictionary will be used, when possible.

IMPLEMENTATION:

It is implemented as a hash table with open addressing, similar to python’s dict.

EXAMPLES:

```python
sage: from sage.structure.coerce_dict importTripleDict
sage: L = TripleDict()
sage: a = 'a'; b = 'b'; c = 'c'
sage: L[a,b,c] = 1
sage: L[a,b,c]
1
sage: L[c,b,a] = -1
sage: sorted(L.items())
[('a', 'b', 'c'), 1], ('c', 'b', 'a'), -1]
sage: del L[a,b,c]
sage: list(L.items())
[('c', 'b', 'a'), -1]
sage: len(L)
1
sage: for i in range(1000):
    ....:     L[i,i,i] = i
sage: len(L)
1001
sage: L = TripleDict(L)
sage: L[c,b,a]
-1
sage: L[a,b,c]
Traceback (most recent call last):
  ...:  KeyError: (a', 'b', 'c')
sage: L[a]
Traceback (most recent call last):
  ...:  KeyError: 'a'
sage: L[a] = 1
Traceback (most recent call last):
  ...:  KeyError: 'a'
```

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copy()
    Return a copy of this \texttt{TripleDict} as Python dict.

    EXAMPLES:

    \begin{verbatim}
    sage: from sage.structure.coerce_dict import TripleDict
    sage: L = TripleDict()
    sage: L[1,2,3] = 42
    sage: L.copy()
    \{(1, 2, 3): 42\}
    \end{verbatim}

items()
    Iterate over the (key, value) pairs of this \texttt{TripleDict}.

    EXAMPLES:

    \begin{verbatim}
    sage: from sage.structure.coerce_dict import TripleDict
    sage: L = TripleDict()
    sage: L[1,2,3] = None
    sage: L.items()
    <generator object at ...>
    sage: list(L.items())
    \[((1, 2, 3), None)\]
    \end{verbatim}

class sage.structure.coerce_dict.TripleDictEraser
    Bases: object
    Erases items from a \texttt{TripleDict} when a weak reference becomes invalid.

    This is of internal use only. Instances of this class will be passed as a callback function when creating a weak reference.

    EXAMPLES:

    \begin{verbatim}
    sage: from sage.structure.coerce_dict import TripleDict
    sage: class A: pass
    sage: a = A()
    sage: T = TripleDict()
    sage: T[a,ZZ,None] = 1
    sage: T[ZZ,a,1] = 2
    sage: T[a,a,ZZ] = 3
    sage: len(T)
    3
    sage: del a
    sage: import gc
    sage: n = gc.collect()
    sage: len(T)  # indirect doctest
    0
    \end{verbatim}

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5.7 Exceptions raised by the coercion model

```python
definition sage.structure.coerce_exceptions.CoercionException
    Bases: TypeError

This is the baseclass of exceptions that the coercion model raises when trying to discover coercions. We do not use standard Python exceptions to avoid inadvertently catching and suppressing real errors.

Usually one raises this to indicate the attempted action is not implemented/appropriate, but if there are other things to try not to immediately abort to the user.
CHAPTER SIX

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