EXAMPLES OF GROUPS

The `groups` object may be used to access examples of various groups. Using tab-completion on this object is an easy way to discover and quickly create the groups that are available (as listed here).

Let `<tab>` indicate pressing the tab key. So begin by typing `groups.<tab>` to see primary divisions, followed by (for example) `groups.matrix.<tab>` to access various groups implemented as sets of matrices.

- **Permutation Groups** (`groups.permutation.<tab>`)
  - `groups.permutation.Symmetric`
  - `groups.permutation.Alternating`
  - `groups.permutation.KleinFour`
  - `groups.permutation.Quaternion`
  - `groups.permutation.Cyclic`
  - `groups.permutation.ComplexReflection`
  - `groups.permutation.Dihedral`
  - `groups.permutation.DiCyclic`
  - `groups.permutation.Mathieu`
  - `groups.permutation.Suzuki`
  - `groups.permutation.PGL`
  - `groups.permutation.PSL`
  - `groups.permutation.PSp`
  - `groups.permutation.PSU`
  - `groups.permutation.PGU`
  - `groups.permutation.Transitive`
  - `groups.permutation.RubiksCube`

- **Matrix Groups** (`groups.matrix.<tab>`)
• Finitely Presented Groups (groups.presentation.<tab>)
  - groups.presentation.Alternating
  - groups.presentation.Cyclic
  - groups.presentation.Dihedral
  - groups.presentation.DiCyclic
  - groups.presentation.FGAbelian
  - groups.presentation.KleinFour
  - groups.presentation.Quaternion
  - groups.presentation.Symmetric

• Affine Groups (groups.affine.<tab>)
  - groups.affine.Affine
  - groups.affine.Euclidean

• Lie Groups (groups.lie.<tab>)
  - groups.lie.Nilpotent

• Miscellaneous Groups (groups.misc.<tab>)
  - Coxeter, reflection and related groups
    - groups.misc.Braid
    - groups.misc.CoxeterGroup
    - groups.misc.ReflectionGroup
    - groups.misc.RightAngledArtin
    - groups.misc.WeylGroup
  - other miscellaneous groups
    - groups.misc.AdditiveAbelian
    - groups.misc.AdditiveCyclic
    - groups.misc.Free
    - groups.misc.SemimonomialTransformation
BASE CLASS FOR GROUPS

class sage.groups.group.AbelianGroup
    Bases: sage.groups.group.Group
    Generic abelian group.

    is_abelian()
    Return True.

    EXAMPLES:

    sage: from sage.groups.group import AbelianGroup
    sage: G = AbelianGroup()
    sage: G.is_abelian()
    True

class sage.groups.group.AlgebraicGroup
    Bases: sage.groups.group.Group

class sage.groups.group.FiniteGroup
    Bases: sage.groups.group.Group
    Generic finite group.

    is_finite()
    Return True.

    EXAMPLES:

    sage: from sage.groups.group import FiniteGroup
    sage: G = FiniteGroup()
    sage: G.is_finite()
    True

class sage.groups.group.Group
    Bases: sage.structure.parent.Parent
    Base class for all groups

    is_abelian()
    Test whether this group is abelian.

    EXAMPLES:

    sage: from sage.groups.group import Group
    sage: G = Group()
    sage: G.is_abelian()
    Traceback (most recent call last):
    ...
is_commutative()
Test whether this group is commutative.
This is an alias for is_abelian, largely to make groups work well with the Factorization class.
(Note for developers: Derived classes should override is_abelian, not is_commutative.)
EXAMPLES:
```
sage: SL(2, 7).is_commutative()
False
```

is_finite()
Returns True if this group is finite.
EXAMPLES:
```
sage: from sage.groups.group import Group
sage: G = Group()
sage: G.is_finite()
Traceback (most recent call last):
...
NotImplementedError
```

is_multiplicative()
Returns True if the group operation is given by * (rather than +).
Override for additive groups.
EXAMPLES:
```
sage: from sage.groups.group import Group
sage: G = Group()
sage: G.is_multiplicative()
True
```

order()
Return the number of elements of this group.
This is either a positive integer or infinity.
EXAMPLES:
```
sage: from sage.groups.group import Group
sage: G = Group()
sage: G.order()
Traceback (most recent call last):
...
NotImplementedError
```

quotient (H)
Return the quotient of this group by the normal subgroup $H$.
EXAMPLES:
sage: from sage.groups.group import Group
sage: G = Group()
sage: G.quotient(G)
Traceback (most recent call last):
...  
NotImplementedError

sage.groups.group.is_Group(x)
Return whether x is a group object.

INPUT:
- x – anything.

OUTPUT:
Boolean.

EXAMPLES:

sage: F.<a,b> = FreeGroup()
sage: from sage.groups.group import is_Group
sage: is_Group(F)
True
sage: is_Group("a string")
False
SET OF HOMOMORPHISMS BETWEEN TWO GROUPS.

sage.groups.group_homset.GroupHomset (G, H)

class sage.groups.group_homset.GroupHomset_generic (G, H)
    Bases: sage.categories.homset.HomsetWithBase

    This class will not work since morphism.GroupHomomorphism_coercion is undefined and morphism.GroupHomomorphism_im_gens is undefined.

    natural_map ()

sage.groups.group_homset.is_GroupHomset (H)
GROUP HOMOMORPHISMS FOR GROUPS WITH A GAP BACKEND

EXAMPLES:

```sage
def from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
A = AbelianGroupGap([2, 4])
F.<a,b> = FreeGroup()
f = F.hom([g for g in A.gens()])
K = f.kernel()
K
Group(<free, no generators known>)
```

AUTHORS:

- Simon Brandhorst (2018-02-08): initial version
- Sebastian Oehms (2018-11-15): have this functionality work for permutation groups (trac ticket #26750) and implement section() and natural_map()

```python
class sage.groups.libgap_morphism.GroupHomset_libgap(G, H, category=None, check=True):
    Bases: sage.categories.homset.HomsetWithBase

Homsets of groups with a libgap backend.

Do not call this directly instead use Hom().

INPUT:

- G – a libgap group
- H – a libgap group
- category – a category

OUTPUT:

The homset of two libgap groups.

EXAMPLES:

```sage
def from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
A = AbelianGroupGap([2, 4])
H = A.Hom(A)
H
Set of Morphisms from Abelian group with gap, generator orders (2, 4) to Abelian group with gap, generator orders (2, 4) in Category of finite enumerated commutative groups
```

Element

alias of GroupMorphism_libgap
natural_map()

This method from HomsetWithBase is overloaded here for cases in which both groups have corresponding lists of generators.

OUTPUT:

an instance of the element class of self if there exists a group homomorphism mapping the generators of the domain of self to the according generators of the codomain. Else the method falls back to the default.

EXAMPLES:

```
sage: G = GL(3,2)
sage: P = PGL(3,2)
sage: nat = Hom(G, P).natural_map()
sage: type(nat)
<class 'sage.groups.libgap_morphism.GroupHomset_libgap_with_category.element_class'>
sage: g1, g2 = G.gens()
sage: nat(g1*g2)
(1,2,4,5,7,3,6)
```

class sage.groups.libgap_morphism.GroupMorphism_libgap(homset, gap_hom, check=True)

Bases: sage.categories.morphism.Morphism

This wraps GAP group homomorphisms.

Checking if the input defines a group homomorphism can be expensive if the group is large.

INPUT:

- homset – the parent
- gap_hom – a sage.libs.gap.element.GapElement consisting of a group homomorphism
- check – (default: True) check if the gap_hom is a group homomorphism; this can be expensive

EXAMPLES:

```
sage: from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
sage: A = AbelianGroupGap([2, 4])
sage: A.hom([g^2 for g in A.gens()])
Group endomorphism of Abelian group with gap, generator orders (2, 4)
```

Homomorphisms can be defined between different kinds of GAP groups:

```
sage: G = MatrixGroup([Matrix(ZZ, 2, [0,1,1,0])])
sage: f = A.hom([G.0, G(1)])
sage: f
Group morphism:
From: Abelian group with gap, generator orders (2, 4)
To: Matrix group over Integer Ring with 1 generators ([0 1]
[1 0])
```

10 Chapter 4. Group homomorphisms for groups with a GAP backend
Homomorphisms can be defined between GAP groups and permutation groups:

```python
sage: S = Sp(4,3)
sage: P = PSp(4,3)
sage: pr = S.hom(P gens())
sage: E = copy(S one().matrix())
sage: E[3,0] = 2; e = S(E)
sage: pr(e)
```

```
gap ()
Return the underlying LibGAP group homomorphism.

EXAMPLES:

```python
sage: from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
sage: A = AbelianGroupGap([2,4])
sage: f = A.hom([g^2 for g in A.gens()])
sage: f.gap()
[ f1, f2 ] -> [ <identity> of ..., f3 ]
```

image (J, *args, **kwds)
The image of an element or a subgroup.

INPUT:

• J – a subgroup or an element of the domain of self

OUTPUT:

The image of J under self.

Note: pushforward is the method that is used when a map is called on anything that is not an element of its domain. For historical reasons, we keep the alias image() for this method.

EXAMPLES:

```python
sage: G.<a,b> = FreeGroup()
sage: H = G / (G([1]), G([2])^3)
sage: f = G.hom(H gens())
sage: f.pushforward(GS)
Subgroup generated by [(3,4,5)(10,18,14)(11,19,15)(12,20,16)(13,21,17)] of
(The projective general unitary group of degree 3 over Finite Field of size 2)
```
kernel()

Return the kernel of self.

EXAMPLES:

```python
sage: from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
sage: A1 = AbelianGroupGap([6, 6])
sage: A2 = AbelianGroupGap([3, 3])
sage: f = A1.hom(A2.gens())
sage: f.kernel()
Subgroup of Abelian group with gap, generator orders (6, 6)
generated by (f1*f2, f3*f4)
sage: f.kernel().order()
4
sage: S = Sp(6,3)
sage: P = PSp(6,3)
sage: pr = Hom(S, P).natural_map()
sage: pr.kernel()
Subgroup with 1 generators (
[2 0 0 0 0 0]
[0 2 0 0 0 0]
[0 0 2 0 0 0]
[0 0 0 2 0 0]
[0 0 0 0 2 0]
[0 0 0 0 0 2]
) of Symplectic Group of degree 6 over Finite Field of size 3
```

lift (h)

Return an element of the domain that maps to h.

EXAMPLES:

```python
sage: from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
sage: A = AbelianGroupGap([2,4])
sage: f = A.hom([g^2 for g in A.gens()])
sage: a = A.gens()[1]
sage: f.lift(a^2)
f2
```

If the element is not in the image, we raise an error:

```python
sage: f.lift(a)
Traceback (most recent call last):
... ValueError: f2 is not an element of the image of Group endomorphism
of Abelian group with gap, generator orders (2, 4)
```

preimage (S)

Return the preimage of the subgroup S.

INPUT:

- S – a subgroup of this group

EXAMPLES:

```python
sage: from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
sage: A = AbelianGroupGap([2,4])
sage: B = AbelianGroupGap([4])
```
 sage: f = A.hom([B.one(), B.gen(0)^2])
sage: S = B.subgroup([B.one()])
sage: f.preimage(S) == f.kernel()
True
 sage: S = Sp(4,3)
sage: P = PSp(4,3)
sage: pr = Hom(S, P).natural_map()
sage: PS = P.subgroup([P.gen(0)])
sage: pr.preimage(PS)
Subgroup with 2 generators
([2 0 0 0] [1 0 0 0]
[0 2 0 0] [0 2 0 0]
[0 0 2 0] [0 0 2 0]
[0 0 0 2], [0 0 0 1]) of Symplectic Group of degree 4 over Finite Field of size 3

**pushforward** *(J, *args, **kwds)*
The image of an element or a subgroup.

**INPUT:**
- J – a subgroup or an element of the domain of self

**OUTPUT:**
The image of J under self.

**Note:** pushforward is the method that is used when a map is called on anything that is not an element of its domain. For historical reasons, we keep the alias image() for this method.

**EXAMPLES:**

 sage: G.<a,b> = FreeGroup()
sage: H = G / (G([1]), G([2])^3)
sage: f = G.hom(H.gens())
sage: S = G.subgroup([a.gap()])
sage: f.pushforward(S)
Group([ a ])
sage: x = f.image(a)
sage: x
a
 sage: x.parent()
Finitely presented group < a, b | a, b^3 >
 sage: G = GU(3,2)
sage: P = PGU(3,2)
sage: pr = Hom(G, P).natural_map()
sage: GS = G.subgroup([G.gen(0)])
sage: pr.pushforward(GS)
Subgroup generated by [(3,4,5)(10,18,14)(11,19,15)(12,20,16)(13,21,17)] of
˓
→(The projective general unitary group of degree 3 over Finite Field of size 2)

**section()**
This method returns a section map of self by use of lift(). See section() of sage.categories.map.Map, as well.

**OUTPUT:**
an instance of `sage.categories.morphism.SetMorphism` mapping an element of the codomain of self to one of its preimages

EXAMPLES:

```
sage: G = GU(3,2)
sage: P = PGU(3,2)
sage: pr = Hom(G, P).natural_map()
sage: sect = pr.section()
sage: sect(P.an_element())
[a + 1  a  a]
[ 1  1  0]
[ a  0  0]
```
CHAPTER FIVE

LIBGAP-BASED GROUPS

This module provides helper class for wrapping GAP groups via `libgap`. See `free_group` for an example how they are used.

The parent class keeps track of the GAP element object, to use it in your Python parent you have to derive both from the suitable group parent and `ParentLibGAP`

```python
from sage.groups.libgap_wrapper import ElementLibGAP, ParentLibGAP
from sage.groups.group import Group

class FooElement(ElementLibGAP):
    pass

class FooGroup(Group, ParentLibGAP):
    Element = FooElement
    def __init__(self):
        lg = libgap(libgap.CyclicGroup(3))  # dummy
        ParentLibGAP.__init__(self, lg)
        Group.__init__(self)
```

Note how we call the constructor of both superclasses to initialize `Group` and `ParentLibGAP` separately. The parent class implements its output via LibGAP:

```python
FooGroup()
<pc group of size 3 with 1 generators>

FooGroup().gap()
<type 'sage.libs.gap.element.GapElement'>
```

The element class is a subclass of `MultiplicativeGroupElement`. To use it, you just inherit from `ElementLibGAP`

```python
element = FooGroup().an_element()
element
f1
```

The element class implements group operations and printing via LibGAP:

```python
element._repr_()
'f1'
element * element
f1^2
```

AUTHORS:

- Volker Braun

```python
class sage.groups.libgap_wrapper.ElementLibGAP
    Bases: sage.structure.element.MultiplicativeGroupElement
```
A class for LibGAP-based Sage group elements

INPUT:

- **parent** – the Sage parent
- **libgap_element** – the libgap element that is being wrapped

EXAMPLES:

```sage
from sage.groups.libgap_wrapper import ElementLibGAP, ParentLibGAP
define FooElement(ElementLibGAP):
    Element = FooElement
    def __init__(self):
        lg = libgap(libgap.CyclicGroup(3))     # dummy
        ParentLibGAP.__init__(self, lg)
        Group.__init__(self)

class FooGroup(Group, ParentLibGAP):
    Element = FooElement

c = FooGroup()
```

**gap()**

Returns a LibGAP representation of the element

OUTPUT:

A `GapElement`

EXAMPLES:

```sage
G.<a,b> = FreeGroup('a, b')
x = G([1, 2, -1, -2])
xg = x.gap()
type(xg)
```

**inverse()**

Return the inverse of self.

**is_one()**

Test whether the group element is the trivial element.

OUTPUT:

Boolean.

EXAMPLES:

```sage
G.<a,b> = FreeGroup('a, b')
x = G([1, 2, -1, -2])
x.is_one()
(x * ~x).is_one()
```
class sage.groups.libgap_wrapper.ParentLibGAP(libgap_parent, ambient=None)

Bases: sage.structure.sage_object.SageObject

A class for parents to keep track of the GAP parent.

This is not a complete group in Sage, this class is only a base class that you can use to implement your own groups with LibGAP. See libgap_group for a minimal example of a group that is actually usable.

Your implementation definitely needs to supply

• __reduce__(): serialize the LibGAP group. Since GAP does not support Python pickles natively, you need to figure out yourself how you can recreate the group from a pickle.

INPUT:

• libgap_parent – the libgap element that is the parent in GAP.
• ambient – A derived class of ParentLibGAP or None (default). The ambient class if libgap_parent has been defined as a subgroup.

EXAMPLES:

```python
sage: from sage.groups.libgap_wrapper import ElementLibGAP, ParentLibGAP
sage: from sage.groups.group import Group
sage: class FooElement(ElementLibGAP):
....:    pass
sage: class FooGroup(Group, ParentLibGAP):
....:    Element = FooElement
....:    def __init__(self):
....:        lg = libgap(libgap.CyclicGroup(3)) # dummy
....:        ParentLibGAP.__init__(self, lg)
....:        Group.__init__(self)
sage: FooGroup()  
<pc group of size 3 with 1 generators>
```

ambient()

Return the ambient group of a subgroup.

OUTPUT:

A group containing self. If self has not been defined as a subgroup, we just return self.

EXAMPLES:

```python
sage: G = FreeGroup(3)
sage: G.ambient() is G
True
```

gap()

Returns the gap representation of self

OUTPUT:

A GapElement

EXAMPLES:

```python
sage: G = FreeGroup(3); G
Free Group on generators {x0, x1, x2}
sage: G.gap()
<free group on the generators [ x0, x1, x2 ]>
sage: G.gap().parent()
```

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This can be useful, for example, to call GAP functions that are not wrapped in Sage:

```python
sage: G = FreeGroup(3)
sage: H = G.gap()
sage: H.DirectProduct(H)
<fp group on the generators [ f1, f2, f3, f4, f5, f6 ]>
sage: H.DirectProduct(H).RelatorsOfFpGroup()
[ f1^-1*f4^-1*f1*f4, f1^-1*f5^-1*f1*f5, f1^-1*f6^-1*f1*f6, f2^-1*f4^-1*f2*f4,
  f2^-1*f5^-1*f2*f5, f2^-1*f6^-1*f2*f6, f3^-1*f4^-1*f3*f4, f3^-1*f5^-1*f3*f5,
  f3^-1*f6^-1*f3*f6 ]
```

We can also convert directly to libgap:

```python
sage: libgap(GL(2, ZZ))
GL(2,Integers)
```

**gen (i)**

Return the $i$-th generator of self.

**Warning:** Indexing starts at 0 as usual in Sage/Python. Not as in GAP, where indexing starts at 1.

**INPUT:**

- $i$ – integer between 0 (inclusive) and `ngens()` (exclusive). The index of the generator.

**OUTPUT:**

The $i$-th generator of the group.

**EXAMPLES:**

```python
sage: G = FreeGroup('a, b')
sage: G.gen(0)
a
sage: G.gen(1)
b
```

**generators ()**

Returns the generators of the group.

**EXAMPLES:**

```python
sage: G = FreeGroup(2)
sage: G.gens()
(x0, x1)
sage: H = FreeGroup('a, b, c')
sage: H.gens()
(a, b, c)
```

`generators()` is an alias for `gens()`
```python
sage: G = FreeGroup('a, b')
sage: G.gens()
(a, b)
sage: H = FreeGroup(3, 'x')
sage: H.gens()
(x0, x1, x2)
```

**gens()**

Returns the generators of the group.

**EXAMPLES:**

```python
sage: G = FreeGroup(2)
sage: G.gens()
(x0, x1)
sage: H = FreeGroup('a, b, c')
sage: H.gens()
(a, b, c)
```

**generators()** is an alias for **gens()**

```python
sage: G = FreeGroup('a, b')
sage: G.generators()
(a, b)
sage: H = FreeGroup(3, 'x')
sage: H.generators()
(x0, x1, x2)
```

**is_subgroup()**

Return whether the group was defined as a subgroup of a bigger group.

You can access the containing group with `ambient()`.

**OUTPUT:**

Boolean.

**EXAMPLES:**

```python
sage: G = FreeGroup(3)
sage: G.is_subgroup()
False
```

**ngens()**

Return the number of generators of self.

**OUTPUT:**

Integer.

**EXAMPLES:**

```python
sage: G = FreeGroup(2)
sage: G.ngens()
2
```

**one()**

Returns the identity element of self

**EXAMPLES:**

```python
```
subgroup (generators)

Return the subgroup generated.

INPUT:

• generators – a list/tuple/iterable of group elements.

OUTPUT:

The subgroup generated by generators.

EXAMPLES:

```
sage: F.<a,b> = FreeGroup()
sage: G = F.subgroup([a^2*b]); G
Group([ a^2*b ])
sage: G.gens()
(a^2*b,)
```

Checking that trac ticket #19270 is fixed:

```
sage: gens = [w.matrix() for w in WeylGroup(['B', 3])]
sage: G = MatrixGroup(gens)
sage: import itertools
sage: diagonals = itertools.product((1,-1), repeat=3)
sage: subgroup_gens = [diagonal_matrix(L) for L in diagonals]
sage: G.subgroup(subgroup_gens)
Subgroup with 8 generators of Matrix group over Rational Field with 48 → generators
```
CHAPTER SIX

GENERIC LIBGAP-BASED GROUP

This is useful if you need to use a GAP group implementation in Sage that does not have a dedicated Sage interface. If you want to implement your own group class, you should not derive from this but directly from \texttt{ParentLibGAP}.

EXAMPLES:

```python
sage: F.<a,b> = FreeGroup()
sage: G_gap = libgap.Group([ (a*b^2).gap() ])
sage: from sage.groups.libgap_group import GroupLibGAP
sage: G = GroupLibGAP(G_gap); G
Group([ a*b^2 ])
sage: type(G)
<class 'sage.groups.libgap_group.GroupLibGAP_with_category'>
sage: G.gens()
(a*b^2,)
```

```python
class sage.groups.libgap_group.GroupLibGAP(*args,**kwds)
    Bases: sage.groups.group.Group, sage.groups.libgap_wrapper.ParentLibGAP

    Group interface for LibGAP-based groups.

    INPUT:

    Same as \texttt{ParentLibGAP}.

    Element
        alias of \texttt{sage.groups.libgap_wrapper.ElementLibGAP}
```
CHAPTER
SEVEN

MIX-IN CLASS FOR GAP-BASED GROUPS

This class adds access to GAP functionality to groups such that parent and element have a `gap()` method that returns a GAP object for the parent/element.

If your group implementation uses libgap, then you should add `GroupMixinLibGAP` as the first class that you are deriving from. This ensures that it properly overrides any default methods that just raise `NotImplementedError`.

```python
class sage.groups.libgap_mixin.GroupMixinLibGAP
    Bases: object

    def cardinality()
        Implements EnumeratedSets.ParentMethods.cardinality().

    EXAMPLES:
    sage: G = Sp(4,GF(3))
    sage: G.cardinality()
    51840
    sage: G = SL(4,GF(3))
    sage: G.cardinality()
    12130560
    sage: F = GF(5); MS = MatrixSpace(F,2,2)
    sage: gens = [MS([[1,2],[-1,1]]),MS([[1,1],[0,1]])]
    sage: G = MatrixGroup(gens)
    sage: G.cardinality()
    480
    sage: G = MatrixGroup([matrix(ZZ,2,[1,1,0,1])])
    sage: G.cardinality()
    +Infinity
    sage: G = Sp(4,GF(3))
    sage: G.cardinality()
    51840
    sage: G = SL(4,GF(3))
    sage: G.cardinality()
    12130560
    sage: F = GF(5); MS = MatrixSpace(F,2,2)
    sage: gens = [MS([[1,2],[-1,1]]),MS([[1,1],[0,1]])]
    sage: G = MatrixGroup(gens)
    sage: G.cardinality()
    sage: G.cardinality()
```

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center()  
Return the center of this linear group as a subgroup.

OUTPUT:  
The center as a subgroup.

EXAMPLES:

```
sage: G = SU(3,GF(2))
sage: G.center()  
Subgroup with 1 generators (  
[ a 0 0]  
[0 a 0]  
[0 0 a])  
of Special Unitary Group of degree 3 over Finite Field in a of size 2^2
```

```
sage: GL(2,GF(3)).center()  
Subgroup with 1 generators (  
[2 0]  
[0 2])  
of General Linear Group of degree 2 over Finite Field of size 3
```

```
sage: GL(3,GF(3)).center()  
Subgroup with 1 generators (  
[2 0 0]  
[0 2 0]  
[0 0 2])  
of General Linear Group of degree 3 over Finite Field of size 3
```

```
sage: GU(3,GF(2)).center()  
Subgroup with 1 generators (  
[a + 1 0 0]  
[0 a + 1 0]  
[0 0 a + 1])  
of General Unitary Group of degree 3 over Finite Field in a of size 2^2
```

```
sage: A = Matrix(FiniteField(5), \([2,0,0],[0,3,0],[0,0,1]\])
sage: B = Matrix(FiniteField(5), \([1,0,0],[0,1,0],[0,1,1]\))
sage: MatrixGroup([A,B]).center()  
Subgroup with 1 generators (  
[1 0 0]  
[0 1 0]  
[0 0 1])  
of Matrix group over Finite Field of size 5 with 2 generators (  
[2 0 0] [1 0 0]  
[0 3 0] [0 1 0]  
[0 0 1], [0 1 1])
```

class character(values)

Returns a group character from values, where values is a list of the values of the character evaluated on the conjugacy classes.

INPUT:
• values – a list of values of the character

OUTPUT: a group character

EXAMPLES:

```
sage: G = MatrixGroup(AlternatingGroup(4))
sage: G.character([1]*len(G.conjugacy_classes_representatives()))
Character of Matrix group over Integer Ring with 12 generators
```

```
sage: G = GL(2,ZZ)
sage: G.character([1,1,1,1])
Traceback (most recent call last):
...
NotImplementedError: only implemented for finite groups
```

**character_table()**
Returns the matrix of values of the irreducible characters of this group \( G \) at its conjugacy classes.

The columns represent the conjugacy classes of \( G \) and the rows represent the different irreducible characters in the ordering given by GAP.

OUTPUT: a matrix defined over a cyclotomic field

EXAMPLES:

```
sage: MatrixGroup(SymmetricGroup(2)).character_table()
[ 1 -1]
[ 1 1]
sage: MatrixGroup(SymmetricGroup(3)).character_table()
[ 1 1 -1]
[ 2 -1 0]
[ 1 1 1]
sage: MatrixGroup(SymmetricGroup(5)).character_table()
[ 1 -1 -1 1 -1 1 1]
[ 4 0 1 -1 -2 1 0]
[ 5 1 -1 0 -1 -1 1]
[ 6 0 0 1 0 0 -2]
[ 5 -1 1 0 1 -1 1]
[ 4 0 -1 -1 2 1 0]
[ 1 1 1 1 1 1 1]
```

**class_function(values)**
Return the class function with given values.

INPUT:

• values – list/tuple/iterable of numbers. The values of the class function on the conjugacy classes, in that order.

EXAMPLES:

```
sage: G = GL(2,GF(3))
sage: chi = G.class_function(range(8))
sage: list(chi)
[0, 1, 2, 3, 4, 5, 6, 7]
```

**conjugacy_class(g)**
Return the conjugacy class of \( g \).

OUTPUT:
The conjugacy class of $g$ in the group $self$. If $self$ is the group denoted by $G$, this method computes the set $\{x^{-1}gx \mid x \in G\}$.

**EXAMPLES:**

```python
sage: G = SL(2, QQ)
sage: g = G([[1,1],[0,1]])
sage: G.conjugacy_class(g)
Conjugacy class of [1 1]
[0 1] in Special Linear Group of degree 2 over Rational Field
```

**conjugacy_class_representatives**(*args, **kwds)

Deprecated: Use `conjugacy_classes_representatives()` instead. See trac ticket #22783 for details.

**conjugacy_classes()**

Return a list with all the conjugacy classes of $self$.

**EXAMPLES:**

```python
sage: G = SL(2, GF(2))
sage: G.conjugacy_classes()
(Conjugacy class of [1 0]
[0 1] in Special Linear Group of degree 2 over Finite Field of size 2,
Conjugacy class of [0 1]
[1 0] in Special Linear Group of degree 2 over Finite Field of size 2,
Conjugacy class of [0 1]
[1 1] in Special Linear Group of degree 2 over Finite Field of size 2)
```

```python
sage: GL(2,ZZ).conjugacy_classes()
Traceback (most recent call last):
...
NotImplementedError: only implemented for finite groups
```

**conjugacy_classes_representatives()**

Return a set of representatives for each of the conjugacy classes of the group.

**EXAMPLES:**

```python
sage: G = SU(3,GF(2))
sage: len(G.conjugacy_classes_representatives())
16
sage: G = GL(2,GF(3))
sage: G.conjugacy_classes_representatives()
{[1 0] [0 2] [2 0] [0 2] [0 1] [0 1] [2 0]
[0 1], [1 1], [0 2], [1 2], [1 0], [1 2], [1 1], [0 1]}
sage: len(GU(2,GF(5)).conjugacy_classes_representatives())
36
sage: GL(2,ZZ).conjugacy_classes_representatives()
Traceback (most recent call last):
...
NotImplementedError: only implemented for finite groups
```
**intersection** *(other)*

Return the intersection of two groups (if it makes sense) as a subgroup of the first group.

**EXAMPLES:**

```
sage: A = Matrix([[0, 1/2, 0], (2, 0, 0), (0, 0, 1)])
sage: B = Matrix([[0, 1/2, 0], (-2, -1, 2), (0, 0, 1)])
sage: G = MatrixGroup([A, B])
sage: len(G)  # isomorphic to S_3
6
sage: G.intersection(GL(3,ZZ))
Subgroup with 1 generators ([1 0 0]
[-2 -1 2]
[0 0 1]) of Matrix group over Rational Field with 2 generators ([0 1/2 0]
[2 0 0] [-2 -1 2]
[0 0 1], [0 0 1])
sage: GL(3,ZZ).intersection(G)
Subgroup with 1 generators ([1 0 0]
[-2 -1 2]
[0 0 1]) of General Linear Group of degree 3 over Integer Ring
sage: G.intersection(SL(3,ZZ))
Subgroup with 0 generators () of Matrix group over Rational Field with 2 generators ([0 1/2 0]
[2 0 0] [-2 -1 2]
[0 0 1], [0 0 1])
```

**irreducible_characters()**

Return the irreducible characters of the group.

**OUTPUT:**

A tuple containing all irreducible characters.

**EXAMPLES:**

```
sage: G = GL(2,2)
sage: G.irreducible_characters()
(Character of General Linear Group of degree 2 over Finite Field of size 2,
 Character of General Linear Group of degree 2 over Finite Field of size 2,
 Character of General Linear Group of degree 2 over Finite Field of size 2)
sage: GL(2,ZZ).irreducible_characters()
Traceback (most recent call last):
...
NotImplementedError: only implemented for finite groups
```

**is_abelian()**

Test whether the group is Abelian.

**OUTPUT:**

Boolean. True if this group is an Abelian group.
EXAMPLES:

```
sage: SL(1, 17).is_abelian()
sage: SL(2, 17).is_abelian()
```

```is_finite()```
Test whether the matrix group is finite.

**OUTPUT:**
Boolean.

**EXAMPLES:**

```
sage: G = GL(2,GF(3))
sage: G.is_finite()
sage: SL(2,ZZ).is_finite()
```

```is_isomorphic(H)```
Test whether `self` and `H` are isomorphic groups.

**INPUT:**

• `H` — a group.

**OUTPUT:**
Boolean.

**EXAMPLES:**

```
sage: m1 = matrix(GF(3), [[1,1],[0,1]])
sage: m2 = matrix(GF(3), [[1,2],[0,1]])
sage: F = MatrixGroup(m1)
sage: G = MatrixGroup(m1, m2)
sage: H = MatrixGroup(m2)
sage: F.is_isomorphic(G)
sage: G.is_isomorphic(H)
sage: F.is_isomorphic(H)
sage: F==G, G==H, F==H
```

```list()```
List all elements of this group.

**OUTPUT:**
A tuple containing all group elements in a random but fixed order.

**EXAMPLES:**

```
sage: F = GF(3)
sage: gens = [matrix(F, 2, [1,0,-1,1]), matrix(F, 2, [1,1,0,1])]sage: G = MatrixGroup(gens)
sage: G.cardinality()
```

(continues on next page)
An example over a ring (see trac ticket #5241):

```python
sage: M1 = matrix(ZZ,2,[[1,0],[0,-1]])
sage: M2 = matrix(ZZ,2,[[1,0],[0,-1]])
sage: M3 = matrix(ZZ,2,[[1,0],[0,-1]])
sage: MG = MatrixGroup([M1, M2, M3])
sage: MG.list()
( [-1 0] [-1 0] [ 1 0] [ 1 0]
 [ 0 -1], [ 0 1], [ 0 -1], [0 1] )
sage: MG.list()[1]
[-1 0]
[ 0 1]
sage: MG.list()[1].parent()
Matrix group over Integer Ring with 3 generators ( [-1 0] [ 1 0] [-1 0]
 [ 0 -1], [ 0 1], [ 0 -1] )
```

An example over a field (see trac ticket #10515):

```python
sage: gens = [matrix(QQ,2,[1,0,0,1])]
sage: MatrixGroup(gens).list()
( [1 0]
 [0 1] )
```

Another example over a ring (see trac ticket #9437):

```python
sage: len(SL(2, Zmod(4)).list())
48
```

An error is raised if the group is not finite:

```python
sage: GL(2,ZZ).list()
Traceback (most recent call last):
  ...
NotImplementedError: group must be finite
```

**order()**


**EXAMPLES:**
random_element()

Return a random element of this group.

OUTPUT:

A group element.

EXAMPLES:

sage: G = Sp(4,GF(3))
sage: G.random_element()  # random
[2 1 1 1]
[1 0 2 1]
[0 1 1 0]
[1 0 0 1]
sage: G.random_element() in G
True

sage: F = GF(5); MS = MatrixSpace(F,2,2)
sage: gens = [MS([[1,2],[-1,1]]), MS([[1,1],[0,1]])]
sage: G = MatrixGroup(gens)
sage: G.random_element()  # random
trivial_character()  
Returns the trivial character of this group.

OUTPUT: a group character

EXAMPLES:

```
sage: MatrixGroup(SymmetricGroup(3)).trivial_character()
Character of Matrix group over Integer Ring with 6 generators

sage: GL(2,ZZ).trivial_character()
Traceback (most recent call last):
...
NotImplementedError: only implemented for finite groups
```
See pari:polgalois for the PARI documentation of these objects.

```python
class sage.groups.pari_group.PariGroup(x, degree)
    Bases: object

    EXAMPLES:
    sage: PariGroup([6, -1, 2, "S3"], 3)
    PARI group [6, -1, 2, S3] of degree 3
    sage: R.<x> = PolynomialRing(QQ)
    sage: f = x^4 - 17*x^3 - 2*x + 1
    sage: G = f.galois_group(pari_group=True); G
    PARI group [24, -1, 5, "S4"] of degree 4
```

cardinality()
Return the order of self.

    EXAMPLES:
    sage: R.<x> = PolynomialRing(QQ)
    sage: f1 = x^4 - 17*x^3 - 2*x + 1
    sage: G1 = f1.galois_group(pari_group=True)
    sage: G1.order()
    24

degree()
Return the degree of self.

    EXAMPLES:
    sage: R.<x> = PolynomialRing(QQ)
    sage: f1 = x^4 - 17*x^3 - 2*x + 1
    sage: G1 = f1.galois_group(pari_group=True)
    sage: G1.degree()
    4

order()
Return the order of self.

    EXAMPLES:
    sage: R.<x> = PolynomialRing(QQ)
    sage: f1 = x^4 - 17*x^3 - 2*x + 1
    sage: G1 = f1.galois_group(pari_group=True)
    sage: G1.order()
    24
permutation_group()
MISCELLANEOUS GENERIC FUNCTIONS

A collection of functions implementing generic algorithms in arbitrary groups, including additive and multiplicative groups.

In all cases the group operation is specified by a parameter ‘operation’, which is a string either one of the set of multiplication_names or addition_names specified below, or ‘other’. In the latter case, the caller must provide an identity, inverse() and op() functions.

```
multiplication_names = ( 'multiplication', 'times', 'product', '*' )
addition_names = ( 'addition', 'plus', 'sum', '+' )
```

Also included are a generic function for computing multiples (or powers), and an iterator for general multiples and powers.

EXAMPLES:

Some examples in the multiplicative group of a finite field:

- Discrete logs:
  ```
sage: K = GF(3^6,'b')
sage: b = K.gen()
sage: a = b^210
sage: discrete_log(a, b, K.order()-1)
210
  ```

- Linear relation finder:
  ```
sage: F.<a>=GF(3^6,'a')
sage: a=multiplicative_order().factor()
2^3 * 7 * 13
sage: b=a^7
sage: c=a^13
sage: linear_relation(b,c,'*')
(13, 7)
sage: b^13==c^7
True
  ```

- Orders of elements:
  ```
sage: from sage.groups.generic import order_from_multiple, order_from_bounds
sage: k.<a> = GF(5^5)
sage: b = a^4
sage: order_from_multiple(b,5^5-1,operation='*')
781
  ```

Some examples in the group of points of an elliptic curve over a finite field:

- **Discrete logs:**

  ```python
  sage: F = GF(37^2, 'a')
sage: E = EllipticCurve(F, [1, 1])
sage: F.<a> = GF(37^2, 'a')
sage: E = EllipticCurve(F, [1, 1])
sage: P = E(25*a + 16, 15*a + 7)
sage: P.order()
  672
sage: Q = 39*P; Q
(36*a + 32 : 5*a + 12 : 1)
sage: discrete_log(Q, P, P.order(), operation='+')
39
  ```

- **Linear relation finder:**

  ```python
  sage: F.<a> = GF(3^6, 'a')
sage: E = EllipticCurve([a^5 + 2*a^3 + 2*a^2 + 2*a, a^4 + a^3 + 2*a + 1])
sage: P = E(a^5 + a^4 + a^3 + a^2 + a + 2, 0)
sage: Q = E(2*a^3 + 2*a^2 + 2*a, a^3 + 2*a^2 + 1)
sage: linear_relation(P, Q, '+')
(1, 2)
sage: P == 2*Q
True
  ```

- **Orders of elements:**

  ```python
  sage: from sage.groups.generic import order_from_multiple, order_from_bounds
sage: k.<a> = GF(5^5)
sage: E = EllipticCurve(k, [2, 4])
sage: P = E(3*a^4 + 3*a, 2*a + 1)
sage: M = E.cardinality(); M
3227
sage: plist = M.prime_factors()
sage: order_from_multiple(P, M, plist, operation='+')
3227
sage: Q = E(0, 2)
sage: order_from_multiple(Q, M, plist, operation='+')
7
sage: order_from_bounds(Q, Hasse_bounds(5^5), operation='+')
7
  ```

sage.groups.generic.bsgs(a, b, bounds, operation='*', identity=None, inverse=None, op=None)

Totally generic discrete baby-step giant-step function.

Solves \( na = b \) (or \( a^n = b \)) with \( lb \leq n \leq ub \) where \( bounds = (lb, ub) \), raising an error if no such \( n \) exists.

- \( a \) and \( b \) must be elements of some group with given identity, inverse of \( x \) given by \( inverse(x) \), and group operation on \( x, y \) by \( op(x, y) \).

If operation is ‘*’ or ‘+’ then the other arguments are provided automatically; otherwise they must be provided by the caller.

**INPUT:**
• $a$ - group element
• $b$ - group element
• bounds - a 2-tuple of integers $(lower, upper)$ with $0 \leq lower \leq upper$
• operation - string: ‘*’, ‘+’, ‘other’
• identity - the identity element of the group
• inverse() - function of 1 argument $x$ returning inverse of $x$
• op() - function of 2 arguments $x, y$ returning $x*y$ in group

OUTPUT:
An integer $n$ such that $a^n = b$ (or $na = b$). If no such $n$ exists, this function raises a ValueError exception.

NOTE: This is a generalization of discrete logarithm. One situation where this version is useful is to find the order of an element in a group where we only have bounds on the group order (see the elliptic curve example below).

ALGORITHM: Baby step giant step. Time and space are soft $O(\sqrt{n})$ where $n$ is the difference between upper and lower bounds.

EXAMPLES:

```sage
from sage.groups.generic import bsgs
sage: b = Mod(2,37); a = b^20
sage: bsgs(b, a, (0,36))
20

sage: p=next_prime(10^20)
sage: a=Mod(2,p); b=a^(10^25)
sage: bsgs(a, b, (10^25-10^6,10^25+10^6)) == 10^25
True

sage: K = GF(3^6,'b')
sage: a = K.gen()
sage: b = a^210
sage: bsgs(a, b, (0,K.order()-1))
210

sage: K.<z>=CyclotomicField(230)
sage: w=z^500
sage: bsgs(z,w,(0,229))
40
```

An additive example in an elliptic curve group:

```sage
sage: F.<a> = GF(37^5)
sage: E = EllipticCurve(F, [1,1])
sage: P = E.lift_x(a); P
(a : 28*a^4 + 15*a^3 + 14*a^2 + 7 : 1)

sage: bsgs(P,P.parent()(),Hasse_bounds(F.order()),operation='+')
69327408
```

This will return a multiple of the order of $P$:

```sage
37```
Totally generic discrete log function.

**INPUT:**

- `a` - group element
- `base` - group element (the base)
- `ord` - integer (multiple of order of base, or None)
- `bounds` - a priori bounds on the log
- `operation` - string: `'*'`, `'+'`, `other'
- `identity` - the group’s identity
- `inverse()` - function of 1 argument `x` returning inverse of `x`
- `op()` - function of 2 arguments `x, y` returning `x*y` in group

`a` and `base` must be elements of some group with identity given by `identity`, inverse of `x` by `inverse(x)`, and group operation on `x, y` by `op(x, y)`.

If operation is `'*'` or `'+` then the other arguments are provided automatically; otherwise they must be provided by the caller.

**OUTPUT:** Returns an integer `n` such that `b^n = a` (or `nb = a`), assuming that `ord` is a multiple of the order of the base `b`. If `ord` is not specified, an attempt is made to compute it.

If no such `n` exists, this function raises a `ValueError` exception.

**Warning:** If `x` has a log method, it is likely to be vastly faster than using this function. E.g., if `x` is an integer modulo `n`, use its log method instead!

**ALGORITHM:** Pohlig-Hellman and Baby step giant step.

**EXAMPLES:**

```python
sage: b = Mod(2,37); a = b^20
sage: discrete_log(a, b)
20
sage: b = Mod(2,997); a = b^20
sage: discrete_log(a, b)
20
sage: K = GF(3^6,'b')
sage: b = K.gen()
210
sage: a = b^210
sage: discrete_log(a, b, K.order()-1)
210
sage: b = Mod(1,37); x = Mod(2,37)
Traceback (most recent call last):
...
ValueError: No discrete log of 2 found to base 1
```

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...  

ValueError: No discrete log of 2 found to base 1

See trac ticket #2356:

```python
sage: F.<w> = GF(121)
sage: v = w^120
sage: v.log(w)
0
sage: K.<z>=CyclotomicField(230)
sage: w=z^50
sage: discrete_log(w,z)
50
```

An example where the order is infinite: note that we must give an upper bound here:

```python
sage: K.<a> = QuadraticField(23)
sage: eps = 5*a-24  # a fundamental unit
sage: eps.multiplicative_order()
+Infinity
sage: eta = eps^100
sage: discrete_log(eta,eps,bounds=(0,1000))
100
```

In this case we cannot detect negative powers:

```python
sage: eta = eps^(-3)
sage: discrete_log(eta,eps,bounds=(0,100))
Traceback (most recent call last):
...  

ValueError: No discrete log of -11515*a - 55224 found to base 5*a - 24
```

But we can invert the base (and negate the result) instead:

```python
sage: - discrete_log(eta^-1,eps,bounds=(0,100))
-3
```

An additive example: elliptic curve DLOG:

```python
sage: F=GF(37^2,'a')
sage: E=EllipticCurve(F,[1,1])
sage: F.<a>=GF(37^2,'a')
sage: E=EllipticCurve(F,[1,1])
sage: P=E(25*a + 16 , 15*a + 7 )
sage: P.order()
672
sage: Q=39*P; Q
(36*a + 32 : 5*a + 12 : 1)
sage: discrete_log(Q,P,P.order(),operation=')
39
```

An example of big smooth group:

```python
sage: F.<a>=GF(2^63)
sage: g=F.gen()
```

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AUTHORS:

- William Stein and David Joyner (2005-01-05)
- John Cremona (2008-02-29) rewrite using `dict()` and make generic

\begin{verbatim}
sage.groups.generic.discrete_log_generic(a, base, ord=None, bounds=None, operation='*', identity=None, inverse=None, op=None)

Alias for `discrete_log`
\end{verbatim}

\begin{verbatim}
sage.groups.generic.discrete_log_lambda(a, base, bounds, operation='*',
                                         hash_function=<built-in function hash>)

Pollard Lambda algorithm for computing discrete logarithms. It uses only a logarithmic amount of memory. It's useful if you have bounds on the logarithm. If you are computing logarithms in a whole finite group, you should use Pollard Rho algorithm.

INPUT:

- \(a\) – a group element
- \(base\) – a group element
- \(bounds\) – a couple (lb,ub) representing the range where we look for a logarithm
- \(operation\) – string: ‘+’, ‘*’ or ‘other’
- \(hash\_function\) – having an efficient hash function is critical for this algorithm

OUTPUT: Returns an integer \(n\) such that \(a = base^n\) (or \(a = n * base\))

ALGORITHM: Pollard Lambda, if bounds are \((lb,ub)\) it has time complexity \(O(\sqrt{ub-lb})\) and space complexity \(O(\log(ub-lb))\)

EXAMPLES:

\begin{verbatim}
sage: F.<a> = GF(2^63)
sage: discrete_log_lambda(a^1234567, a, (1200000,1250000))
1234567

sage: E = EllipticCurve(F, [1,1])
sage: P = E.lift_x(a); P
(a : 28*a^4 + 15*a^3 + 14*a^2 + 7 : 1)
sage: discrete_log_lambda(P.parent()(0), P, Hasse_bounds(F.order()), operation=('+', hash_function=hash)
# long time (10s on sage.math, 2011)
69327408
\end{verbatim}

This will return a multiple of the order of \(P\):

\begin{verbatim}
sage: K.<a> = GF(89**5)
sage: hs = lambda x: hash(x) + 15
sage: discrete_log_lambda(a**(89**3 - 3), a, (89**2, 89**4), operation = '*',
                                         hash_function = hs)
# long time (10s on sage.math, 2011)
704966
\end{verbatim}

AUTHOR:
Pollard Rho algorithm for computing discrete logarithm in cyclic group of prime order. If the group order is very small it falls back to the baby step giant step algorithm.

**INPUT:**

- `a` – a group element
- `base` – a group element
- `ord` – the order of `base` or `None`, in this case we try to compute it
- `operation` – a string (default: `'*'`) denoting whether we are in an additive group or a multiplicative one
- `hash_function` – having an efficient hash function is critical for this algorithm (see examples)

**OUTPUT:** an integer $n$ such that $a = base^n$ (or $a = n * base$)

**ALGORITHM:** Pollard rho for discrete logarithm, adapted from the article of Edlyn Teske, ‘A space efficient algorithm for group structure computation’.

**EXAMPLES:**

```python
sage: F.<a> = GF(2^13)
sage: g = F.gen()
sage: discrete_log_rho(g^1234, g)
1234
sage: F.<a> = GF(37^5)
sage: E = EllipticCurve(F, [1,1])
sage: G = (3*31*2^4)*E.lift_x(a)
sage: discrete_log_rho(12345*G, G, ord=46591, operation='+')
12345
```

It also works with matrices:

```python
sage: A = matrix(GF(50021),
[[10577,23999,28893],[14601,41019,30188],[3081,736,27092]])
sage: discrete_log_rho(A^1234567, A)
1234567
```

Beware, the order must be prime:

```python
sage: I = IntegerModRing(171980)
sage: discrete_log_rho(I(2), I(3))
Traceback (most recent call last):
  ... ValueError: for Pollard rho algorithm the order of the group must be prime
```

If it fails to find a suitable logarithm, it raises a `ValueError`:

```python
sage: I = IntegerModRing(171980)
sage: discrete_log_rho(I(31002),I(15501))
Traceback (most recent call last):
  ... ValueError: Pollard rho algorithm failed to find a logarithm
```

The main limitation on the hash function is that we don’t want to have $\text{hash}(x * y) = \text{hash}(x) + \text{hash}(y)$:
If this happens, we can provide a better hash function:

```python
sage: discrete_log_rho(I(123456),I(1),operation='+', hash_function=lambda x:→hash(x*x))
123456
```

AUTHOR:

- Yann Laigle-Chapuy (2009-09-05)

\[ \text{sage.groups.generic.linear_relation}(P, Q, \text{operation}='+', \text{identity}=None, \text{inverse}=None, \text{op}=None) \]

Function which solves the equation \( aP=mQ \) or \( P^a=Q^m \).

Additive version: returns \((a, m)\) with minimal \( m > 0 \) such that \( aP = mQ \). Special case: if \( \langle P \rangle \) and \( \langle Q \rangle \) intersect only in \( \{0\} \) then \((a, m) = (0, n)\) where \( n \) is \( Q.\text{additive_order()} \).

Multiplicative version: returns \((a, m)\) with minimal \( m > 0 \) such that \( P^a = Q^m \). Special case: if \( \langle P \rangle \) and \( \langle Q \rangle \) intersect only in \( \{1\} \) then \((a, m) = (0, n)\) where \( n \) is \( Q.\text{multiplicative_order()} \).

ALGORITHM:

Uses the generic \texttt{bsgs()} function, and so works in general finite abelian groups.

EXAMPLES:

An additive example (in an elliptic curve group):

```python
sage: F.<a>=GF(3^6,'a')
sage: E=EllipticCurve([a^5 + 2*a^3 + 2*a^2 + 2*a, a^4 + a^3 + 2*a + 1])
sage: P=E(a^5 + a^4 + a^3 + a^2 + a + 2 , 0)
sage: Q=E(2*a^3 + 2*a^2 + 2*a , a^3 + 2*a^2 + 1)
sage: linear_relation(P,Q,'+')(1, 2)
sage: P == 2*Q
True
```

A multiplicative example (in a finite field’s multiplicative group):

```python
sage: F.<a>=GF(3^6,'a')
sage: a.multiplicative_order().factor() 2^3 * 7 * 13
sage: b=a^7
sage: c=a^13
sage: linear_relation(b,c,'*')(13, 7)
sage: b^13==c^7
True
```

\[ \text{sage.groups.generic.merge_points}(P1, P2, \text{operation}='+', \text{identity}=None, \text{inverse}=None, \text{op}=None, \text{check}=True) \]

Returns a group element whose order is the lcm of the given elements.
INPUT:

- P1 – a pair \((g_1, n_1)\) where \(g_1\) is a group element of order \(n_1\)
- P2 – a pair \((g_2, n_2)\) where \(g_2\) is a group element of order \(n_2\)
- operation – string: ‘+’ (default) or ‘*’ or other. If other, the following must be supplied:
  - identity: the identity element for the group;
  - inverse(): a function of one argument giving the inverse of a group element;
  - op(): a function of 2 arguments defining the group binary operation.

OUTPUT:

A pair \((g_3, n_3)\) where \(g_3\) has order \(n_3 = \text{lcm}(n_1, n_2)\).

EXAMPLES:

```
sage: from sage.groups.generic import merge_points
sage: F.<a>=GF(3^6,'a')
sage: b = a^7
sage: c = a^13
sage: ob = (3^6-1)//7
sage: oc = (3^6-1)//13
sage: merge_points((b,ob),(c,oc),operation='*')
(a^4 + 2*a^3 + 2*a^2, 728)
sage: d,od = merge_points((b,ob),(c,oc),operation='*')
sage: od == d.multiplicative_order()
True
sage: od == lcm(ob,oc)
True
sage: E=EllipticCurve([a^5 + 2*a^3 + 2*a^2 + 2*a, a^4 + a^3 + 2*a + 1])
sage: P=E(2*a^5 + 2*a^4 + a^3 + 2 , a^4 + a^3 + a^2 + 2*a + 2)
sage: P.order() 7
sage: Q=E(2*a^5 + 2*a^4 + 1 , a^5 + 2*a^3 + 2*a + 2 )
Sage: Q.order()
4
sage: R,m = merge_points((P,7),(Q,4), operation='+')
sage: R.order() == m
True
sage: m == lcm(7,4)
True
```

```
sage.groups.generic.multiple(a, n, operation='*', identity=None, inverse=None, op=None)
```

Returns either \(na\) or \(a^n\), where \(n\) is any integer and \(a\) is a Python object on which a group operation such as addition or multiplication is defined. Uses the standard binary algorithm.

INPUT: See the documentation for `discrete_logarithm()`.

EXAMPLES:

```
sage: multiple(2,5)
32
sage: multiple(RealField()('2.5'),4)
39.0625000000000
sage: multiple(2,-3)
1/8
sage: multiple(2,100,'+') == 100*2
```

(continues on next page)
True
\[
sage: \text{multiple}(2, 100) == 2^{*}100
\]
True
\[
sage: \text{multiple}(2, -100,) == 2^{*}-100
\]
True
\[
sage: R.<x>=\mathbb{Z}[]
\]
\[
sage: \text{multiple}(x, 100)
\]
x^{100}
\[
sage: \text{multiple}(x, 100, '+')
\]
100*x
\[
sage: \text{multiple}(x, -10)
\]
1/x^{10}

Idempotence is detected, making the following fast:
\[
\begin{align*}
\text{sage: multiple}(1, 10^{1000}) & \quad 1 \\
\text{sage: E=EllipticCurve'}(\text{389a1}') & \\
\text{sage: P=E(-1,1)} & \\
\text{sage: multiple}(P, 10, '+') & \quad (6456613235873542773209599489/22817025904944891235367494656 : \\
\quad \rightarrow & \quad 525532176124281192881231818644174845702936831/ \\
\quad \rightarrow & \quad 3446581505217248068297884384990762467229696 : 1) \\
\text{sage: multiple}(P, -10, '+') & \quad (6456613235873542773209599489/22817025904944891235367494656 : \\
\quad \rightarrow & \quad 528978775762948440949529703029165608170166527/ \\
\quad \rightarrow & \quad 3446581505217248068297884384990762467229696 : 1) \\
\end{align*}
\]

\[
\text{class sage.groups.generic.multiples}(P, n, P0=None, indexed=False, operation='+', op=None)
\]

Return an iterator which runs through \(P0+i*P\) for \(i\) in \(\text{range}(n)\).

\(P\) and \(P0\) must be Sage objects in some group; if the operation is multiplication then the returned values are instead \(P0*P**i\).

EXAM P L E S:
\[
\begin{align*}
\text{sage: list(multiples(1,10))} & \quad [0, 1, 2, 3, 4, 5, 6, 7, 8, 9] \\
\text{sage: list(multiples(1,10,100))} & \quad [100, 101, 102, 103, 104, 105, 106, 107, 108, 109] \\
\text{sage: E=EllipticCurve'}(\text{389a1}') & \\
\text{sage: P=E(-1,1)} & \\
\text{sage: for Q in multiples(P,5): print}((Q, Q.height()/P.height()) & \quad ((0 : 1 : 0), 0.000000000000000) \\
\text{} & \quad ((-1 : 1 : 1), 1.000000000000000) \\
\text{} & \quad ((10/9 : -35/27 : 1), 4.000000000000000) \\
\text{} & \quad ((26/361 : -5720/6859 : 1), 9.000000000000000) \\
\text{} & \quad ((47503/16641 : 9862190/2146689 : 1), 16.000000000000000) \\
\text{sage: R.<x>=\mathbb{Z}[]} & \\
\text{sage: list(multiples(x,5))} & \quad [0, x, 2*x, 3*x, 4*x] \\
\text{sage: list(multiples(x,5,operation='*'))} & \quad [1, x, x^2, x^3, x^4] \\
\end{align*}
\]
Sage: list(multiples(x,5,indexed=True))
[(0, 0), (1, x), (2, 2*x), (3, 3*x), (4, 4*x)]
Sage: list(multiples(x,5,indexed=True,operation='*'))
[(0, 1), (1, x), (2, x^2), (3, x^3), (4, x^4)]
Sage: for i,y in multiples(x,5,indexed=True):
print( "{} times {} = {}");print( "{} times {} = {}");print( "{} times {} = {}");print( "{} times {} = {}");print( "{} times {} = {}");
0 times x = 0
1 times x = x
2 times x = 2 * x
3 times x = 3 * x
4 times x = 4 * x
Sage: for i,n in multiples(3,5,indexed=True,operation='*):
print("3 to the power {} = {}");print("3 to the power {} = {}");print("3 to the power {} = {}");print("3 to the power {} = {}");print("3 to the power {} = {}");
3 to the power 0 = 1
3 to the power 1 = 3
3 to the power 2 = 9
3 to the power 3 = 27
3 to the power 4 = 81

next ()
Returns the next item in this multiples iterator.

Sage.groups.generic.order_from_bounds (P, bounds, d=None, operation='+', identity=None, inverse=None, op=None)
Generic function to find order of a group element, given only upper and lower bounds for a multiple of the order (e.g. bounds on the order of the group of which it is an element)

INPUT:

• P - a Sage object which is a group element
• bounds - a 2-tuple (lb, ub) such that m * P = 0 (or P ** m = 1) for some m with lb <= m <= ub.
• d - (optional) a positive integer; only m which are multiples of this will be considered.
• operation - string: '+' (default) or '*' or other. If other, the following must be supplied:
  – identity: the identity element for the group;
  – inverse(): a function of one argument giving the inverse of a group element;
  – op(): a function of 2 arguments defining the group binary operation.

Note: Typically lb and ub will be bounds on the group order, and from previous calculation we know that the group order is divisible by d.

EXAMPLES:

sage: from sage.groups.generic import order_from_bounds
sage: k.<a> = GF(5^5)
sage: b = a^4
sage: order_from Bounds(b, (5^4, 5^5), operation='*')
781
sage: E = EllipticCurve(k,[2,4])
sage: P = E(3*a^4 + 3*a , 2*a + 1 )
sage: bounds = Hasse_bounds(5^5)
sage: Q = E(0,2)
sage: order_from_bounds(Q, bounds, operation='*')
Generic function to find order of a group element given a multiple of its order.

INPUT:

- \( P \) - a Sage object which is a group element;
- \( m \) - a Sage integer which is a multiple of the order of \( P \), i.e. we require that \( m \cdot P = 0 \) (or \( P^m = 1 \));
- \( \text{check} \) - a Boolean (default: True), indicating whether we check if \( m \) really is a multiple of the order;
- \( \text{factorization} \) - the factorization of \( m \), or None in which case this function will need to factor \( m \);
- \( \text{plist} \) - a list of the prime factors of \( m \), or None - kept for compatibility only, prefer the use of \( \text{factorization} \);
- \( \text{operation} \) - string: '+' (default) or '*'.

Note: It is more efficient for the caller to factor \( m \) and cache the factors for subsequent calls.

EXAMPLES:

```
sage: from sage.groups.generic import order_from_multiple
sage: k.<a> = GF(5^5)
sage: b = a^4
sage: order_from_multiple(b, 5^5-1, operation='*')
781
sage: E = EllipticCurve(k, [2,4])
sage: P = E(3*a^4 + 3*a, 2*a + 1)
sage: M = E.order(); M
3227
sage: F = M.factor()
sage: order_from_multiple(P, M, factorization=F, operation='+')
3227
sage: Q = E(0,2)
sage: order_from_multiple(Q, M, factorization=F, operation='+')
7
```

```
sage: K.<z>=CyclotomicField(230)
sage: w=z^50
sage: order_from_multiple(w, (200,250), operation='*')
23
```
sage: K.<a> = GF(3^60)
sage: order_from_multiple(a, 3^60-1, operation='*', check=False)
42391158275216203514294433200

sage.groups.generic.structure_description(G, latex=False)

Return a string that tries to describe the structure of $G$.

This methods wraps GAP's StructureDescription method.

For full details, including the form of the returned string and the algorithm to build it, see GAP's documentation.

INPUT:

• latex – a boolean (default: False). If True return a LaTeX formatted string.

OUTPUT:

• string

**Warning:** From GAP's documentation: The string returned by StructureDescription is **not** an isomorphism invariant: non-isomorphic groups can have the same string value, and two isomorphic groups in different representations can produce different strings.

EXAMPLES:

```
sage: G = CyclicPermutationGroup(6)
sage: G.structure_description()  
'C6'
sage: G.structure_description(latex=True)  
'C_{6}'
sage: G2 = G.direct_product(G, maps=False)
sage: LatexExpr(G2.structure_description(latex=True))
\( C_{6} \times C_{6} \)
```

This method is mainly intended for small groups or groups with few normal subgroups. Even then there are some surprises:

```
sage: D3 = DihedralGroup(3)
sage: D3.structure_description()  
'S3'
```

We use the Sage notation for the degree of dihedral groups:

```
sage: D4 = DihedralGroup(4)
sage: D4.structure_description()  
'D4'
```

Works for finitely presented groups (trac ticket #17573):

```
sage: F.<x, y> = FreeGroup()  
sage: G=F / [x^2*y^-1, x^3*y^2, x*y*x^-1*y^-1]  
sage: G.structure_description()  
'C7'
```

And matrix groups (trac ticket #17573):
sage: groups.matrix.GL(4,2).structure_description()
'A8'
Free groups and finitely presented groups are implemented as a wrapper over the corresponding GAP objects. A free group can be created by giving the number of generators, or their names. It is also possible to create indexed generators:

```
sage: G.<x,y,z> = FreeGroup(); G
Free Group on generators {x, y, z}
sage: FreeGroup(3)
Free Group on generators {x0, x1, x2}
sage: FreeGroup('a,b,c')
Free Group on generators {a, b, c}
sage: FreeGroup(3,'t')
Free Group on generators {t0, t1, t2}
```

The elements can be created by operating with the generators, or by passing a list with the indices of the letters to the group:

```
EXAMPLES:
sage: G.<a,b,c> = FreeGroup()
sage: a*b*c*a
a*b*c*a
sage: G([1,2,3,1])
a*b*c*a
sage: a * b / c * b^2
a*b^3c^-1b^2
sage: G([1,1,2,-1,-3,2])
a^2*b*a^-1*c^-1*b
```

You can use call syntax to replace the generators with a set of arbitrary ring elements:

```
sage: g = a * b / c * b^2
sage: g(1,2,3)
8/3
sage: M1 = identity_matrix(2)
sage: M2 = matrix([[1,1],[0,1]])
sage: M3 = matrix([[0,1],[1,0]])
sage: g([M1, M2, M3])
[1 3]
[1 2]
```

AUTHORS:
- Miguel Angel Marco Buzunariz
- Volker Braun
Construct a Free Group.

**INPUT:**
- `n` – integer or `None` (default). The number of generators. If not specified the `names` are counted.
- `names` – string or list/tuple/iterable of strings (default: `'x'`). The generator names or name prefix.
- `index_set` – (optional) an index set for the generators; if specified then the optional keyword `abelian` can be used.
- `abelian` – (default: `False`) whether to construct a free abelian group or a free group.

**Note:** If you want to create a free group, it is currently preferential to use `Groups().free(...)` as that does not load GAP.

**EXAMPLES:**

```python
sage: G.<a,b> = FreeGroup(); G
Free Group on generators {a, b}
sage: H = FreeGroup('a, b')
sage: G is H
True
sage: FreeGroup(0)
Free Group on generators {}
```

The entry can be either a string with the names of the generators, or the number of generators and the prefix of the names to be given. The default prefix is `'x'`.

```python
sage: FreeGroup(3)
Free Group on generators {x0, x1, x2}
sage: FreeGroup(3, 'g')
Free Group on generators {g0, g1, g2}
sage: FreeGroup()
Free Group on generators {x}
```

We give two examples using the `index_set` option:

```python
sage: FreeGroup(index_set=ZZ)
Free group indexed by Integer Ring
sage: FreeGroup(index_set=ZZ, abelian=True)
Free abelian group indexed by Integer Ring
```

```python
class sage.groups.free_group.FreeGroupElement (parent, x)
Bases: sage.groups.libgap_wrapper.ElementLibGAP
A wrapper of GAP's Free Group elements.

**INPUT:**
- `x` – something that determines the group element. Either a `GapElement` or the Tietze list (see `Tietze()`) of the group element.

**EXAMPLES:**
```
```python
sage: G = FreeGroup('a, b')
sage: x = G([1, 2, -1, -2])
sage: x
a*b*a^-1*b^-1
sage: y = G([2, 2, 1, -2, -2, -2])
sage: y
b^3*a*b^-3
sage: x*y
a*b*a^-1*b^2*a*b^-3
sage: y*x
b^3*a*b^-3*a*b*a^-1*b^-1
sage: x^(-1)
b*a*b^-1*a^-1
sage: x == x*y*y^(-1)
True
```

### Tietze()

Return the Tietze list of the element.

The Tietze list of a word is a list of integers that represent the letters in the word. A positive integer \( i \) represents the letter corresponding to the \( i \)-th generator of the group. Negative integers represent the inverses of generators.

**OUTPUT:**

A tuple of integers.

**EXAMPLES:**

```python
sage: G.<a,b> = FreeGroup()
sage: a.Tietze()
(1,)
sage: x = a^2 * b^(-3) * a^(-2)
sage: x.Tietze()
(1, 1, -2, -2, -2, -1, -1)
```

### fox_derivative(gen, im_gens=None, ring=None)

Return the Fox derivative of `self` with respect to a given generator `gen` of the free group.

Let \( F \) be a free group with free generators \( x_1, x_2, \ldots, x_n \). Let \( j \in \{1, 2, \ldots, n\} \). Let \( a_1, a_2, \ldots, a_n \) be \( n \) invertible elements of a ring \( A \). Let \( a : F \to A^\times \) be the (unique) homomorphism from \( F \) to the multiplicative group of invertible elements of \( A \) which sends each \( x_i \) to \( a_i \). Then, we can define a map \( \partial_j : F \to A \) by the requirements that

\[
\partial_j(x_i) = \delta_{i,j}
\]

for all indices \( i \) and \( j \)

and

\[
\partial_j(uv) = \partial_j(u) + a(u)\partial_j(v)
\]

for all \( u, v \in F \).

This map \( \partial_j \) is called the \( j \)-th Fox derivative on \( F \) induced by \((a_1, a_2, \ldots, a_n)\).

The most well-known case is when \( A \) is the group ring \( \mathbb{Z}[F] \) of \( F \) over \( \mathbb{Z} \), and when \( a_i = x_i \in A \). In this case, \( \partial_j \) is simply called the \( j \)-th Fox derivative on \( F \).

**INPUT:**

- `gen` – the generator with respect to which the derivative will be computed. If this is \( x_j \), then the method will return \( \partial_j \).
• **im_gens** (optional) – the images of the generators (given as a list or iterable). This is the list \((a_1, a_2, \ldots, a_n)\). If not provided, it defaults to \((x_1, x_2, \ldots, x_n)\) in the group ring \(\mathbb{Z}[F]\).

• **ring** (optional) – the ring in which the elements of the list \((a_1, a_2, \ldots, a_n)\) lie. If not provided, this ring is inferred from these elements.

**OUTPUT:**

The fox derivative of `self` with respect to `gen` (induced by `im_gens`). By default, it is an element of the group algebra with integer coefficients. If `im_gens` are provided, the result lives in the algebra where `im_gens` live.

**EXAMPLES:**

```
sage: G = FreeGroup(5)
sage: G.inject_variables()
Defining x0, x1, x2, x3, x4
sage: (-x0*x1*x0*x2*x0^x0).fox_derivative(x0)
-x0^0 - 1 + x0^0 - 1*x1 - x0^0 - 1*x1*x0*x2*x0^0^0 - 1
sage: (-x0*x1*x0*x2*x0^x0).fox_derivative(x1)
x0^0 - 1
sage: (-x0*x1*x0*x2*x0^x0).fox_derivative(x2)
x0^0 - 1*x1*x0
sage: (-x0*x1*x0*x2*x0^x0).fox_derivative(x3)
0
```

If `im_gens` is given, the images of the generators are mapped to them:

```
sage: F=FreeGroup(3)
sage: a=F([2,1,3,-1,2])
sage: a.fox_derivative(F([1]))
x1 - x1*x0*x2*x0^0 - 1
sage: R.<t>=LaurentPolynomialRing(ZZ)
sage: a.fox_derivative(F([1]),[t,t,t])
t - t^0^0^2
sage: S.<t1,t2,t3>=LaurentPolynomialRing(ZZ)
sage: a.fox_derivative(F([1]),[t1,t2,t3])
-t2*t3 + t^2
sage: R.<x,y,z>=QQ[]
sage: a.fox_derivative(F([1]),[x,y,z])
-y*z + y
sage: a.inverse().fox_derivative(F([1]),[x,y,z])
(z - 1)/(y*z)
```

The optional parameter `ring` determines the ring \(A\):

```
sage: u = a.fox_derivative(F([1]), [1,2,3], ring=QQ)
sage: u
-4
sage: parent(u)
Rational Field
sage: u = a.fox_derivative(F([1]), [1,2,3], ring=R)
sage: u
-4
sage: parent(u)
Multivariate Polynomial Ring in x, y, z over Rational Field
```

**syllables**()

Return the syllables of the word.
Consider a free group element $g = x_1^{n_1}x_2^{n_2}\cdots x_k^{n_k}$. The uniquely-determined subwords $x_i^{e_i}$ consisting only of powers of a single generator are called the syllables of $g$.

**OUTPUT:**

The tuple of syllables. Each syllable is given as a pair $(x_i, e_i)$ consisting of a generator and a non-zero integer.

**EXAMPLES:**

```
sage: G.<a,b> = FreeGroup()
sage: w = a^2 * b^-1 * a^3
sage: w.syllables()
((a, 2), (b, -1), (a, 3))
```

```python
class sage.groups.free_group.FreeGroup_class(generators, libgap_free_group=None):
    Bases: sage.structure.unique_representation.UniqueRepresentation,
           sage.groups.group.Group, sage.groups.libgap_wrapper.ParentLibGAP

    A class that wraps GAP's FreeGroup

    See FreeGroup() for details.

    Element

    alias of FreeGroupElement

    abelian_invariants()

    Return the Abelian invariants of self.

    The Abelian invariants are given by a list of integers $i_1\ldots i_j$, such that the abelianization of the group is isomorphic to

    \[ \mathbb{Z}/(i_1) \times \cdots \times \mathbb{Z}/(i_j) \]

    **EXAMPLES:**

    ```
sage: F.<a,b> = FreeGroup()
sage: F.abelian_invariants()
(0, 0)
```

quotient (relations)

Return the quotient of self by the normal subgroup generated by the given elements.

This quotient is a finitely presented groups with the same generators as self, and relations given by the elements of relations.

**INPUT:**

- relations – A list/tuple/iterable with the elements of the free group.

**OUTPUT:**

A finitely presented group, with generators corresponding to the generators of the free group, and relations corresponding to the elements in relations.

**EXAMPLES:**

```
sage: F.<a,b> = FreeGroup()
sage: F.quotient([a*b^2*a, b^3])
Finitely presented group < a, b | a*b^2*a, b^3 >
```

Division is shorthand for quotient()
Finitely presented group $\langle a, b \mid a*b^2*a, b^3 \rangle$

Relations are converted to the free group, even if they are not elements of it (if possible)

```python
sage: F1.<a,b,c,d>=FreeGroup()
sage: F2.<a,b>=FreeGroup()
sage: r=a*b/a
sage: r.parent()
Free Group on generators {a, b}
sage: F1/[r]
Finitely presented group $\langle a, b, c, d \mid a*b*a^-1 \rangle$
```

**rank()**

Return the number of generators of self.

Alias for `ngens()`.

**OUTPUT:**

Integer.

**EXAMPLES:**

```python
sage: G = FreeGroup('a, b'); G
Free Group on generators {a, b}
sage: G.rank()
2
sage: H = FreeGroup(3, 'x')
sage: H
Free Group on generators {x0, x1, x2}
sage: H.rank()
3
```

`sage.groups.free_group.is_FreeGroup(x)`

Test whether `x` is a `FreeGroup_class`.

**INPUT:**

- `x` – anything.

**OUTPUT:**

Boolean.

**EXAMPLES:**

```python
sage: from sage.groups.free_group import is_FreeGroup
sage: is_FreeGroup('a string')
False
sage: is_FreeGroup(FreeGroup(0))
True
sage: is_FreeGroup(FreeGroup(index_set=ZZ))
True
```

`sage.groups.free_group.wrap_FreeGroup(libgap_free_group)`

Wrap a LibGAP free group.

This function changes the comparison method of `libgap_free_group` to comparison by Python `id`. If you want to put the LibGAP free group into a container (set, dict) then you should understand the implications.
of \_set\_compare\_by\_id(). To be safe, it is recommended that you just work with the resulting Sage \texttt{FreeGroup\_class}.

**INPUT:**

- \texttt{libgap\_free\_group} – a LibGAP free group.

**OUTPUT:**

A Sage \texttt{FreeGroup\_class}.

**EXAMPLES:**

First construct a LibGAP free group:

```python
sage: F = libgap.FreeGroup(['a', 'b'])
sage: type(F)
<type 'sage.libs.gap.element.GapElement'>
```

Now wrap it:

```python
sage: from sage.groups.free_group import wrap\_FreeGroup
sage: wrap\_FreeGroup(F)
Free Group on generators \{a, b\}
```
Finitely presented groups are constructed as quotients of *free_group*:

```python
sage: F.<a,b,c> = FreeGroup()
sage: G = F / [a^2, b^2, c^2, a*b*c*a*b*c]
sage: G
Finitely presented group < a, b, c | a^2, b^2, c^2, (a*b*c)^2 >
```

One can create their elements by multiplying the generators or by specifying a Tietze list (see *Tietze()*) as in the case of free groups:

```python
sage: G.gen(0) * G.gen(1)
a*b
sage: G([1,2,-1])
a*b*a^-1
sage: a.parent()
Free Group on generators {a, b, c}
sage: G.inject_variables()
Defining a, b, c
sage: a.parent()
Finitely presented group < a, b, c | a^2, b^2, c^2, (a*b*c)^2 >
```

Notice that, even if they are represented in the same way, the elements of a finitely presented group and the elements of the corresponding free group are not the same thing. However, they can be converted from one parent to the other:

```python
sage: F.<a,b,c> = FreeGroup()
sage: G = F / [a^2,b^2,c^2,a*b*c*a*b*c]
sage: F([1])
a
sage: G([1])
a
sage: F([1]) == G([1])
False
sage: G(a*b/c)
a*b*c^-1
sage: F(G(a*b/c))
a*b*c^-1
```

Finitely presented groups are implemented via GAP. You can use the *gap()* method to access the underlying LibGAP object:

```python
sage: G = FreeGroup(2)
sage: G.inject_variables()
```

(continues on next page)
Defining $x_0$, $x_1$

```
sage: H = G / (x0^2, (x0*x1)^2, x1^2)
sage: H.gap()
<fp group on the generators [ x0, x1 ]>
```

This can be useful, for example, to use GAP functions that are not yet wrapped in Sage:

```
sage: H.gap().LowerCentralSeries()
[ Group(<fp, no generators known>), Group(<fp, no generators known>) ]
```

The same holds for the group elements:

```
sage: G = FreeGroup(2)
sage: H = G / (G([1, 1]), G([2, 2, 2]), G([1, 2, -1, -2])); H
Finitely presented group < x0, x1 | x0^2, x1^3, x0*x1*x0^-1*x1^-1 >
sage: a = H([1])
sage: a.gap()
0
sage: a.gap().Order()
2
sage: type(_)
# note that the above output is not a Sage integer
<type 'sage.libs.gap.element.GapElement_Integer'>
```

You can use call syntax to replace the generators with a set of arbitrary ring elements. For example, take the free abelian group obtained by modding out the commutator subgroup of the free group:

```
sage: G = FreeGroup(2)
sage: G_ab = G / [G([1, 2, -1, -2])]; G_ab
Finitely presented group < x0, x1 | x0^2, x1^3, x0*x1*x0^-1*x1^-1 >
sage: a, b = G_ab.gens()
sage: g = a * b
sage: M1 = matrix([[1,0],[0,2]])
sage: M2 = matrix([[0,1],[1,0]])
sage: g(M1, M2)
15
[1 0]
[0 4]
sage: M1*M2 == M2*M1
False
sage: g(M1, M2)
Traceback (most recent call last):
... ValueError: the values do not satisfy all relations of the group
```

**Warning:** Some methods are not guaranteed to finish since the word problem for finitely presented groups is, in general, undecidable. In those cases the process may run until the available memory is exhausted.

**REFERENCES:**

- Wikipedia article Presentation_of_a_group
- Wikipedia article Word_problem_for_groups
class sage.groups.finitely_presented.FinitelyPresentedGroup (free_group, relations)

Bases: sage.groups.libgap_mixin.GroupMixinLibGAP, sage.structure.unique_representation.UniqueRepresentation, sage.groups.group.Group, sage.groups.libgap_wrapper.ParentLibGAP

A class that wraps GAP’s Finitely Presented Groups.

**Warning:** You should use `quotient()` to construct finitely presented groups as quotients of free groups.

**EXAMPLES:**

```python
sage: G.<a,b> = FreeGroup()
sage: H = G / [a, b^3]
sage: H
Finitely presented group < a, b | a, b^3 >
sage: H.gens()
(a, b)

sage: F.<a,b> = FreeGroup('a, b')
sage: J = F / (F([1]), F([2, 2, 2]))
sage: J is H
True
sage: G = FreeGroup(2)
sage: H = G / (G([1, 1]), G([2, 2, 2]))
sage: H.gens()
(x0, x1)
sage: H.gen(0)
x0
sage: H.ngens()
2
sage: H.gap()
<fp group on the generators [ x0, x1 ]>
sage: type(_)
<type 'sage.libs.gap.element.GapElement'>
```

**Element**

alias of `FinitelyPresentedGroupElement`

**abelian_invariants()**

Return the abelian invariants of self.

The abelian invariants are given by a list of integers \((i_1, \ldots, i_j)\), such that the abelianization of the group is isomorphic to \(\mathbb{Z}/(i_1) \times \cdots \times \mathbb{Z}/(i_j)\).

**EXAMPLES:**

```python
sage: G = FreeGroup(4, 'g')
sage: G.inject_variables()
Defining g0, g1, g2, g3
sage: H = G.quotient([g1^2, g2*g1*g2^(-1)*g1^(-1), g1*g3^(-2), g0^4])
sage: H.abelian_invariants()
(0, 4, 4)
```
ALGORITHM:
Uses GAP.

**alexander_matrix**(im_gens=None)
Return the Alexander matrix of the group.

This matrix is given by the fox derivatives of the relations with respect to the generators.

* im_gens — (optional) the images of the generators

OUTPUT:
A matrix with coefficients in the group algebra. If im_gens is given, the coefficients will live in the same algebra as the given values. The result depends on the (fixed) choice of presentation.

EXAMPLES:

```
sage: G.<a,b,c> = FreeGroup()
sage: H = G.quotient([a*b/a/b, a*c/a/c, c*b/c/b])
sage: H.alexander_matrix()
[ 1 - a*b*a^-1 0 0 0]
[ 1 - a*c*a^-1 0 a - a*c*a^-1*a*c^-1]
[ 0 a - c*b*c^-1*b^-1 1 - c*b*c^-1]
```

If we introduce the images of the generators, we obtain the result in the corresponding algebra.

```
sage: G.<a,b,c,d,e> = FreeGroup()
sage: H = G.quotient([a*b/a/b, a*c/a/c, a*d/a/d, b*c*d/(c*d*b), b*c*d/(d*b*c)])
sage: H.alexander_matrix()
[ 1 - a*b*a^-1 a - a*b*a^-1*b^-1 0 0 0]
[ 1 - a*c*a^-1 0 a - a*c*a^-1*c^-1]
[ 0 a - c*b*c^-1*b^-1 1 - c*b*c^-1]
```

```
sage: R.<t1,t2,t3,t4> = LaurentPolynomialRing(ZZ)
sage: H.alexander_matrix([t1,t2,t3,t4])
[ -t2 + 1 t1 - 1 0 0 0]
[ -t3 + 1 0 t1 - 1 0 0]
[ -t4 + 1 0 0 t1 - 1 0]
[ 0 -t3*t4 + 1 t2 - 1 t2*t3 - t3 0]
[ 0 -t4 + 1 -t2*t4 + t2 t2*t3 - 1 0]
```

**as_permutation_group**(limit=4096000)
Return an isomorphic permutation group.

The generators of the resulting group correspond to the images by the isomorphism of the generators of the given group.

INPUT:

* limit — integer (default: 4096000). The maximal number of cosets before the computation is aborted.

OUTPUT:
A Sage \texttt{PermutationGroup()}. If the number of cosets exceeds the given limit, a \texttt{ValueError} is returned.

**EXAMPLES:**

```python
sage: G.<a,b> = FreeGroup()
sage: H = G / (a^2, b^3, a*b*a^-b)
sage: H.as_permutation_group()
Permutation Group with generators [(1,2)(3,5)(4,6), (1,3,4)(2,5,6)]
```

```python
sage: G.<a,b> = FreeGroup()
sage: H = G / [a^3*b]
sage: H.as_permutation_group(limit=1000)
Traceback (most recent call last):
...  
ValueError: Coset enumeration exceeded limit, is the group finite?
```

**ALGORITHM:**

Uses GAP’s coset enumeration on the trivial subgroup.

**Warning:** This is in general not a decidable problem (in fact, it is not even possible to check if the group is finite or not). If the group is infinite, or too big, you should be prepared for a long computation that consumes all the memory without finishing if you do not set a sensible limit.

**cardinality (limit=4096000)**

Compute the cardinality of \texttt{self}.

**INPUT:**

- \texttt{limit} – integer (default: 4096000). The maximal number of cosets before the computation is aborted.

**OUTPUT:**

Integer or \texttt{Infinity}. The number of elements in the group.

**EXAMPLES:**

```python
sage: G.<a,b> = FreeGroup('a, b')
sage: H = G / (a^2, b^3, a*b*a^-b)
sage: H.cardinality()
6
```

```python
sage: F.<a,b,c> = FreeGroup()
sage: J = F / ([F([1]), F([2, 2])])
sage: J.cardinality()
+Infinity
```

**ALGORITHM:**

Uses GAP.

**Warning:** This is in general not a decidable problem, so it is not guaranteed to give an answer. If the group is infinite, or too big, you should be prepared for a long computation that consumes all the memory without finishing if you do not set a sensible limit.
direct_product \((H, \text{reduced}=False, \text{new_names}=True)\)

Return the direct product of self with finitely presented group \(H\).

Calls GAP function DirectProduct, which returns the direct product of a list of groups of any representation.

From [Joh1990] (pg 45, proposition 4): If \(G, H\) are groups presented by \(\langle X \mid R\rangle\) and \(\langle Y \mid S\rangle\) respectively, then their direct product has the presentation \(\langle X,Y\mid R,S, [X,Y]\rangle\) where \([X,Y]\) denotes the set of commutators \(\{x^{-1}y^{-1}xy \mid x \in X, y \in Y\}\).

INPUT:

- \(H\) – a finitely presented group
- \(\text{reduced}\) – (default: False) boolean; if True, then attempt to reduce the presentation of the product group
- \(\text{new_names}\) – (default: True) boolean; If True, then lexicographical variable names are assigned to the generators of the group to be returned. If False, the group to be returned keeps the generator names of the two groups forming the direct product. Note that one cannot ask to reduce the output and ask to keep the old variable names, as they may change meaning in the output group if its presentation is reduced.

OUTPUT:

The direct product of self with \(H\) as a finitely presented group.

EXAMPLES:

The direct product of self with \(H\) as a finitely presented group.

```
sage: G = FreeGroup()
sage: C12 = ( G / [G([1,1,1,1])] ).direct_product( G / [G([1,1,1])]); C12
Finitely presented group < a, b | a^4, b^3, a^-1*b^-1*a*b >
sage: C12.order(), C12.as_permutation_group().is_cyclic()
(12, True)
sage: klein = ( G / [G([1,1])] ).direct_product( G / [G([1,1])]); klein
Finitely presented group < a, b | a^2, b^2, a^-1*b^-1*a*b >
sage: klein.order(), klein.as_permutation_group().is_cyclic()
(4, False)
```

We can keep the variable names from self and \(H\) to examine how new relations are formed:

```
sage: F = FreeGroup("a"); G = FreeGroup("g")
sage: X = G / [G.0^12]; A = F / [F.0^6]
sage: X.direct_product(A, new_names=False)
Finitely presented group < g, a | g^12, a^6, g^-1*a^-1*g*a >
sage: A.direct_product(X, new_names=False)
Finitely presented group < a, g | a^6, g^12, a^-1*g^-1*a*g >
```

Or we can attempt to reduce the output group presentation:

```
sage: F = FreeGroup("a"); G = FreeGroup("g")
sage: X = G / [G.0]; A = F / [F.0]
sage: X.direct_product(A, new_names=True)
Finitely presented group < a, b | a, b, a^-1*b^-1*a*b >
sage: X.direct_product(A, reduced=True, new_names=True)
Finitely presented group < | >
```

But we cannot do both:
AUTHORS:

- Davis Shurbert (2013-07-20): initial version

epimorphisms \((H)\)

Return the epimorphisms from \(self\) to \(H\), up to automorphism of \(H\).

INPUT:

- \(H\) – Another group

EXAMPLES:

```
sage: F = FreeGroup(3)
sage: G = F / (F([1, 2, 3, 1, 2, 3]), F([1, 1, 1]))
sage: H = AlternatingGroup(3)
sage: G.epimorphisms(H)

[Generic morphism:
  From: Finitely presented group < x0, x1, x2 | (x0*x1*x2)^2, x0^3 >
  To: Alternating group of order 3!/2 as a permutation group
  Defn: x0 |--> ()
  x1 |--> (1,3,2)
  x2 |--> (1,2,3),
Generic morphism:
  From: Finitely presented group < x0, x1, x2 | (x0*x1*x2)^2, x0^3 >
  To: Alternating group of order 3!/2 as a permutation group
  Defn: x0 |--> (1,3,2)
  x1 |--> (1,3,2)
  x2 |--> (1,2,3),
Generic morphism:
  From: Finitely presented group < x0, x1, x2 | (x0*x1*x2)^2, x0^3 >
  To: Alternating group of order 3!/2 as a permutation group
  Defn: x0 |--> (1,3,2)
  x1 |--> (1,2,3)
  x2 |--> (1,2,3),
Generic morphism:
  From: Finitely presented group < x0, x1, x2 | (x0*x1*x2)^2, x0^3 >
  To: Alternating group of order 3!/2 as a permutation group
  Defn: x0 |--> (1,2,3)
  x1 |--> (1,2,3)
  x2 |--> (1,2,3),
```

ALGORITHM:

Uses libgap’s GQuotients function.

free_group ()

Return the free group (without relations).

OUTPUT:

A FreeGroup().

EXAMPLES:

```
sage: G.<a,b,c> = FreeGroup()
sage: H = G / (a^2, b^3, a*b*a*b)
```
sage: H.free_group()
Free Group on generators {a, b, c}
sage: H.free_group() is G
True

**order** (*limit=4096000*)  
Compute the cardinality of self.

**INPUT:**

- limit – integer (default: 4096000). The maximal number of cosets before the computation is aborted.

**OUTPUT:**

Integer or *Infinity*. The number of elements in the group.

**EXAMPLES:**

```python
sage: G.<a,b> = FreeGroup('a, b')
sage: H = G / (a^2, b^3, a*b~a*b~)
sage: H.cardinality()
6
```

**ALGORITHM:**

Uses GAP.

**Warning:** This is in general not a decidable problem, so it is not guaranteed to give an answer. If the group is infinite, or too big, you should be prepared for a long computation that consumes all the memory without finishing if you do not set a sensible limit.

**relations()**  
Return the relations of the group.

**OUTPUT:**

The relations as a tuple of elements of *free_group()*.

**EXAMPLES:**

```python
sage: F.<a,b,c> = FreeGroup()
sage: J = F / (F([1]), F([2, 2, 2]))
sage: J.cardinality()
+Infinity
```

**rewriting_system()**  
Return the rewriting system corresponding to the finitely presented group. This rewriting system can be used to reduce words with respect to the relations.
If the rewriting system is transformed into a confluent one, the reduction process will give as a result the (unique) reduced form of an element.

EXAMPLES:

```python
sage: F.<a,b> = FreeGroup()
sage: G = F / [a^2,b^3,(a*b/a)^3,b*a*b*a]
sage: k = G.rewriting_system()
sage: k
Rewriting system of Finitely presented group < a, b | a^2, b^3, a*b^3*a^-1, (b*a)^2 >
with rules:
  a^2 ---> 1
  b^3 ---> 1
  (b*a)^2 ---> 1
  a*b^3*a^-1 ---> 1

sage: G([1,1,2,2,2])
a^2*b^3
sage: k.reduce(G([1,1,2,2,2]))
1
sage: k.reduce(G([2,2,1]))
b^2*a
sage: k.make_confluent()
sage: k.reduce(G([2,2,1]))
a*b
```

semidirect_product \((H, \text{hom}, \text{check}=\text{True}, \text{reduced}=\text{False})\)

The semidirect product of self with \(H\) via \(\text{hom} \).

If there exists a homomorphism \(\phi\) from a group \(G\) to the automorphism group of a group \(H\), then we can define the semidirect product of \(G\) with \(H\) via \(\phi\) as the Cartesian product of \(G\) and \(H\) with the operation

\[
(g_1,h_1)(g_2,h_2) = (g_1g_2, \phi(h_1)h_2).
\]

INPUT:

- \(H\) – Finitely presented group which is implicitly acted on by \text{self} and can be naturally embedded as a normal subgroup of the semidirect product.
- \(\text{hom}\) – Homomorphism from \text{self} to the automorphism group of \(H\). Given as a pair, with generators of \text{self} in the first slot and the images of the corresponding generators in the second. These images must be automorphisms of \(H\), given again as a pair of generators and images.
- \(\text{check}\) – Boolean (default True). If False the defining homomorphism and automorphism images are not tested for validity. This test can be costly with large groups, so it can be bypassed if the user is confident that his morphisms are valid.
- \(\text{reduced}\) – Boolean (default False). If True then the method attempts to reduce the presentation of the output group.

OUTPUT:

The semidirect product of \text{self} with \(H\) via \text{hom} as a finitely presented group. See \texttt{PermutationGroup_generic.semidirect_product} for a more in depth explanation of a semidirect product.

AUTHORS:

- Davis Shurbert (8-1-2013)
EXAMPLES:

Group of order 12 as two isomorphic semidirect products:

```sage
d4 = groups.presentation.Dihedral(4)
c3 = groups.presentation.Cyclic(3)
alpha1 = ([c3.gen(0)], [c3.gen(0)])
alpha2 = ([c3.gen(0)], [c3([1,1])])
s1 = d4.semidirect_product(c3, ([d4.gen(1), d4.gen(0)], [alpha1, alpha2]))
c2 = groups.presentation.Cyclic(2)
c12 = groups.presentation.DiCyclic(3)
a = c12([1]); b = c12([-2])
alpha = (c12.gens(), [a, b])
s2 = c2.semidirect_product(c12, ([c2.0], [alpha]))
s1.is_isomorphic(s2)
# I Forcing finiteness test
True
```

Dihedral groups can be constructed as semidirect products of cyclic groups:

```sage
c2 = groups.presentation.Cyclic(2)
c8 = groups.presentation.Cyclic(8)
hom = ([c2.gens()], [([c8([1])]), [c8([-1])]])
cdihedral = c2.semidirect_product(c8, hom)
cdihedral.as_permutation_group().is_isomorphic(DihedralGroup(8))
True
```

You can attempt to reduce the presentation of the output group:

```sage
cdihedral = c2.semidirect_product(c8, hom, reduced=True)
cdihedral
Finitely presented group < a, b | a^2, (a*b)^2, b^8 >
cdihedral.as_permutation_group().is_isomorphic(DihedralGroup(8))
True
```

You can turn off the checks for the validity of the input morphisms. This check is expensive but behavior is unpredictable if inputs are invalid and are not caught by these tests:

```sage
c5 = groups.presentation.Cyclic(5)
c12 = groups.presentation.Cyclic(12)
hom = ([c5.gens()], [([c12.gens()], c12.gens())])
sp = c5.semidirect_product(c12, hom, check=False)
sp
Finitely presented group < a, b | a^5, b^12, a^-1*b*a*b^-1 >
sp.as_permutation_group().is_cyclic(), sp.order()
(True, 60)
```

`simplification_isomorphism()`

Return an isomorphism from `self` to a finitely presented group with a (hopefully) simpler presentation.

EXAMPLES:
sage: G.<a,b,c> = FreeGroup()
sage: H = G / [a*b*c, a*b^2, c*b/c^2]
sage: I = H.simplification_isomorphism()
sage: I
Generic morphism:
  From: Finitely presented group < a, b, c | a*b*c, a*b^2, c*b/c^2 >
  To:  Finitely presented group < b | >
  Defn: a |--> b^-2
        b |--> b
        c |--> b
sage: I(a)
b^-2
sage: I(b)
b
sage: I(c)
b
ALGORITHM:
Uses GAP.
simplified()
Return an isomorphic group with a (hopefully) simpler presentation.

OUTPUT:
A new finitely presented group. Use simplification_isomorphism() if you want to know the isomorphism.

EXAMPLES:

sage: G.<x,y> = FreeGroup()
sage: H = G / [x ^5, y ^4, y*x*y^3*x ^3]
sage: H
Finitely presented group < x, y | x^5, y^4, y*x*y^3*x^3 >
sage: H.simplified()
Finitely presented group < x, y | y^4, y*x*y^-1*x^-2, x^5 >

A more complicate example:

sage: G.<e0, e1, e2, e3, e4, e5, e6, e7, e8, e9> = FreeGroup()
sage:rels = [e6, e5, e3, e9, e4*e7^-1*e6, e9*e7^-1*e0, ....:    e0*e1^-1*e2, e5*e1^-1*e8, e4*e3^-1*e8, e2]
sage: H = G.quotient(rels); H
Finitely presented group < e0, e1, e2, e3, e4, e5, e6, e7, e8, e9 | e6, e5, e3, e9, e4*e7^-1*e6, e9*e7^-1*e0, e0*e1^-1*e2, e5*e1^-1*e8, e4*e3^-1*e8, e2 >
sage: H.simplified()
Finitely presented group < e0 | e0^2 >

structure_description (G, latex=False)
Return a string that tries to describe the structure of G.

This methods wraps GAP’s StructureDescription method.

For full details, including the form of the returned string and the algorithm to build it, see GAP’s documentation.

INPUT:
- latex – a boolean (default: False). If True return a LaTeX formatted string.
OUTPUT:

• string

**Warning:** From GAP’s documentation: The string returned by `StructureDescription` is **not** an isomorphism invariant: non-isomorphic groups can have the same string value, and two isomorphic groups in different representations can produce different strings.

**EXAMPLES:**

```python
sage: G = CyclicPermutationGroup(6)
sage: G.structure_description()
'C6'
sage: G.structure_description(latex=True)
'C_{6}'
sage: G2 = G.direct_product(G, maps=False)
sage: LatexExpr(G2.structure_description(latex=True))
C_{6} \times C_{6}
```

This method is mainly intended for small groups or groups with few normal subgroups. Even then there are some surprises:

```python
sage: D3 = DihedralGroup(3)
sage: D3.structure_description()
'S3'
```

We use the Sage notation for the degree of dihedral groups:

```python
sage: D4 = DihedralGroup(4)
sage: D4.structure_description()
'D4'
```

Works for finitely presented groups (trac ticket #17573):

```python
sage: F.<x, y> = FreeGroup()
sage: G=F / [x^2*y^-1, x^3*y^2, x*y*x^-1*y^-1]
sage: G.structure_description()
'C7'
```

And matrix groups (trac ticket #17573):

```python
sage: groups.matrix.GL(4,2).structure_description()
'A8'
```

**class** `sage.groups.finitely_presented.FinitelyPresentedGroupElement`

**Bases:** `sage.groups.free_group.FreeGroupElement`<br>

A wrapper of GAP’s Finitely Presented Group elements.

The elements are created by passing the Tietze list that determines them.

**EXAMPLES:**

```python
sage: G = FreeGroup('a, b')
sage: H = G / [G([1]), G([2, 2, 2])]
sage: H([1, 2, 1, -1])
```

(continues on next page)
a*b
sage: H([1, 2, 1, -2])
a*b*a*b^-1
sage: x = H([1, 2, -1, -2])
sage: x
a*b*a^-1*b^-1
sage: y = H([2, 2, 2, 1, -2, -2, -2])
sage: y
b^3*a*b^-3
sage: x*y
a*b*a^-1*b^2*a*b^-3
sage: x^(-1)
b*a*b^-1*a^-1

Tietze()

Return the Tietze list of the element.

The Tietze list of a word is a list of integers that represent the letters in the word. A positive integer \( i \) represents the letter corresponding to the \( i \)-th generator of the group. Negative integers represent the inverses of generators.

OUTPUT:

A tuple of integers.

EXAMPLES:

sage: G = FreeGroup('a, b')
sage: H = G / (G([1]), G([2, 2, 2]))
sage: H.inject_variables()
Defining a, b
sage: a.Tietze()
(1,)
sage: x = a^2*b^(-3)*a^(-2)
sage: x.Tietze()
(1, 1, -2, -2, -2, -1, -1)

class sage.groups.finitely_presented.GroupMorphismWithGensImages

Bases: sage.categories.morphism.SetMorphism

Class used for morphisms from finitely presented groups to other groups. It just adds the images of the generators at the end of the representation.

EXAMPLES:

sage: F = FreeGroup(3)
sage: G = F / [F([1, 2, 3, 1, 2, 3]), F([1, 1, 1])]
sage: H = AlternatingGroup(3)
sage: HS = G.Hom(H)
sage: from sage.groups.finitely_presented import GroupMorphismWithGensImages
sage: GroupMorphismWithGensImages(HS, lambda a: H.one())
Generic morphism:
From: Finitely presented group < x0, x1, x2 | (x0*x1*x2)^2, x0^3 >
To: Alternating group of order 3!/2 as a permutation group
Defn: x0 |--> ()
x1 |--> ()
x2 |--> ()
class sage.groups.finitely_presented.RewritingSystem(G)
    Bases: object

A class that wraps GAP’s rewriting systems.

A rewriting system is a set of rules that allow to transform one word in the group to an equivalent one.

If the rewriting system is confluent, then the transformed word is a unique reduced form of the element of the group.

**Warning:** Note that the process of making a rewriting system confluent might not end.

INPUT:

- G – a group

REFERENCES:

- Wikipedia article Knuth-Bendix_completion_algorithm

EXAMPLES:

```
sage: F.<a,b> = FreeGroup()
sage: G = F / [a*b*a/b]
sage: k = G.rewriting_system()
sage: k
Rewriting system of Finitely presented group < a, b | a*b*a^-1*b^-1 >
with rules:
    a*b*a^-1*b^-1 ---> 1

sage: k.reduce(a*b*a*b)
(a*b)^2
sage: k.make_confluent()
sage: k
Rewriting system of Finitely presented group < a, b | a*b*a^-1*b^-1 >
with rules:
    b^-1*a^-1 ---> a^-1 *b^-1
    b^-1*a ---> a *b^-1
    b*a^-1 ---> a^-1 *b
    b*a ---> a *b

sage: k.reduce(a*b*a*b)
a^2*b^2
```

**Todo:**

- Include support for different orderings (currently only shortlex is used).
- Include the GAP package kbmag for more functionalities, including automatic structures and faster compiled functions.

**AUTHORS:**

- Miguel Angel Marco Buzunariz (2013-12-16)

**finitely_presented_group**()

The finitely presented group where the rewriting system is defined.

**EXAMPLES:**
sage: F = FreeGroup(3)
sage: G = F / [ [1,2,3], [-1,-2,-3], [1,1], [2,2] ]
sage: k = G.rewriting_system()
sage: k.make_confluent()
sage: k
Rewriting system of Finitely presented group < x0, x1, x2 | x0*x1*x2, x0^-1*x1^-1*x2^-1, x0^2, x1^2 >
with rules:
  x0^-1 ---> x0
  x1^-1 ---> x1
  x2^-1 ---> x2
  x0^2 ---> 1
  x0*x1 ---> x2
  x0*x2 ---> x1
  x1*x0 ---> x2
  x1^2 ---> 1
  x1*x2 ---> x0
  x2*x0 ---> x1
  x2*x1 ---> x0
  x2^2 ---> 1
sage: k.finitely_presented_group()
Finitely presented group < x0, x1, x2 | x0*x1*x2, x0^-1*x1^-1*x2^-1, x0^2, x1^-2 >

free_group()
The free group after which the rewriting system is defined

EXAMPLES:

sage: F = FreeGroup(3)
sage: G = F / [ [1,2,3], [-1,-2,-3] ]
sage: k = G.rewriting_system()
sage: k.free_group()
Free Group on generators {x0, x1, x2}

gap()
The gap representation of the rewriting system.

EXAMPLES:

sage: F.<a,b>=FreeGroup()
sage: G=F/[a*a,b*b]
sage: k=G.rewriting_system()
sage: k.gap()
Knuth Bendix Rewriting System for Monoid( [ a, A, b, B ] ) with rules
[ [ a^2, <identity ...> ], [ a*A, <identity ...> ],
  [ A*a, <identity ...> ], [ b^2, <identity ...> ],
  [ b*B, <identity ...> ], [ B*b, <identity ...> ] ]

is_confluent()
Return True if the system is confluent and False otherwise.

EXAMPLES:

sage: F = FreeGroup(3)
sage: G = F / [F([1,2,1,2,1,3,-1]),F([2,2,2,1,1,2]),F([1,2,3])]  
sage: k = G.rewriting_system()
sage: k.is_confluent()

False

sage: k

Rewriting system of Finitely presented group < x0, x1, x2 | (x0*x1)^2*x0*x2*x0^-1, x1^3*x0^2*x1, x0*x1*x2 >
with rules:
  x0*x1*x2 ---> 1
  x1^3*x0^2*x1 ---> 1
  (x0*x1)^2*x0*x2*x0^-1 ---> 1

sage: k.make_confluent()

sage: k.is_confluent()

True

sage: k

Rewriting system of Finitely presented group < x0, x1, x2 | (x0*x1)^2*x0*x2*x0^-1, x1^3*x0^2*x1, x0*x1*x2 >
with rules:
  x0^-1 ---> x0
  x1^-1 ---> x1
  x0^2 ---> 1
  x0*x1 ---> x2^-1
  x0*x2^-1 ---> x1
  x1*x0 ---> x2
  x1^2 ---> 1
  x1*x2^-1 ---> x0*x2
  x1*x2 ---> x0
  x2^-1*x0 ---> x0
  x2^-1*x1 ---> x0
  x2^-2 ---> x2
  x2*x0 ---> x1
  x2*x1 ---> x0
  x2^-2 ---> x2^-1

make_confluent()

Applies Knuth-Bendix algorithm to try to transform the rewriting system into a confluent one.

Note that this method does not return any object, just changes the rewriting system internally.

Warning: This algorithm is not granted to finish. Although it may be useful in some occasions to run it, interrupt it manually after some time and use then the transformed rewriting system. Even if it is not confluent, it could be used to reduce some words.

ALGORITHM:

Uses GAP’s MakeConfluent.

EXAMPLES:

sage: F.<a,b> = FreeGroup()
sage: G = F / [a^2,b^3,(a*b/a)^3,b*a*b*a]
sage: k = G.rewriting_system()
sage: k

Rewriting system of Finitely presented group < a, b | a^2, b^3, a*b^3*a^-1, (b*a)^2 >
with rules:
  a^2 ---> 1
  b^3 ---> 1
(continued from previous page)

\[(b*a)^2 \quad \rightarrow \quad 1\]
\[a*b^3*a^-1 \quad \rightarrow \quad 1\]

```
sage: k.make_confluent()
sage: k
Rewriting system of Finitely presented group < a, b | a^2, b^3, a*b^3*a^-1, \omega \rightarrow (b*a)^2 >
with rules:
  a^-1 \quad \rightarrow \quad a
  a^2 \quad \rightarrow \quad 1
  b^-1*a \quad \rightarrow \quad a*b
  b^-2 \quad \rightarrow \quad b
  b*a \quad \rightarrow \quad a*b^-1
  b^2 \quad \rightarrow \quad b^-1
```

**reduce** *(element)*
Applies the rules in the rewriting system to the element, to obtain a reduced form.

If the rewriting system is confluent, this reduced form is unique for all words representing the same element.

**EXAMPLES:**
```
sage: F.<a,b> = FreeGroup()
sage: G = F/\[a^2, b^3, (a*b/a)^3, b*a*b*a\]
sage: k = G.rewriting_system()
sage: k.reduce(b^4)
b
sage: k.reduce(a*b*a)
a*b*a
```

**rules()**
Return the rules that form the rewriting system.

**OUTPUT:**
A dictionary containing the rules of the rewriting system. Each key is a word in the free group, and its corresponding value is the word to which it is reduced.

**EXAMPLES:**
```
sage: F.<a,b> = FreeGroup()
sage: G = F/\[a*a*a,b*b*a*a\]
sage: k = G.rewriting_system()
sage: k
Rewriting system of Finitely presented group < a, b | a^3, b^2*a^2 >
with rules:
  a^3 \quad \rightarrow \quad 1
  b^2*a^2 \quad \rightarrow \quad 1
```
```
sage: k.rules()
\{
a^3: 1, b^2*a^2: 1
\}
sage: k.make_confluent()
sage: sorted(k.rules().items())
\[
\{(a^-2, a), (a^-1*b^-1, a*b), (a^-1*b, b^-1), (a^2, a^-1),
(a*b^-1, b), (b^-1*a^2, a*b), (b^-1*a, b), (b^-2, a^-1),
(b*a^-1, b^-1), (b*a, a*b), (b^2, a)
\}
```

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Wrap a GAP finitely presented group.

This function changes the comparison method of `libgap_free_group` to comparison by Python id. If you want to put the LibGAP free group into a container (set, dict) then you should understand the implications of `_set_compare_by_id()`. To be safe, it is recommended that you just work with the resulting Sage `FinitelyPresentedGroup`.

**INPUT:**

- `libgap_fpgroup` – a LibGAP finitely presented group

**OUTPUT:**

A Sage `FinitelyPresentedGroup`.

**EXAMPLES:**

First construct a LibGAP finitely presented group:

```python
sage: F = libgap.FreeGroup(['a', 'b'])
sage: a_cubed = F.GeneratorsOfGroup()[0] ^ 3
sage: P = F / libgap([a_cubed]); P
<fp group of size infinity on the generators [ a, b ]>
sage: type(P)
<type 'sage.libs.gap.element.GapElement'>
```

Now wrap it:

```python
sage: from sage.groups.finitely_presented import wrap_FpGroup
sage: wrap_FpGroup(P)
Finitely presented group < a, b | a^3 >
```
CHAPTER
TWELVE

NAMED FINITELY PRESENTED GROUPS

Construct groups of small order and “named” groups as quotients of free groups. These groups are available through tab completion by typing `groups.presentation.<tab>` or by importing the required methods. Tab completion is made available through Sage’s group catalog. Some examples are engineered from entries in [TW1980].

Groups available as finite presentations:

- Alternating group, \( A_n \) of order \( n!/2 \) - `groups.presentation.Alternating`
- Cyclic group, \( C_n \) of order \( n \) - `groups.presentation.Cyclic`
- Dicyclic group, nonabelian groups of order \( 4n \) with a unique element of order 2 - `groups.presentation.DiCyclic`
- Dihedral group, \( D_n \) of order \( 2n \) - `groups.presentation.Dihedral`
- Finitely generated abelian group, \( \mathbb{Z}_{n_1} \times \mathbb{Z}_{n_2} \times \cdots \times \mathbb{Z}_{n_k} \) - `groups.presentation.FGAbelian`
- Finitely generated Heisenberg group - `groups.presentation.Heisenberg`
- Klein four group, \( C_2 \times C_2 \) - `groups.presentation.KleinFour`
- Quaternion group of order 8 - `groups.presentation.Quaternion`
- Symmetric group, \( S_n \) of order \( n! \) - `groups.presentation.Symmetric`

AUTHORS:

- Davis Shurbert (2013-06-21): initial version

EXAMPLES:

```sage
sage: groups.presentation.Cyclic(4)
Finitely presented group < a | a^4 >
```

You can also import the desired functions:

```sage
sage: from sage.groups.finitely_presented_named import CyclicPresentation
```

```sage
sage: CyclicPresentation(4)
Finitely presented group < a | a^4 >
```

```sage
sage.groups.finitely_presented_named.AlternatingPresentation(n)
Build the Alternating group of order \( n!/2 \) as a finitely presented group.

INPUT:

- \( n \) – The size of the underlying set of arbitrary symbols being acted on by the Alternating group of order \( n!/2 \).```
Alternating group as a finite presentation, implementation uses GAP to find an isomorphism from a permutation representation to a finitely presented group representation. Due to this fact, the exact output presentation may not be the same for every method call on a constant \( n \).

**EXAMPLES:**

```python
sage: A6 = groups.presentation.Alternating(6)
sage: A6.as_permutation_group().is_isomorphic(AlternatingGroup(6)), A6.order()
(True, 360)
```

```
sage.groups.finitely_presented_named.BinaryDihedralPresentation(n)
Build a binary dihedral group of order 4\( n \) as a finitely presented group.

The binary dihedral group \( BD_n \) has the following presentation (note that there is a typo in [Sun]):

\[
BD_n = \langle x, y, z | x^2 = y^2 = z^n = xyz \rangle.
\]

**INPUT:**

- \( n \) – the value \( n \)

**OUTPUT:**

The binary dihedral group of order 4\( n \) as finite presentation.

**EXAMPLES:**

```python
sage: groups.presentation.BinaryDihedral(9)
Finitely presented group < x, y, z | x^-2*y^2, x^-2*z^9, x^-1*y*z >
```

```
sage.groups.finitely_presented_named.CyclicPresentation(n)
Build cyclic group of order \( n \) as a finitely presented group.

**INPUT:**

- \( n \) – The order of the cyclic presentation to be returned.

**OUTPUT:**

The cyclic group of order \( n \) as finite presentation.

**EXAMPLES:**

```python
sage: groups.presentation.Cyclic(10)
Finitely presented group < a | a^10 >
sage: n = 8; C = groups.presentation.Cyclic(n)
sage: C.as_permutation_group().is_isomorphic(CyclicPermutationGroup(n))
True
```

```
sage.groups.finitely_presented_named.DiCyclicPresentation(n)
Build the dicyclic group of order 4\( n \), for \( n \geq 2 \), as a finitely presented group.

**INPUT:**

- \( n \) – positive integer, 2 or greater, determining the order of the group (4\( n \)).

**OUTPUT:**

The dicyclic group of order 4\( n \) is defined by the presentation

\[
\langle a, x | a^{2n} = 1, x^2 = a^n, x^{-1}ax = a^{-1} \rangle
\]
Note: This group is also available as a permutation group via \texttt{groups.permutation.DiCyclic}.

EXAMPLES:

```python
sage: D = groups.presentation.DiCyclic(9); D
Finitely presented group < a, b | a^18, b^2*a^-9, b^-1*a*b*a >
sage: D.as_permutation_group().is_isomorphic(groups.permutation.DiCyclic(9))
True
```

`sage.groups.finitely_presented_named.DihedralPresentation(n)`
Build the Dihedral group of order $2n$ as a finitely presented group.

INPUT:

- $n$ – The size of the set that $D_n$ is acting on.

OUTPUT:

Dihedral group of order $2n$.

EXAMPLES:

```python
sage: D = groups.presentation.Dihedral(7); D
Finitely presented group < a, b | a^7, b^2, (a*b)^2 >
sage: D.as_permutation_group().is_isomorphic(DihedralGroup(7))
True
```

`sage.groups.finitely_presented_named.FinitelyGeneratedAbelianPresentation(int_list)`
Return canonical presentation of finitely generated abelian group.

INPUT:

- \texttt{int_list} – List of integers defining the group to be returned, the defining list is reduced to the invariants of the input list before generating the corresponding group.

OUTPUT:

Finitely generated abelian group, $\mathbb{Z}_{n_1} \times \mathbb{Z}_{n_2} \times \cdots \times \mathbb{Z}_{n_k}$ as a finite presentation, where $n_i$ forms the invariants of the input list.

EXAMPLES:

```python
sage: groups.presentation.FGAbelian([2,2])
Finitely presented group < a, b | a^2, b^2, a^-1*b^-1*a*b >
sage: groups.presentation.FGAbelian([2,3])
Finitely presented group < a | a^6 >
sage: groups.presentation.FGAbelian([2,4])
Finitely presented group < a, b | a^2, b^4, a^-1*b^-1*a*b >
```

You can create free abelian groups:

```python
sage: groups.presentation.FGAbelian([0])
Finitely presented group < a | >
sage: groups.presentation.FGAbelian([0,0])
Finitely presented group < a, b | a^-1*b^-1*a*b >
sage: groups.presentation.FGAbelian([0,0,0])
Finitely presented group < a, b, c | a^-1*b^-1*a*b, a^-1*c^-1*a*c, b^-1*c^-1*l*b*c >
```

And various infinite abelian groups:
Outputs are reduced to minimal generators and relations:

\[
sage: \text{groups.presentation.FGAbelian([3,5,2,7,3])}\\
\text{Finitely presented group < a, b | a^3, b^2 \cdot 10, a^{-1}b^{-1}a \cdot b >}\\
sage: \text{groups.presentation.FGAbelian([3,210])}\\
\text{Finitely presented group < a, b | a^3, b^2 \cdot 10, a^{-1}b^{-1}a \cdot b >}
\]

The trivial group is an acceptable output:

\[
sage: \text{groups.presentation.FGAbelian([])}\\
\text{Finitely presented group < | >}\\
sage: \text{groups.presentation.FGAbelian([1])}\\
\text{Finitely presented group < | >}\\
sage: \text{groups.presentation.FGAbelian([1,1,1,1,1,1,1,1,1,1])}\\
\text{Finitely presented group < | >}
\]

Input list must consist of positive integers:

\[
sage: \text{groups.presentation.FGAbelian([2,6,3,9,-4])}\\
\text{Traceback (most recent call last):}\\
...\\
\text{ValueError: input list must contain nonnegative entries}\\
sage: \text{groups.presentation.FGAbelian([2,'a',4])}\\
\text{Traceback (most recent call last):}\\
...\\
\text{TypeError: unable to convert 'a' to an integer}
\]

Return a finite presentation of the Heisenberg group.

The Heisenberg group is the group of \((n+2) \times (n+2)\) matrices over a ring \(R\) with diagonal elements equal to 1, first row and last column possibly nonzero, and all the other entries equal to zero.

**INPUT:**

- \(n\) – the degree of the Heisenberg group
- \(p\) – (optional) a prime number, where we construct the Heisenberg group over the finite field \(\mathbb{Z}/p\mathbb{Z}\)

**OUTPUT:**

Finitely generated Heisenberg group over the finite field of order \(p\) or over the integers.

**See also:**

*HeisenbergGroup*

**EXAMPLES:**

\[
sage: H = \text{groups.presentation.Heisenberg(); H}\\
\text{Finitely presented group < x1, y1, z | x1*y1*x1^(-1)*y1^(-1)*z^(-1), z*x1*z^(-1)*x1^(-1), z*y1*z^(-1)*y1^(-1) >}\\
sage: H.order()\n\]

(continues on next page)
 sage: A = matrix([[1, 1, 0], [0, 1, 0], [0, 0, 1]])
 sage: B = matrix([[1, 0, 0], [0, 1, 1], [0, 0, 1]])
 sage: C = matrix([[1, 0, 1], [0, 1, 0], [0, 0, 1]])
 sage: r1(A, B, C)
 [1 0 0]
 [0 1 0]
 [0 0 1]
 sage: r2(A, B, C)
 [1 0 0]
 [0 1 0]
 [0 0 1]
 sage: r3(A, B, C)
 [1 0 0]
 [0 1 0]
 [0 0 1]
 sage: p = 3
 sage: Hp = groups.presentation.Heisenberg(p=3)
 sage: Hp.order() == p**3
 True
 sage: Hnp = groups.presentation.Heisenberg(n=2, p=3)
 sage: len(Hnp.relations())
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REFERENCES:

• Wikipedia article Heisenberg_group

sage.groups.finitely_presented_named.KleinFourPresentation()
Build the Klein group of order 4 as a finitely presented group.

OUTPUT:
Klein four group ($C_2 \times C_2$) as a finitely presented group.

EXAMPLES:

 sage: K = groups.presentation.KleinFour(); K
Finitely presented group < a, b | a^2, b^2, a^-1*b^-1*a*b >

sage.groups.finitely_presented_named.QuaternionPresentation()
Build the Quaternion group of order 8 as a finitely presented group.

OUTPUT:
Quaternion group as a finite presentation.

EXAMPLES:

 sage: Q = groups.presentation.Quaternion(); Q
Finitely presented group < a, b | a^4, b^2*a^-2, a*b*a*b^-1 >
 sage: Q.as_permutation_group().is_isomorphic(QuaternionGroup())
 True

sage.groups.finitely_presented_named.SymmetricPresentation(n)
Build the Symmetric group of order $n!$ as a finitely presented group.

INPUT:

• $n$ – The size of the underlying set of arbitrary symbols being acted on by the Symmetric group of order $n!$. 


OUTPUT:
Symmetric group as a finite presentation, implementation uses GAP to find an isomorphism from a permutation representation to a finitely presented group representation. Due to this fact, the exact output presentation may not be the same for every method call on a constant $n$.

EXAMPLES:

```python
sage: S4 = groups.presentation.Symmetric(4)
sage: S4.as_permutation_group().is_isomorphic(SymmetricGroup(4))
True
```
Braid groups are implemented as a particular case of finitely presented groups, but with a lot of specific methods for braids.

A braid group can be created by giving the number of strands, and the name of the generators:

```
sage: BraidGroup(3)
Braid group on 3 strands
sage: BraidGroup(3,'a')
Braid group on 3 strands
sage: BraidGroup(3,'a').gens()
(a0, a1)
sage: BraidGroup(3,'a,b').gens()
(a, b)
```

The elements can be created by operating with the generators, or by passing a list with the indices of the letters to the group:

```
sage: B.<s0,s1,s2> = BraidGroup(4)
sage: s0*s1*s0
s0*s1*s0
sage: B.([1,2,1])
s0*s1*s0
```

The mapping class action of the braid group over the free group is also implemented, see `MappingClassGroupAction` for an explanation. This action is left multiplication of a free group element by a braid:

```
sage: B.<b0,b1,b2> = BraidGroup()
sage: F.<f0,f1,f2,f3> = FreeGroup()
sage: B.strands() == F.rank()  # necessary for the action to be defined
True
sage: f1 * b1
f1*f2*f1^-1
sage: f0 * b1
f0
sage: f1 * b1
f1*f2*f1^-1
sage: f1^-1 * b1
f1^-1*f1^-1
```

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• Søren Fuglede Jørgensen
• Robert Lipshitz
• Thierry Monteil: add a __hash__ method consistent with the word problem to ensure correct Cayley graph computations.
• Sebastian Oehms (July and Nov 2018): add other versions for burau_matrix (unitary + simple, see trac ticket #25760 and trac ticket #26657)

class sage.groups.braid.Braid(parent, x, check=True)
Bases: sage.groups.artin.FiniteTypeArtinGroupElement

An element of a braid group.
It is a particular case of element of a finitely presented group.

EXAMPLES:

```
sage: B.<s0,s1,s2> = BraidGroup(3)
sage: B
Braid group on 4 strands
sage: s0*s1/s2/s1
s0*s1*s2^-1*s1^-1
sage: B((1, 2, -3, -2))
s0*s1*s2^-1*s1^-1
```

LKB_matrix (variables='x, y')
Return the Lawrence-Krammer-Bigelow representation matrix.
The matrix is expressed in the basis \{e_{i,j} | 1 \leq i < j \leq n\}, where the indices are ordered lexicographically. It is a matrix whose entries are in the ring of Laurent polynomials on the given variables. By default, the variables are 'x' and 'y'.

INPUT:
• variables – string (default: 'x, y'). A string containing the names of the variables, separated by a comma.

OUTPUT:
The matrix corresponding to the Lawrence-Krammer-Bigelow representation of the braid.

EXAMPLES:

```
sage: B = BraidGroup(3)
sage: b = B([1, 2, 1])
sage: b.LKB_matrix()
[ 0 -x^4*y + x^3*y -x^4*y]
[ 0 -x^3*y 0]
[ -x^2*y x^3*y - x^2*y 0]
sage: c = B([2, 1, 2])
sage: c.LKB_matrix()
[ 0 -x^4*y + x^3*y -x^4*y]
[ 0 -x^3*y 0]
[ -x^2*y x^3*y - x^2*y 0]
```

REFERENCES:
• [Big2003]
**TL_matrix***(drain_size, variab=None, sparse=True)***

Return the matrix representation of the Temperley–Lieb–Jones representation of the braid in a certain basis.

The basis is given by non-intersecting pairings of \((n + d)\) points, where \(n\) is the number of strands, \(d\) is given by drain_size, and the pairings satisfy certain rules. See *TL_basis_with_drain()* for details.

We use the convention that the eigenvalues of the standard generators are 1 and \(-A^4\), where \(A\) is a variable of a Laurent polynomial ring.

When \(d = n - 2\) and the variables are picked appropriately, the resulting representation is equivalent to the reduced Burau representation.

**INPUT:**

- **drain_size** – integer between 0 and the number of strands (both inclusive)
- **variab** – variable (default: None); the variable in the entries of the matrices; if None, then use a default variable in \(\mathbb{Z}[A, A^{-1}]\)
- **sparse** – boolean (default: True); whether or not the result should be given as a sparse matrix

**OUTPUT:**

The matrix of the TL representation of the braid.

The parameter sparse can be set to False if it is expected that the resulting matrix will not be sparse. We currently make no attempt at guessing this.

**EXAMPLES:**

Let us calculate a few examples for \(B_4\) with \(d = 0\):

```
sage: B = BraidGroup(4)
sage: b = B([1, 2, -3])
sage: b.TL_matrix(0)
[1 - A^4 -A^-2]
[ -A^6 0]
sage: R.<x> = LaurentPolynomialRing(GF(2))
sage: b.TL_matrix(0, variab=x)
[1 + x^4 x^-2]
[x^6 0]
sage: b = B([])
sage: b.TL_matrix(0)
[1 0]
[0 1]
```

Test of one of the relations in \(B_8\):

```
sage: B = BraidGroup(8)
sage: d = 0
sage: B([4,5,4]).TL_matrix(d) == B([5,4,5]).TL_matrix(d)
True
```

An element of the kernel of the Burau representation, following [Big1999]:

```
sage: B = BraidGroup(6)
sage: psi1 = B([4, -5, -2, 1])
sage: psi2 = B([-4, 5, 5, 2, -1, -1])
sage: w1 = psi1^(-1) * B([3]) * psi1
(continues on next page)```
REFERENCES:

- [Big1999]
- [Jon2005]

alexander_polynomial (var='t', normalized=True)

Return the Alexander polynomial of the closure of the braid.

INPUT:

- var - string (default: 't'); the name of the variable in the entries of the matrix
- normalized - boolean (default: True); whether to return the normalized Alexander polynomial

OUTPUT:

The Alexander polynomial of the braid closure of the braid.

This is computed using the reduced Burau representation. The unnormalized Alexander polynomial is a Laurent polynomial, which is only well-defined up to multiplication by plus or minus times a power of \( t \).

We normalize the polynomial by dividing by the largest power of \( t \) and then if the resulting constant coefficient is negative, we multiply by \(-1\).

EXAMPLES:

We first construct the trefoil:

```
sage: B = BraidGroup(3)
sage: b = B([1,2,1,2])
sage: b.alexander_polynomial(normalized=False)
1 - t + t^2
sage: b.alexander_polynomial()
t^-2 - t^-1 + 1
```

Next we construct the figure 8 knot:

```
sage: b = B([-1,2,-1,2])
sage: b.alexander_polynomial(normalized=False)
-t^-2 + 3*t^-1 - 1
sage: b.alexander_polynomial()
t^-2 - 3*t^-1 + 1
```

Our last example is the Kinoshita-Terasaka knot:

```
sage: B = BraidGroup(4)
sage: b = B([1,1,3,2,-3,-1,1,2,-1,-3,-2])
sage: b.alexander_polynomial(normalized=False)
-t^-1
sage: b.alexander_polynomial()
1
```
REFERENCES:

- Wikipedia article Alexander_polynomial

\texttt{burau\_matrix}(\texttt{var=\textquoteleft t\textquoteright}, \texttt{reduced=False})

Return the Burau matrix of the braid.

INPUT:

- \texttt{var} – string (default: \textquoteleft t\textquoteright); the name of the variable in the entries of the matrix
- \texttt{reduced} – boolean (default: False); whether to return the reduced or unreduced Burau representation, can be one of the following:
  - True or 'increasing' - returns the reduced form using the basis given by \( e_1 - e_i \) for \( 2 \leq i \leq n \)
  - 'unitary' - the unitary form according to Squier [Squ1984]
  - 'simple' - returns the reduced form using the basis given by simple roots \( e_i - e_{i+1} \), which yields the matrices given on the Wikipedia page

OUTPUT:

The Burau matrix of the braid. It is a matrix whose entries are Laurent polynomials in the variable \texttt{var}. If \texttt{reduced} is True, return the matrix for the reduced Burau representation instead in the format specified. If \texttt{reduced} is 'unitary', a triple \( M, \text{Madj}, H \) is returned, where \( M \) is the Burau matrix in the unitary form, \text{Madj} the adjoined to \( M \) and \( H \) the hermitian form.

EXAMPLES:

\begin{verbatim}
sage: B = BraidGroup(4)
sage: B.inject_variables()
Defining s0, sl, s2
sage: b = s0*s1/s2/s1
sage: b.burau_matrix()
[[ 1 - t  0  t - t^2  t^2],
 [ 1  0  0  0  0],
 [ 0  0  1  0  0],
 [ 0  t^-2 -t^-2 + t^-1 -t^-1 + 1]]
sage: s2.burau_matrix('x')
[[ 1  0  0  0],
 [ 0  1  0  0],
 [ 0  0  1 - x x],
 [ 0  0  1  0]]
sage: s0.burau_matrix(reduced=True)
[-t  0  0]
[-t  1  0]
[-t  0  1]
\end{verbatim}

Using the different reduced forms:

\begin{verbatim}
sage: b.burau_matrix(reduced='simple')
[[ 1 - t -t^-1 + 1 -1],
 [ 1 -t^-1 + 1 -1],
 [ 1  t -t^-1  0]]
sage: M, Madj, H = b.burau_matrix(reduced='unitary')
sage: M
[-t^-2 + 1  t    t^2]
[t^-1 - t  1 - t^2 -t^3]  
\end{verbatim}
sage: Madj
[ -t^-2 -t^-1 0]

sage: H
[ 1 - t^2 -t^-1 + t -t^2]
[ t^-1 -t^-2 + 1 -t]  
[ t^-2 -t^-3 0]

sage: M * H * Madj == H
True

REFERENCES:

- Wikipedia article Burau_representation
- [Squ1984]

centralizer()

Return a list of generators of the centralizer of the braid.

EXAMPLES:

sage: B = BraidGroup(4)
sage: b = B([2, -1, 3, 2])
sage: b.centralizer()
[s1*s0*s2*s1, s0*s2]

components_in_closure()

Return the number of components of the trace closure of the braid.

OUTPUT:

Positive integer.

EXAMPLES:

sage: B = BraidGroup(5)
sage: b = B([1, -3])   # Three disjoint unknots
sage: b.components_in_closure()
3
sage: b = B([1, 2, 3, 4])   # The unknot
sage: b.components_in_closure()
1

conjugating_braid(other)

Return a conjugating braid, if it exists.

INPUT:

- other – the other braid to look for conjugating braid

EXAMPLES:

sage: B = BraidGroup(3)
sage: a = B([2, -1, -1])
sage: b = B([2, 1, 2, 1])
sage: c = b * a / b
sage: d = a.conjugating_braid(c)
sage: d * c / d == a
True
sage: d
s1*s0
sage: d * a / d == c
False

gcd(other)
Return the greatest common divisor of the two braids.

INPUT:

• other – the other braid with respect with the gcd is computed

EXAMPLES:

sage: B = BraidGroup(3)
sage: b = B([1, 2, -1, -2, -2, 1])
sage: c = B([1, 2, 1])
sage: b.gcd(c)
s0^-1*s1^-1*s0^-2*s1^2*s0
sage: c.gcd(b)
s0^-1*s1^-1*s0^-2*s1^2*s0

is_conjugated(other)
Check if the two braids are conjugated.

INPUT:

• other – the other braid to check for conjugacy

EXAMPLES:

sage: B = BraidGroup(3)
sage: a = B([2, 2, -1, -1])
sage: b = B([2, 1, 2, 1])
sage: c = b * a / b
sage: c.is_conjugated(a)
True
sage: c.is_conjugated(b)
False

is_periodic()
Check weather the braid is periodic.

EXAMPLES:

sage: B = BraidGroup(3)
sage: a = B([2, 2, -1, -1, 2, 2])
sage: b = B([2, 1, 2, 1])
sage: a.is_periodic()
False
sage: b.is_periodic()
True

is_pseudoanosov()
Check if the braid is pseudo-anosov.
EXAMPLES:

```python
sage: B = BraidGroup(3)
sage: a = B([2, 2, -1, -1, 2, 2])
sage: b = B([2, 1, 2, 1])
sage: a.is_pseudoanosov()
True
sage: b.is_pseudoanosov()
False
```

```
is_reducible()
Check whether the braid is reducible.

EXAMPLES:

```python
sage: B = BraidGroup(3)
sage: b = B([1, 2, -1])
sage: b.is_reducible()
True
sage: a = B([2, 2, -1, -1, 2, 2])
sage: a.is_reducible()
False
```

```
jones_polynomial(\text{variab}=None,\text{skein_normalization}=False)
Return the Jones polynomial of the trace closure of the braid.

The normalization is so that the unknot has Jones polynomial 1. If \text{skein_normalization} is True, the variable of the result is replaced by a itself to the power of 4, so that the result agrees with the conventions of [Lic1997] (which in particular differs slightly from the conventions used otherwise in this class), had one used the conventional Kauffman bracket variable notation directly.

If \text{variab} is None return a polynomial in the variable \(A\) or \(t\), depending on the value \text{skein_normalization}. In particular, if \text{skein_normalization} is False, return the result in terms of the variable \(t\), also used in [Lic1997].

INPUT:

- \text{variab} – variable (default: None); the variable in the resulting polynomial; if unspecified, use either a default variable in \(ZZ[A, A^{-1}]\) or the variable \(t\) in the symbolic ring
- \text{skein_normalization} – boolean (default: False); determines the variable of the resulting polynomial

OUTPUT:

If \text{skein_normalization} if False, this returns an element in the symbolic ring as the Jones polynomial of the closure might have fractional powers when the closure of the braid is not a knot. Otherwise the result is a Laurent polynomial in \text{variab}.

EXAMPLES:

The unknot:

```python
sage: B = BraidGroup(9)
sage: b = B([1, 2, 3, 4, 5, 6, 7, 8])
sage: b.jones_polynomial()
```

Two unlinked unknots:
sage: B = BraidGroup(2)
sage: b = B([[]])
sage: b.jones_polynomial()
-sqrt(t) - 1/sqrt(t)

The Hopf link:

sage: B = BraidGroup(2)
sage: b = B([-1, -1])
sage: b.jones_polynomial()
-1/sqrt(t) - 1/t^(5/2)

Different representations of the trefoil and one of its mirror:

sage: B = BraidGroup(2)
sage: b = B([-1, -1, -1])
sage: b.jones_polynomial(skein_normalization=True)
-A^-16 + A^-12 + A^-4
sage: b.jones_polynomial()
1/t + 1/t^3 - 1/t^4
sage: B = BraidGroup(3)
sage: b = B([-1, -2, -1, -2])
sage: b.jones_polynomial(skein_normalization=True)
-A^-16 + A^-12 + A^-4
sage: R.<x> = LaurentPolynomialRing(GF(2))
sage: b.jones_polynomial(skein_normalization=True, variab=x)
x^-16 + x^-12 + x^-4
sage: B = BraidGroup(3)
sage: b = B([1, 2, 1, 2])
sage: b.jones_polynomial(skein_normalization=True)
A^4 + A^12 - A^16

K11n42 (the mirror of the “Kinoshita-Terasaka” knot) and K11n34 (the mirror of the “Conway” knot):

sage: B = BraidGroup(4)
sage: b11n42 = B([1, -2, 3, -2, 3, -2, -2, -1, 2, -3, -3, 2, 2])
sage: b11n34 = B([1, 1, 2, -3, 2, -3, 1, -2, -2, -3, -3])
sage: bool(b11n42.jones_polynomial() == b11n34.jones_polynomial())
True

\texttt{lcm} (\texttt{other})

Return the least common multiple of the two braids.

\textbf{INPUT:}

- \texttt{other} -- the other braid with respect with the lcm is computed

\textbf{EXAMPLES:}

sage: B = BraidGroup(3)
sage: b = B([1, 2, -1, -2, -2, 1])
sage: c = B([1, 2, 1])
sage: b.lcm(c)
(s0*s1)^2*s0

\texttt{markov_trace} (\texttt{variab=None, normalized=True})

Return the Markov trace of the braid.
The normalization is so that in the underlying braid group representation, the eigenvalues of the standard generators of the braid group are 1 and $-A^4$.

**INPUT:**

- `variab` – variable (default: None); the variable in the resulting polynomial; if None, then use the variable $A$ in $\mathbb{Z}[A, A^{-1}]$
- `normalized` – boolean (default: True); if specified to be False, return instead a rescaled Laurent polynomial version of the Markov trace

**OUTPUT:**

If `normalized` is False, return instead the Markov trace of the braid, normalized by a factor of $(A^2 + A^{-2})^n$. The result is then a Laurent polynomial in `variab`. Otherwise it is a quotient of Laurent polynomials in `variab`.

**EXAMPLES:**

```sage
B = BraidGroup(4)
b = B([1, 2, -3])
mt = b.markov_trace(); mt
A^4/(A^12 + 3*A^8 + 3*A^4 + 1)
mt.factor()
A^4 * (A^4 + 1)^-3
```

We now give the non-normalized Markov trace:

```sage
mt = b.markov_trace(normalized=False); mt
A^-4 + 1
mt.parent()
Univariate Laurent Polynomial Ring in A over Integer Ring
```

**`permutation()`**

Return the permutation induced by the braid in its strands.

**OUTPUT:**

A permutation.

**EXAMPLES:**

```sage
B.<s0,s1,s2> = BraidGroup()
b = s0*s1/s2/s1
b.permutation()
[4, 1, 3, 2]
b.permutation().cycle_string()
'(1,4,2)'
```

**`plot`**

Plot the braid

The following options are available:

- `color` – (default: 'rainbow') the color of the strands. Possible values are:
  - 'rainbow', uses `rainbow()` according to the number of strands.
  - a valid color name for `bezier_path()` and `line()`. Used for all strands.
  - a list or a tuple of colors for each individual strand.
- **orientation** – (default: 'bottom-top') determines how the braid is printed. The possible values are:
  - 'bottom-top', the braid is printed from bottom to top
  - 'top-bottom', the braid is printed from top to bottom
  - 'left-right', the braid is printed from left to right
- **gap** – floating point number (default: 0.05). determines the size of the gap left when a strand goes under another.
- **aspect_ratio** – floating point number (default: 1). The aspect ratio.
- ****kwds** – other keyword options that are passed to bezier_path() and line().

**EXAMPLES:**

```python
sage: B = BraidGroup(4, 's')
sage: b = B([1, 2, 3, 1, 2, 1])
sage: b.plot()
Graphics object consisting of 30 graphics primitives
sage: b.plot(color=['red', 'blue', 'red', 'blue'])
Graphics object consisting of 30 graphics primitives
```

**plot3d** *(color='rainbow')*

Plots the braid in 3d.

The following option is available:

- **color** – (default: 'rainbow') the color of the strands. Possible values are:
  - 'rainbow', uses rainbow() according to the number of strands.
  - a valid color name for bezier3d(). Used for all strands.
  - a list or a tuple of colors for each individual strand.

**EXAMPLES:**

```python
sage: B = BraidGroup(4, 's')
sage: b = B([1, 2, 3, 1, 2, 1])
sage: b.plot3d()
Graphics3d Object
sage: b.plot3d(color='red')
Graphics3d Object
sage: b.plot3d(color=['red', 'blue', 'red', 'blue'])
Graphics3d Object
```

**right_normal_form()**

Return the right normal form of the braid.

**EXAMPLES:**

```python
sage: B = BraidGroup(4)
sage: b = B([1, 2, 1, -2, 3, 1])
sage: b.right_normal_form()
(s1*s0, s0*s2, 1)
```
**rigidity()**

Return the rigidity of self.

**EXAMPLES:**

```python
sage: B = BraidGroup(3)
sage: b = B([2, 1, 2, 1])
sage: a = B([2, 2, -1, -1, 2, 2])
sage: a.rigidity()
6
sage: b.rigidity()
0
```

**sliding_circuits()**

Return the sliding circuits of the braid.

**OUTPUT:**

A list of sliding circuits. Each sliding circuit is itself a list of braids.

**EXAMPLES:**

```python
sage: B = BraidGroup(3)
sage: a = B([2, 2, -1, -1, 2, 2])
sage: a.sliding_circuits()
[[s0^-1*s1^-1*s0^-1)^2*s1^3*s0^2*s1^3],
 [s0^-1*s1^-1*s0^-1)^2*s1^2*s0^2*s1^2],
 [s0^-1*s1^-1*s0^-1)^2*s1^4*s0^2*s1^2],
 [s0^-1*s1^-1*s0^-1)^2*s1^2*s0^2*s1^4],
 [s0^-1*s1^-1*s0^-1)^2*s1^5*s0^2*s1^2],
]
sage: b = B([2, 1, 2, 1])
sage: b.sliding_circuits()
[[s0*s1*s0^2, (s0*s1)^2]]
```

**strands()**

Return the number of strands in the braid.

**EXAMPLES:**

```python
sage: B = BraidGroup(4)
sage: b = B([1, 2, -1, 3, -2])
sage: b.strands()
4
```

**super_summit_set()**

Return a list with the super summit set of the braid

**EXAMPLES:**

```python
sage: B = BraidGroup(3)
sage: b = B([1, 2, -1, -2, -2, 1])
sage: b.super_summit_set()
[s0^-1*s1^-1*s0^-1)^2*s1^2*s0^2*s1^2]
```
\[(s0^{-1}s1^{-1}s0^{-1})^2s1^2s0^3s1,\]
\[(s0^{-1}s1^{-1}s0^{-1})^2s1s0^3s1^2,\]
\[s0^{-1}s1^{-1}s0^{-2}s1^{-1}s0s1^3s0]\]

**thurston_type()**
Return the thurston_type of self.

**OUTPUT:**
One of 'reducible', 'periodic' or 'pseudo-anosov'.

**EXAMPLES:**

```python
sage: B = BraidGroup(3)
sage: b = B([1, 2, -1])
sage: b.thurston_type()
'reducible'
sage: a = B([2, 2, -1, -1, 2, 2])
sage: a.thurston_type()
'pseudo-anosov'
sage: c = B([2, 1, 2, 1])
sage: c.thurston_type()
'periodic'
```

**tropical_coordinates()**
Return the tropical coordinates of self in the braid group $B_n$.

**OUTPUT:**
- a list of $2n$ tropical integers

**EXAMPLES:**

```python
sage: B = BraidGroup(3)
sage: b = B([1])
sage: tc = b.tropical_coordinates(); tc
[1, 0, 0, 2, 0, 1]
sage: tc[0].parent()
Tropical semiring over Integer Ring
sage: b = B([-2, -2, -1, -1, 2, 2, 1, 1])
sage: b.tropical_coordinates()
[1, -19, -12, 9, 0, 13]
```

**REFERENCES:**
- [DW2007]
- [Deh2011]

**ultra_summit_set()**
Return a list with the orbits of the ultra summit set of self

**EXAMPLES:**

```python
sage: B = BraidGroup(3)
sage: a = B([2, 2, -1, -1, 2, 2])
sage: b = B([2, 1, 2, 1])
sage: b.ultra_summit_set()
[[s0*s1*s0^2, (s0*s1)^2]]
```
Construct a Braid Group

INPUT:

• \(n\) – integer or None (default). The number of strands. If not specified the names are counted and the group is assumed to have one more strand than generators.

• \(\text{name}\) – string or list/tuple/iterable of strings (default: 'x'). The generator names or name prefix.

EXAMPLES:

```python
sage: B.<a,b> = BraidGroup(); B
Braid group on 3 strands
sage: H = BraidGroup('a, b')
sage: B is H
True
sage: BraidGroup(3)
Braid group on 3 strands
```

The entry can be either a string with the names of the generators, or the number of generators and the prefix of the names to be given. The default prefix is 's'

```python
sage: B=BraidGroup(3); B.generators()
(s0, s1)
sage: BraidGroup(3, 'g').generators()
(g0, g1)
```

Since the word problem for the braid groups is solvable, their Cayley graph can be locally obtained as follows (see trac ticket #16059):

```python
sage: def ball(group, radius):
......:     ret = set()
......:     ret.add(group.one())
......:     for length in range(1, radius):
......:         for w in Words(alphabet=group.gens(), length=length):
......:             ret.add(prod(w))
......:     return ret
sage: B = BraidGroup(4)
sage: GB = B.cayley_graph(elements=ball(B, 4), generators=B.gens()); GB
Digraph on 31 vertices
```

Since the braid group has nontrivial relations, this graph contains less vertices than the one associated to the free group (which is a tree):
class sage.groups.braid.BraidGroup_class(names)

Bases: sage.groups.artin.FiniteTypeArtinGroup

The braid group on \( n \) strands.

.. code-block::

    sage: B1 = BraidGroup(5)
    sage: B1
    Braid group on 5 strands
    sage: B2 = BraidGroup(3)
    sage: B1==B2
    False
    sage: B2 is BraidGroup(3)
    True

Delta(*args, **kwds)

    Deprecated: Use delta() instead. See trac ticket #24664 for details.

Element

    alias of Braid

TL_basis_with_drain(drain_size)

    Return a basis of a summand of the Temperley–Lieb–Jones representation of self.

    The basis elements are given by non-intersecting pairings of \( n + d \) points in a square with \( n \) points marked ‘on the top’ and \( d \) points ‘on the bottom’ so that every bottom point is paired with a top point. Here, \( n \) is the number of strands of the braid group, and \( d \) is specified by drain_size.

    A basis element is specified as a list of integers obtained by considering the pairings as obtained as the ‘highest term’ of trivalent trees marked by Jones–Wenzl projectors (see e.g. [Wan2010]). In practice, this is a list of non-negative integers whose first element is drain_size, whose last element is 0, and satisfying that consecutive integers have difference 1. Moreover, the length of each basis element is \( n + 1 \).

    Given these rules, the list of lists is constructed recursively in the natural way.

    INPUT:
    
    * drain_size – integer between 0 and the number of strands (both inclusive)

    OUTPUT:

    A list of basis elements, each of which is a list of integers.

    EXAMPLES:

    We calculate the basis for the appropriate vector space for \( B_5 \) when \( d = 3 \):

    .. code-block::

        sage: B = BraidGroup(5)
        sage: B.TL_basis_with_drain(3)
        [[[3, 4, 3, 2, 1, 0],
          [3, 2, 3, 2, 1, 0],
          [3, 2, 1, 2, 1, 0],
          [3, 2, 1, 0, 1, 0]]

    The number of basis elements hopefully corresponds to the general formula for the dimension of the representation spaces:
sage: B = BraidGroup(10)
sage: d = 2
sage: B.dimension_of_TL_space(d) == len(B.TL_basis_with_drain(d))
True

**TL_representation** *(drain_size, variab=None)*

Return representation matrices of the Temperley–Lieb–Jones representation of standard braid group generators and inverses of *self*.

The basis is given by non-intersecting pairings of \((n + d)\) points, where \(n\) is the number of strands, and \(d\) is given by *drain_size*, and the pairings satisfy certain rules. See *TL_basis_with_drain()* for details. This basis has the useful property that all resulting entries can be regarded as Laurent polynomials.

We use the convention that the eigenvalues of the standard generators are 1 and \(-A^4\), where \(A\) is the generator of the Laurent polynomial ring.

When \(d = n - 2\) and the variables are picked appropriately, the resulting representation is equivalent to the reduced Burau representation. When \(d = n\), the resulting representation is trivial and 1-dimensional.

**INPUT:**

- *drain_size* – integer between 0 and the number of strands (both inclusive)
- *variab* – variable (default: None); the variable in the entries of the matrices; if None, then use a default variable in \(\mathbb{Z}[A, A^{-1}]\)

**OUTPUT:**

A list of matrices corresponding to the representations of each of the standard generators and their inverses.

**EXAMPLES:**

```python
sage: B = BraidGroup(4)
sage: B.TL_representation(0)
[([ 1 0] [ 1 0]
  [ A^2 -A^4], [ A^-2 -A^-4]
),
 [0 1], [ 0 1]
],
[ [ 1 0] [ 1 0]
  [ A^2 -A^4], [ A^-2 -A^-4]
)]
sage: R.<A> = LaurentPolynomialRing(GF(2))
sage: B.TL_representation(0, variab=A)
[([ 1 0] [ 1 0]
  [A^2 A^4], [A^-2 A^-4]
),
 [A^4 A^2] [A^-4 A^-2]
 [0 1], [ 0 1]
],
[ [ 1 0] [ 1 0]
  [A^2 A^4], [A^-2 A^-4]
)]
```

(continued from previous page)

```python
sage: B = BraidGroup(8)
sage: B.TL_representation(8)
([(1], [1]),
 ([1], [1]),
 ([1], [1]),
 ([1], [1]),
 ([1], [1]),
 ([1], [1]),
 ([1], [1])]
```

**an_element()**

Return an element of the braid group.

This is used both for illustration and testing purposes.

**EXAMPLES:**

```python
sage: B = BraidGroup(2)
sage: B.an_element()
s
```

**as_permutation_group()**

Return an isomorphic permutation group.

**OUTPUT:**

Raises a `ValueError` error since braid groups are infinite.

**cardinality()**

Return the number of group elements.

**OUTPUT:**

Infinity.

**dimension_of_TL_space(drain_size)**

Return the dimension of a particular Temperley–Lieb representation summand of `self`.

Following the notation of `TL_basis_with_drain()`, the summand is the one corresponding to the number of drains being fixed to be `drain_size`.

**INPUT:**

- `drain_size` – integer between 0 and the number of strands (both inclusive)

**EXAMPLES:**

Calculation of the dimension of the representation of \( B_8 \) corresponding to having 2 drains:

```python
sage: B = BraidGroup(8)
sage: B.dimension_of_TL_space(2)
28
```

The direct sum of endomorphism spaces of these vector spaces make up the entire Temperley–Lieb algebra:

```python
sage: import sage.combinat.diagram_algebras as da
sage: B = BraidGroup(6)
sage: dimensions = [B.dimension_of_TL_space(d)**2 for d in [0, 2, 4, 6]]
sage: total_dim = sum(dimensions)
sage: total_dim == len(list(da.temperley_lieb_diagrams(6)))  # long time
True
```
**mapping_class_action**($F$)

Return the action of self in the free group $F$ as mapping class group.

This action corresponds to the action of the braid over the punctured disk, whose fundamental group is the free group on as many generators as strands.

In Sage, this action is the result of multiplying a free group element with a braid. So you generally do not have to construct this action yourself.

**OUTPUT:**

A `MappingClassGroupAction`.

**EXAMPLES**

```python
sage: B = BraidGroup(3)
sage: B.inject_variables()
Defining s0, s1
sage: F.<a,b,c> = FreeGroup(3)
sage: A = B.mapping_class_action(F)
sage: A(a, s0)
a*b*a^-1
sage: a * s0       # simpler notation
a*b*a^-1
```

**order**()

Return the number of group elements.

**OUTPUT:**

Infinity.

**some_elements**()

Return a list of some elements of the braid group.

This is used both for illustration and testing purposes.

**EXAMPLES**

```python
sage: B = BraidGroup(3)
sage: B.some_elements()
[s0, s0*s1, (s0*s1)^3]
```

**strands**()

Return the number of strands.

**OUTPUT:**

Integer.

**EXAMPLES**

```python
sage: B = BraidGroup(4)
sage: B.strands()
4
```

**class** `sage.groups.braid.MappingClassGroupAction`($G$, $M$)

**Bases:** `sage.categories.action.Action`

The right action of the braid group the free group as the mapping class group of the punctured disk.

That is, this action is the action of the braid over the punctured disk, whose fundamental group is the free group on as many generators as strands.
This action is defined as follows:

\[
x_j \cdot \sigma_i = \begin{cases} 
  x_j \cdot x_{j+1} \cdot x_j^{-1} & \text{if } i = j \\
  x_{j-1} & \text{if } i = j - 1 \\
  x_j & \text{otherwise}
\end{cases}
\]

where \( \sigma_i \) are the generators of the braid group on \( n \) strands, and \( x_j \) the generators of the free group of rank \( n \).

You should left multiplication of the free group element by the braid to compute the action. Alternatively, use the \texttt{mapping_class_action()} method of the braid group to construct this action.

**EXAMPLES:**

```
sage: B.<s0,s1,s2> = BraidGroup(4)
sage: F.<x0,x1,x2,x3> = FreeGroup(4)
sage: x0 * s1
x0
sage: x1 * s1
x1*x2*x1^-1
sage: x1^-1 * s1
x1*x2^-1*x1^-1

sage: A = B.mapping_class_action(F)
sage: A
Right action by Braid group on 4 strands on Free Group on generators {x0, x1, x2, \ldots, x3}
sage: A(x0, s1)
x0
sage: A(x1, s1)
x1*x2*x1^-1
sage: A(x1^-1, s1)
x1*x2^-1*x1^-1
```
INDEXED FREE GROUPS

Free groups and free abelian groups implemented using an indexed set of generators.

AUTHORS:

- Travis Scrimshaw (2013-10-16): Initial version

```python
class sage.groups.indexed_free_group.IndexedFreeAbelianGroup(indices, prefix, category=None, **kwds):
    Bases: sage.groups.indexed_free_group.IndexedGroup, sage.groups.group.AbelianGroup

    An indexed free abelian group.

    EXAMPLES:
    
    sage: G = Groups().Commutative().free(index_set=ZZ)
    sage: G
    Free abelian group indexed by Integer Ring
    sage: G = Groups().Commutative().free(index_set='abcde')
    sage: G
    Free abelian group indexed by {'a', 'b', 'c', 'd', 'e'}
```

class Element(F, x)

    Bases: sage.monoids.indexed_free_monoid.IndexedFreeAbelianMonoidElement, sage.groups.indexed_free_group.IndexedFreeGroup.Element

    gen(x)

    The generator indexed by x of self.

    EXAMPLES:
    
    sage: G = Groups().Commutative().free(index_set=ZZ)
    sage: G.gen(0)
    F[0]
    sage: G.gen(2)
    F[2]
```

one()

    Return the identity element of self.

    EXAMPLES:
    
    sage: G = Groups().Commutative().free(index_set=ZZ)
    sage: G.one()
    1
class sage.groupsindexed_free_group.IndexedFreeGroup(indices, prefix, category=None, **kwds)

Bases: sage.groups.indexed_free_group.IndexedGroup, sage.groups.group.Group

An indexed free group.

EXAMPLES:

```
sage: G = Groups().free(index_set=ZZ)
sage: G
Free group indexed by Integer Ring
sage: G = Groups().free(index_set='abcde')
sage: G
Free group indexed by {'a', 'b', 'c', 'd', 'e'}
```

class Element(F, x)

Bases: sage.monoids.indexed_free_monoid.IndexedFreeMonoidElement

length()

Return the length of self.

EXAMPLES:

```
sage: G = Groups().free(index_set=ZZ)
sage: a,b,c,d,e = [G.gen(i) for i in range(5)]
sage: elt = a*c^-3*b^-2*a
sage: elt.length()
7
sage: len(elt)
7
sage: G = Groups().free(index_set=ZZ)
sage: a,b,c,d,e = [G.gen(i) for i in range(5)]
sage: elt = a*c^-3*b^-2*a
sage: elt.length()
7
sage: len(elt)
7
```

to_word_list()

Return self as a word represented as a list whose entries are the pairs (i, s) where i is the index and s is the sign.

EXAMPLES:

```
sage: G = Groups().free(index_set=ZZ)
sage: a,b,c,d,e = [G.gen(i) for i in range(5)]
sage: x = a*b^2*e*a^-1
sage: x.to_word_list()
[(0, 1), (1, 1), (1, 1), (4, 1), (0, -1)]
```

gen(x)

The generator indexed by x of self.

EXAMPLES:

```
sage: G = Groups().free(index_set=ZZ)
sage: G.gen(0)
F[0]
```

(continues on next page)
sage: G.gen(2)
F[2]

one()

Return the identity element of self.

EXAMPLES:

sage: G = Groups().free(ZZ)
sage: G.one()
1

class sage.groups.indexed_free_group.IndexedGroup(indices, prefix, category=None, names=None, **kwds)

Bases: sage.monoids.indexed_free_monoid.IndexedMonoid

Base class for free (abelian) groups whose generators are indexed by a set.

sage: G = Groups().Commutative().free(index_set=ZZ)
sage: G.is_finite()
False
sage: G = Groups().Commutative().free(index_set='abc')
sage: G.is_finite()
False
sage: G = Groups().Commutative().free(index_set=[])  
 sage: G.is_finite()
True

gens()

Return the group generators of self.

EXAMPLES:

sage: G = Groups.free(index_set=ZZ)
sage: G.group_generators()
Lazy family (Generator map from Integer Ring to Free group indexed by Integer Ring(i))_{i in Integer Ring}
sage: G = Groups().free(index_set='abcde')
sage: sorted(G.group_generators())
[F['a'], F['b'], F['c'], F['d'], F['e']]

group_generators()

Return the group generators of self.

EXAMPLES:

sage: G = Groups.free(index_set=ZZ)
sage: G.group_generators()
Lazy family (Generator map from Integer Ring to Free group indexed by Integer Ring(i))_{i in Integer Ring}
sage: G = Groups().free(index_set='abcde')
sage: sorted(G.group_generators())
[F['a'], F['b'], F['c'], F['d'], F['e']]

order()

Return the number of elements of self, which is $\infty$ unless this is the trivial group.

EXAMPLES:
```python
sage: G = Groups().free(index_set='abc')
sage: G.order()
+Infinity
sage: G.rank()
3
sage: G = Groups().Commutative().free(index_set='abc')
sage: G.rank()
3
```

```
 rank()

Return the rank of self.

This is the number of generators of self.

EXAMPLES:

```
```
A right-angled Artin group (often abbreviated as RAAG) is a group which has a presentation whose only relations are commutators between generators. These are also known as graph groups, since they are (uniquely) encoded by (simple) graphs, or partially commutative groups.

AUTHORS:
- Travis Scrimshaw (2013-09-01): Initial version
- Travis Scrimshaw (2018-02-05): Made compatible with ArtinGroup

```python
class sage.groups.raag.RightAngledArtinGroup(G, names)
Bases: sage.groups.artin.ArtinGroup
```

The right-angled Artin group defined by a graph $G$.

Let $\Gamma = \{V(\Gamma), E(\Gamma)\}$ be a simple graph. A right-angled Artin group (commonly abbreviated as RAAG) is the group

$$A_\Gamma = \langle g_v : v \in V(\Gamma) \mid [g_u, g_v] \text{ if } \{u, v\} \notin E(\Gamma) \rangle.$$ 

These are sometimes known as graph groups or partially commutative groups. This RAAG’s contains both free groups, given by the complete graphs, and free abelian groups, given by disjoint vertices.

**Warning:** This is the opposite convention of some papers.

Right-angled Artin groups contain many remarkable properties and have a very rich structure despite their simple presentation. Here are some known facts:

- The word problem is solvable.
- They are known to be rigid; that is for any finite simple graphs $\Delta$ and $\Gamma$, we have $A_\Delta \cong A_\Gamma$ if and only if $\Delta \cong \Gamma$ [Dro1987].
- They embed as a finite index subgroup of a right-angled Coxeter group (which is the same definition as above except with the additional relations $g_v^2 = 1$ for all $v \in V(\Gamma)$).
- In [BB1997], it was shown they contain subgroups that satisfy the property $FP_2$ but are not finitely presented by considering the kernel of $\phi : A_\Gamma \rightarrow \mathbb{Z}$ by $g_v \mapsto 1$ (i.e. words of exponent sum 0).
- $A_\Gamma$ has a finite $K(\pi, 1)$ space.
- $A_\Gamma$ acts freely and cocompactly on a finite dimensional $CAT(0)$ space, and so it is biautomatic.
- Given an Artin group $B$ with generators $s_i$, then any subgroup generated by a collection of $v_i = s_i^{k_i}$ where $k_i \geq 2$ is a RAAG where $[v_i, v_j] = 1$ if and only if $[s_i, s_j] = 1$ [CP2001].
The normal forms for RAAG’s in Sage are those described in [VW1994] and gathers commuting groups together.

**INPUT:**

- G – a graph
- names – a string or a list of generator names

**EXAMPLES:**

```
sage: Gamma = Graph(4)
sage: G = RightAngledArtinGroup(Gamma)
sage: a,b,c,d = G.gens()
sage: a*c*d^4*a^-3*b
v0^-2*v1*v2*v3^4
```

```
sage: Gamma = Graphs.CompleteGraph(4)
sage: G = RightAngledArtinGroup(Gamma)
sage: a,b,c,d = G.gens()
sage: a*c*d^4*a^-3*b
v0*v2*v3^4*v0^-3*v1
```

```
sage: Gamma = Graphs.CycleGraph(5)
sage: G = RightAngledArtinGroup(Gamma)
sage: G
Right-angled Artin group of Cycle graph
sage: a,b,c,d,e = G.gens()
sage: d*b*a*d
v1*v3^2*v0
```

We create the previous example but with different variable names:

```
sage: G.<a,b,c,d,e> = RightAngledArtinGroup(Gamma)
sage: G
Right-angled Artin group of Cycle graph
sage: d*b*a*d
b*d^2*a
sage: e^-1*c*b*e*b^-1*c^-4
c^-3
```

**REFERENCES:**

- [Cha2006]
- [BB1997]
- [Dro1987]
- [CP2001]
- [VW1994]
- [Wikipedia article Artin_group#Right-angled_Artin_groups]

**class** *Element (parent, lst)*

Bases: sage.groups.artin.ArtinGroupElement

An element of a right-angled Artin group (RAAG).

Elements of RAAGs are modeled as lists of pairs \([i, p]\) where \(i\) is the index of a vertex in the defining graph (with some fixed order of the vertices) and \(p\) is the power.
**gen (i)**

Return the $i$-th generator of self.

**EXAMPLES:**

```python
sage: Gamma = graphs.CycleGraph(5)
sage: G = RightAngledArtinGroup(Gamma)
sage: G.gen(2)
v2
```

**gens ()**

Return the generators of self.

**EXAMPLES:**

```python
sage: Gamma = graphs.CycleGraph(5)
sage: G = RightAngledArtinGroup(Gamma)
sage: G.gens()
(v0, v1, v2, v3, v4)
sage: Gamma = Graph([('x', 'y'), ('y', 'zeta')])
sage: G = RightAngledArtinGroup(Gamma)
sage: G.gens()
(vx, vy, vzeta)
```

**graph ()**

Return the defining graph of self.

**EXAMPLES:**

```python
sage: Gamma = graphs.CycleGraph(5)
sage: G = RightAngledArtinGroup(Gamma)
sage: G.graph()
Cycle graph: Graph on 5 vertices
```

**ngens ()**

Return the number of generators of self.

**EXAMPLES:**

```python
sage: Gamma = graphs.CycleGraph(5)
sage: G = RightAngledArtinGroup(Gamma)
sage: G.ngens()
5
```

**one ()**

Return the identity element $1$.

**EXAMPLES:**

```python
sage: Gamma = graphs.CycleGraph(5)
sage: G = RightAngledArtinGroup(Gamma)
sage: G.one()
1
```

**one_element ()**

Return the identity element $1$.

**EXAMPLES:**
Gamma = graphs.CycleGraph(5)
G = RightAngledArtinGroup(Gamma)
G.one()
AUTHORS:

- Mark Shimozono (2013): initial version

class sage.groups.group_exp.GroupExp
    Bases: sage.categories.functor.Functor

A functor that converts a commutative additive group into an isomorphic multiplicative group.

More precisely, given a commutative additive group $G$, define the exponential of $G$ to be the isomorphic group with elements denoted $e^g$ for every $g \in G$ and but with product in multiplicative notation

$$e^g e^h = e^{g+h} \quad \text{for all } g, h \in G.$$ 

The class $GroupExp$ implements the sage functor which sends a commutative additive group $G$ to its exponential.

The creation of an instance of the functor $GroupExp$ requires no input:

```sage
sage: E = GroupExp(); E
Functor from Category of commutative additive groups to Category of groups
```

The $GroupExp$ functor (denoted $E$ in the examples) can be applied to two kinds of input. The first is a commutative additive group. The output is its exponential. This is accomplished by `_apply_functor()`:

```sage
sage: EZ = E(ZZ); EZ
Multiplicative form of Integer Ring
```

Elements of the exponentiated group can be created and manipulated as follows:

```sage
sage: x = EZ(-3); x
-3
sage: x.parent()
Multiplicative form of Integer Ring
sage: EZ(-1)+EZ(6) == EZ(5)
True
sage: EZ(3)^(-1)
-3
sage: EZ.one()
0
```

The second kind of input the $GroupExp$ functor accepts, is a homomorphism of commutative additive groups. The output is the multiplicative form of the homomorphism. This is achieved by `_apply_functor_to_morphism()`:
sage: L = RootSystem(['A',2]).ambient_space()
sage: EL = E(L)
sage: W = L.weyl_group(prefix="s")
sage: s2 = W.simple_reflection(2)
sage: def my_action(mu):
    ....:     return s2.action(mu)
sage: from sage.categories.morphism import SetMorphism
sage: from sage.categories.homset import Hom
sage: F = E(f)
Generic endomorphism of Multiplicative form of Ambient space of the Root system of type ['A', 2]
sage: v = L.an_element(); v
(2, 2, 3)
sage: y = F(EL(v)); y
(2, 3, 2)
sage: y.parent()  # Note: this line is not part of the code snippet provided.
Multiplicative form of Ambient space of the Root system of type ['A', 2]

class sage.groups.group_exp.GroupExpElement (parent, x)


An element in the exponential of a commutative additive group.

INPUT:

- self – the exponentiated group element being created
- parent – the exponential group (parent of self)
- x – the commutative additive group element being wrapped to form self.

EXAMPLES:

sage: G = QQ^2
sage: EG = GroupExp()(G)
sage: z = GroupExpElement(EG, vector(QQ, (1,-3))); z
(1, -3)
sage: z.parent()
Multiplicative form of Vector space of dimension 2 over Rational Field
sage: EG(vector(QQ,(1,-3)))==z
True

inverse()

Invert the element self.

EXAMPLES:

sage: EZ = GroupExp()(ZZ)
sage: EZ(-3).inverse()
3

class sage.groups.group_exp.GroupExp_Class (G)

Bases: sage.structure.unique_representation.UniqueRepresentation, sage.structure.parent.Parent

The multiplicative form of a commutative additive group.

INPUT:
• $G$: a commutative additive group

**OUTPUT:**
• The multiplicative form of $G$.

**EXAMPLES:**

```python
sage: GroupExp()(QQ)
Multiplicative form of Rational Field
```

**Element**
alias of `GroupExpElement`

**an_element()**
Return an element of the multiplicative group.

**EXAMPLES:**

```python
sage: L = RootSystem(['A',2]).weight_lattice()
sage: EL = GroupExp()(L)
sage: x = EL.an_element(); x
sage: x.parent()
Multiplicative form of Weight lattice of the Root system of type ['A', 2]
```

**group_generators()**
Return generators of `self`.

**EXAMPLES:**

```python
sage: GroupExp()(ZZ).group_generators()
(1,)
```

**one()**
Return the identity element of the multiplicative group.

**EXAMPLES:**

```python
sage: G = GroupExp()(ZZ^2)
sage: G.one()
(0, 0)
sage: x = G.an_element(); x
(1, 0)
sage: x == x * G.one()
True
```

**product(x, y)**
Return the product of $x$ and $y$ in the multiplicative group.

**EXAMPLES:**

```python
sage: G = GroupExp()(ZZ)
sage: G.product(G(2),G(7))
9
sage: x = G(2)
sage: x.__mul__(G(7))
9
```
Chapter 16. Functor that converts a commutative additive group into a multiplicative group.
SEMICDIRECT PRODUCT OF GROUPS

AUTHORS:

- Mark Shimozono (2013) initial version

```
class sage.groups.group_semidirect_product.GroupSemidirectProduct (G, H, twist=None, act_to_right=True, prefix0=None, prefix1=None, print_tuple=False, category=Category of groups)
```

**Bases:** `sage.sets.cartesian_product.CartesianProduct`

Return the semidirect product of the groups $G$ and $H$ using the homomorphism `twist`.

**INPUT:**

- $G$ and $H$ – multiplicative groups
- `twist` – (default: None) a function defining a homomorphism (see below)
- `act_to_right` – True or False (default: True)
- `prefix0` – (default: None) optional string
- `prefix1` – (default: None) optional string
- `print_tuple` – True or False (default: False)
- `category` – A category (default: Groups())

A semidirect product of groups $G$ and $H$ is a group structure on the Cartesian product $G \times H$ whose product agrees with that of $G$ on $G \times 1_H$ and with that of $H$ on $1_G \times H$, such that either $1_G \times H$ or $G \times 1_H$ is a normal subgroup. In the former case the group is denoted $G \ltimes H$ and in the latter, $G \rtimes H$.

If `act_to_right` is True, this indicates the group $G \ltimes H$ in which $G$ acts on $H$ by automorphisms. In this case there is a group homomorphism $\phi \in \text{Hom}(G, \text{Aut}(H))$ such that

$$ghg^{-1} = \phi(g)(h).$$

The homomorphism $\phi$ is specified by the input `twist`, which syntactically is the function $G \times H \to H$ defined by

$$\text{twist}(g, h) = \phi(g)(h).$$
The product on $G \ltimes H$ is defined by

$$(g_1, h_1)(g_2, h_2) = g_1 h_1 g_2 h_2$$

$$= g_1 g_2 g_1^{-1} h_1 g_2 h_2$$

$$= (g_1 g_2, \text{twist}(g_2^{-1}, h_1) h_2)$$

If \texttt{act_to_right} is False, the group $G \ltimes H$ is specified by a homomorphism $\psi \in \text{Hom}(H, \text{Aut}(G))$ such that

$$h g h^{-1} = \psi(h)(g)$$

Then \texttt{twist} is the function $H \times G \to G$ defined by

$$\text{twist}(h, g) = \psi(h)(g).$$

so that the product in $G \ltimes H$ is defined by

$$(g_1, h_1)(g_2, h_2) = g_1 h_1 g_2 h_2$$

$$= g_1 h_1 g_2 h_1^{-1} h_1 h_2$$

$$= (g_1 \text{twist}(h_1, g_2), h_1 h_2)$$

If \texttt{prefix0} (resp. \texttt{prefix1}) is not None then it is used as a wrapper for printing elements of $G$ (resp. $H$). If \texttt{print_tuple} is True then elements are printed in the style $(g, h)$ and otherwise in the style $g * h$.

EXAMPLES:

```
sage: G = GL(2, QQ)
sage: V = QQ^2
sage: EV = GroupExp()(V)  # make a multiplicative version of V
sage: def twist(g,v):
....:     return EV(g*v.value)
```

```
sage: H = GroupSemidirectProduct(G, EV, twist=twist, prefix1 = 't'); H
Semidirect product of General Linear Group of degree 2 over Rational Field acting \longrightarrow on Multiplicative form of Vector space of dimension 2 over Rational Field
sage: x = H.an_element(); x
t[(1, 0)]
sage: x^2
t[(2, 0)]
sage: cartan_type = CartanType(['A',2])
sage: W = WeylGroup(cartan_type, prefix="s")
sage: def twist(w,v):
....:     return w*v*(~w)
```

```
sage: WW = GroupSemidirectProduct(W,W, twist=twist, print_tuple=True)
sage: s = Family(cartan_type.index_set(), lambda i: W.simple_reflection(i))
sage: y = WW((s[1],s[2])); y
(s1, s2)
sage: y^2
(1, s2*s1)
sage: y.inverse()
(s1, s1*s2*s1)
```

Todo:

- Functorial constructor for semidirect products for various categories
- Twofold Direct product as a special case of semidirect product
Element
alias of \texttt{GroupSemidirectProductElement}

\texttt{act\_to\_right}()

True if the left factor acts on the right factor and False if the right factor acts on the left factor.

\textbf{EXAMPLES:}

```
sage: def twist(x,y):
    ....: return y
sage: GroupSemidirectProduct(WeylGroup(['A',2],prefix="s"), WeylGroup(['A',3],
    prefix="t"),twist).act_to_right()
True
```

\texttt{group\_generators}()

Return generators of \texttt{self}.

\textbf{EXAMPLES:}

```
sage: twist = lambda x,y: y
sage: import __main__
sage: __main__.twist = twist
sage: EZ = GroupExp()(ZZ)
sage: GroupSemidirectProduct(EZ,EZ,twist,print_tuple=True).group_generators()
((1, 0), (0, 1))
```

\texttt{one}()

The identity element of the semidirect product group.

\textbf{EXAMPLES:}

```
sage: G = GL(2,QQ)
sage: V = QQ^2
sage: EV = GroupExp()(V) # make a multiplicative version of V
sage: def twist(g,v):
    ....: return EV(g*v.value)
sage: one = GroupSemidirectProduct(G, EV, twist=twist, prefix1 = 't').one();
    one
1
sage: one.cartesian_projection(0)
[1 0]
[0 1]
sage: one.cartesian_projection(1)
(0, 0)
```

\texttt{opposite\_semidirect\_product}()

Create the same semidirect product but with the positions of the groups exchanged.

\textbf{EXAMPLES:}

```
sage: G = GL(2,QQ)
sage: L = QQ^2
sage: EL = GroupExp()(L)
sage: H = GroupSemidirectProduct(G, EL, twist = lambda g,v: EL(g*v.value),
    prefix1 = 't'); H
Semidirect product of General Linear Group of degree 2 over Rational Field
acting on Multiplicative form of Vector space of dimension 2 over Rational Field
sage: h = H((Matrix([[0,1],[1,0]]), EL.an_element())); h
```

(continues on next page)
product \((x, y)\)

The product of elements \(x\) and \(y\) in the semidirect product group.

**EXAMPLES:**

```python
sage: G = GL(2, QQ)
sage: V = QQ^2
sage: EV = GroupExp()(V)  # make a multiplicative version of V
sage: def twist(g, v):
....:     return EV(g*v.value)

sage: S = GroupSemidirectProduct(G, EV, twist=twist, prefix1 = 't')

sage: def twist(w, v):
....:     return EV(w.action(v.value))

sage: G = GroupSemidirectProduct(W, EL, twist, prefix1='t')
```

**class** `sage.groups.group_semidirect_product.GroupSemidirectProductElement`

**Bases:** `sage.sets.cartesian_product.CartesianProduct.Element`

Element class for `GroupSemidirectProduct`.

**inverse()**

The inverse of self.

**EXAMPLES:**

```python
sage: L = RootSystem(['A',2]).root_lattice()
sage: from sage.groups.group_exp import GroupExp
sage: EL = GroupExp()(L)
sage: W = L.weyl_group(prefix="s")

sage: def twist(w, v):
....:     return EL(w.action(v.value))

sage: G = GroupSemidirectProduct(W, EL, twist, prefix1='t')
```

**to_opposite()**
Send an element to its image in the opposite semidirect product.

**EXAMPLES:**

```
sage: L = RootSystem(['A',2]).root_lattice(); L
Root lattice of the Root system of type ['A', 2]
sage: from sage.groups.group_exp import GroupExp
sage: EL = GroupExp()(L)
sage: W = L.weyl_group(prefix="s"); W
Weyl Group of type ['A', 2] (as a matrix group acting on the root lattice)
sage: def twist(w,v):
    ....: return EL(w.action(v.value))
sage: G = GroupSemidirectProduct(W, EL, twist, prefix1='t'); G
Semidirect product of Weyl Group of type ['A', 2] (as a matrix group acting on the root lattice) acting on Multiplicative form of Root lattice of the Root system of type ['A', 2]
sage: mu = L.an_element(); mu
sage: w = W.an_element(); w
s1*s2
sage: g = G((w,EL(mu))); g
s1*s2 * t[2*alpha[1] + 2*alpha[2]]
sage: g.to_opposite()
t[-2*alpha[1]] * s1*s2
sage: g.to_opposite().parent()
Semidirect product of Multiplicative form of Root lattice of the Root system of type ['A', 2] acted upon by Weyl Group of type ['A', 2] (as a matrix group acting on the root lattice)
```
MISCELLANEOUS GROUPS

This is a collection of groups that may not fit into some of the other infinite families described elsewhere.
The semimonomial transformation group of degree \( n \) over a ring \( R \) is the semidirect product of the monomial transformation group of degree \( n \) (also known as the complete monomial group over the group of units \( R^\times \) of \( R \)) and the group of ring automorphisms.

The multiplication of two elements \((\phi, \pi, \alpha)(\psi, \sigma, \beta)\) with
- \( \phi, \psi \in R^\times^n \)
- \( \pi, \sigma \in S_n \) (with the multiplication \( \pi \sigma \) done from left to right (like in GAP) – that is, \( (\pi \sigma)(i) = \sigma(\pi(i)) \) for all \( i \).)
- \( \alpha, \beta \in \text{Aut}(R) \)

is defined by

\[
(\phi, \pi, \alpha)(\psi, \sigma, \beta) = (\phi \cdot \psi^{\pi,\alpha}, \pi \sigma, \alpha \circ \beta)
\]

where \( \psi^{\pi,\alpha} = (\alpha(\psi_1), \ldots, \alpha(\psi_n)) \) and the multiplication of vectors is defined elementwisely. (The indexing of vectors is 0-based here, so \( \psi = (\psi_0, \psi_1, \ldots, \psi_n) \).)

**Todo:** Up to now, this group is only implemented for finite fields because of the limited support of automorphisms for arbitrary rings.

**AUTHORS:**
- Thomas Feulner (2012-11-15): initial version

**EXAMPLES:**

```python
sage: S = SemimonomialTransformationGroup(GF(4, 'a'), 4)
sage: G = S.gens()
sage: G[0]*G[1]
((a, 1, 1, 1); (1,2,3,4), Ring endomorphism of Finite Field in a of size 2^2
 Defn: a |--> a)
```

**class** `sage.groups.semmonomial_transformations.semmonomial_transformation_group.SemimonomialActionMat`

The left action of `SemimonomialTransformationGroup` on matrices over the same ring whose number of columns is equal to the degree. See `SemimonomialActionVec` for the definition of the action on the row vectors of such a matrix.
class sage.groups.semimonomial_transformations.semimonomial_transformation_group.SemimonomialActionVec(
    G, V, check=True)

Bases: sage.categories.action.Action

The natural left action of the semimonomial group on vectors.

The action is defined by:

\[(\phi, \pi, \alpha) \cdot (v_0, \ldots, v_{n-1}) := (\alpha(v_{\pi(1)-1}) \cdot \phi_0^{-1}, \ldots, \alpha(v_{\pi(n)-1}) \cdot \phi_{n-1}^{-1}).\]

(The indexing of vectors is 0-based here, so \(\psi = (\psi_0, \psi_1, \ldots, \psi_{n-1}).\))

class sage.groups.semimonomial_transformations.semimonomial_transformation_group.SemimonomialTransformationGroup(
    R, len)

Bases: sage.groups.group.FiniteGroup, sage.structure.unique_representation.UniqueRepresentation

A semimonomial transformation group over a ring.

The semimonomial transformation group of degree \(n\) over a ring \(R\) is the semidirect product of the monomial transformation group of degree \(n\) (also known as the complete monomial group over the group of units \(R^\times\) of \(R\)) and the group of ring automorphisms.

The multiplication of two elements \((\phi, \pi, \alpha)(\psi, \sigma, \beta)\) with

- \(\phi, \psi \in R^\times^n\)
- \(\pi, \sigma \in S_n\) (with the multiplication \(\pi \sigma\) done from left to right (like in GAP) – that is, \((\pi \sigma)(i) = \sigma(\pi(i))\) for all \(i\))
- \(\alpha, \beta \in \text{Aut}(R)\)

is defined by

\[(\phi, \pi, \alpha)(\psi, \sigma, \beta) = (\phi \cdot \psi^{\pi \circ \alpha}, \pi \sigma, \alpha \circ \beta)\]

where \(\psi^{\pi \circ \alpha} = (\alpha(\psi_{\pi(1)-1}), \ldots, \alpha(\psi_{\pi(n)-1}))\) and the multiplication of vectors is defined elementwisely. (The indexing of vectors is 0-based here, so \(\psi = (\psi_0, \psi_1, \ldots, \psi_{n-1}).\))

Todo: Up to now, this group is only implemented for finite fields because of the limited support of automorphisms for arbitrary rings.

EXAMPLES:

```python
sage: F.<a> = GF(9)
sage: S = SemimonomialTransformationGroup(F, 4)
sage: g = S(v = [2, a, 1, 2])
sage: h = S(perm = Permutation('(1,2,3,4)'), autom=F.hom([a**3]))
sage: g*h
(2, a, 1, 2); (1,2,3,4), Ring endomorphism of Finite Field in a of size 3^2
˓→ Defn: a |--> 2*a + 1)
sage: h*g
(2*a + 1, 1, 2, 2); (1,2,3,4), Ring endomorphism of Finite Field in a of size 3^ ˓→2 Defn: a |--> 2*a + 1)
sage: S(g)
(2, a, 1, 2); (), Ring endomorphism of Finite Field in a of size 3^2 Defn: a |--
˓→ a)
sage: S(1)
(1, 1, 1, 1); (), Ring endomorphism of Finite Field in a of size 3^2 Defn: a |--
˓→ a)
```
Element
alias of sage.groups.semimonomial_transformations.semimonomial_transformation.SemimonomialTransformation

base_ring()
Returns the underlying ring of self.

EXAMPLES:

```python
sage: F.<a> = GF(4)
sage: SemimonomialTransformationGroup(F, 3).base_ring() is F
True
```

degree()
Returns the degree of self.

EXAMPLES:

```python
sage: F.<a> = GF(4)
sage: SemimonomialTransformationGroup(F, 3).degree()
3
```

gens()
Return a tuple of generators of self.

EXAMPLES:

```python
sage: F.<a> = GF(4)
sage: SemimonomialTransformationGroup(F, 3).gens()
[((a, 1, 1); (), Ring endomorphism of Finite Field in a of size 2^2
    Defn: a |--> a), ((1, l, 1); (l,2,3), Ring endomorphism of Finite Field in
    a of size 2^2
    Defn: a |--> a), ((1, l, 1); (l,2), Ring endomorphism of Finite Field in a
    of size 2^2
    Defn: a |--> a), ((1, l, 1); (), Ring endomorphism of Finite Field in a
    of size 2^2
    Defn: a |--> a + 1)]
```

order()
Returns the number of elements of self.

EXAMPLES:

```python
sage: F.<a> = GF(4)
sage: SemimonomialTransformationGroup(F, 5).order() == (4-1)**5 * factorial(5) * 2
True
```
ELEMENTS OF A SEMIMONOMIAL TRANSFORMATION GROUP.

The semimonomial transformation group of degree $n$ over a ring $R$ is the semidirect product of the monomial transformation group of degree $n$ (also known as the complete monomial group over the group of units $R^\times$ of $R$) and the group of ring automorphisms.

The multiplication of two elements $(\phi, \pi, \alpha)(\psi, \sigma, \beta)$ with

- $\phi, \psi \in R^\times$\textsuperscript{n}
- $\pi, \sigma \in S_n$ (with the multiplication $\pi \sigma$ done from left to right (like in GAP) – that is, $(\pi \sigma)(i) = \sigma(\pi(i))$ for all $i$.)
- $\alpha, \beta \in Aut(R)$

is defined by

$$(\phi, \pi, \alpha)(\psi, \sigma, \beta) = (\phi \cdot \psi^{\pi, \alpha}, \pi \sigma, \alpha \circ \beta)$$

with $\psi^{\pi, \alpha} = (\alpha(\psi_{\pi(n)-1}), \ldots, \alpha(\psi_{\pi(1)-1}))$ and an elementwisely defined multiplication of vectors. (The indexing of vectors is 0-based here, so $\psi = (\psi_0, \psi_1, \ldots, \psi_{n-1})$.)

The parent is `SemimonomialTransformationGroup`.

AUTHORS:
- Thomas Feulner (2012-11-15): initial version
- Thomas Feulner (2013-12-27): trac ticket #15576 dissolve dependency on `Permutations.options.mul`

EXAMPLES:

```sage
sage: S = SemimonomialTransformationGroup(GF(4, 'a'), 4)
sage: G = S.gens()
sage: G[0]*G[1]
((a, 1, 1, 1); (1,2,3,4), Ring endomorphism of Finite Field in a of size 2^2
 Defn: a |--> a)
```

```sage
class sage.groups.semimonomial_transformations.semimonomial_transformation.SemimonomialTransformation

Bases: sage.structure.element.MultiplicativeGroupElement

An element in the semimonomial group over a ring $R$. See ` SemimonomialTransformationGroup` for the details on the multiplication of two elements.

The init method should never be called directly. Use the call via the parent `SemimonomialTransformationGroup` instead.

EXAMPLES:
```
sage: F.<a> = GF(9)
sage: S = SemimonomialTransformationGroup(F, 4)
sage: g = S(v = [2, a, 1, 2])
sage: h = S(perm = Permutation('(1,2,3,4)'), autom=F.hom([a**3]))
sage: g*h
((2, a, 1, 2); (1,2,3,4), Ring endomorphism of Finite Field in a of size 3^2
\rightarrow Defn: a |--> 2*a + 1)
sage: h*g
((2*a + 1, 1, 2, 2); (1,2,3,4), Ring endomorphism of Finite Field in a of size 3^\
2 Defn: a |--> 2*a + 1)
sage: S(g)
((2, a, 1, 2); (), Ring endomorphism of Finite Field in a of size 3^2 Defn: a |-->
\rightarrow a)
sage: S(1) # the one element in the group
((1, 1, 1, 1); (), Ring endomorphism of Finite Field in a of size 3^2 Defn: a |-->
\rightarrow a)

**get_autom()**

Returns the component corresponding to $Aut(R)$ of self.

**EXAMPLES:**

```
sage: F.<a> = GF(9)
sage: SemimonomialTransformationGroup(F, 4).an_element().get_autom()
Ring endomorphism of Finite Field in a of size 3^2 Defn: a |--> 2*a + 1
```

**get_perm()**

Returns the component corresponding to $S_n$ of self.

**EXAMPLES:**

```
sage: F.<a> = GF(9)
sage: SemimonomialTransformationGroup(F, 4).an_element().get_perm()
[4, 1, 2, 3]
```

**get_v()**

Returns the component corresponding to $R^{imes n}$ of self.

**EXAMPLES:**

```
sage: F.<a> = GF(9)
sage: SemimonomialTransformationGroup(F, 4).an_element().get_v()
(a, 1, 1, 1)
```

**get_v_inverse()**

Returns the (elementwise) inverse of the component corresponding to $R^{imes n}$ of self.

**EXAMPLES:**

```
sage: F.<a> = GF(9)
sage: SemimonomialTransformationGroup(F, 4).an_element().get_v_inverse()
(a + 2, 1, 1, 1)
```

**invert_v()**

Elementwisely invert all entries of `self` which correspond to the component $R^{imes n}$.

The other components of `self` keep unchanged.

**EXAMPLES:**
sage: F.<a> = GF(9)
sage: x = copy(SemimonomialTransformationGroup(F, 4).an_element())
sage: x.invert_v()
sage: x.get_v() == SemimonomialTransformationGroup(F, 4).an_element().get_v_
˓→inverse()
True
This module implements a wrapper of GAP’s ClassFunction function.

NOTE: The ordering of the columns of the character table of a group corresponds to the ordering of the list. However, in general there is no way to canonically list (or index) the conjugacy classes of a group. Therefore the ordering of the columns of the character table of a group is somewhat random.

AUTHORS:
- Franco Saliola (November 2008): initial version
- Volker Braun (October 2010): Bugfixes, exterior and symmetric power.

```python
sage.groups.class_function.ClassFunction(group, values)
```

Construct a class function.

**INPUT:**
- `group` – a group.
- `values` – list/tuple/iterable of numbers. The values of the class function on the conjugacy classes, in that order.

**EXAMPLES:**

```python
sage: G = CyclicPermutationGroup(4)
sage: G.conjugacy_classes()
[Conjugacy class of () in Cyclic group of order 4 as a permutation group,
 Conjugacy class of (1,2,3,4) in Cyclic group of order 4 as a permutation group,
 Conjugacy class of (1,3)(2,4) in Cyclic group of order 4 as a permutation group,
 Conjugacy class of (1,4,3,2) in Cyclic group of order 4 as a permutation group]
sage: values = [1, -1, 1, -1]
sage: chi = ClassFunction(G, values); chi
Character of Cyclic group of order 4 as a permutation group
```

```python
class sage.groups.class_function.ClassFunction_gap(G, values)
```

A wrapper of GAP’s ClassFunction function.

**Note:** It is not checked whether the given values describes a character, since GAP does not do this.

**EXAMPLES:**

```python
sage: G = CyclicPermutationGroup(4)
sage: values = [1, -1, 1, -1]
sage: chi = ClassFunction(G, values); chi
```
Character of Cyclic group of order 4 as a permutation group

sage: loads(dumps(chi)) == chi
True

adams_operation($k$)

Return the $k$-th Adams operation on self.

Let $G$ be a finite group. The $k$-th Adams operation $\Psi^k$ is given by

$$\Psi^k(\chi)(g) = \chi(g^k).$$

The Adams operations turn the representation ring of $G$ into a $\lambda$-ring.

EXAMPLES:

sage: G = groups.permutation.Alternating(5)
sage: chars = G.irreducible_characters()
sage: [chi.adams_operation(2).values() for chi in chars]
[[1, 1, 1, 1, 1],
 [3, 3, 0, -zeta5^3 - zeta5^2, zeta5^3 + zeta5^2 + 1],
 [3, 3, 0, zeta5^3 + zeta5^2 + 1, -zeta5^3 - zeta5^2],
 [4, 4, 1, -1, -1],
 [5, 5, -1, 0, 0]]
sage: chars[4].adams_operation(2).decompose()
((1, Character of Alternating group of order 5!/2 as a permutation group),
 (-1, Character of Alternating group of order 5!/2 as a permutation group),
 (-1, Character of Alternating group of order 5!/2 as a permutation group),
 (2, Character of Alternating group of order 5!/2 as a permutation group))

REFERENCES:

• Wikipedia article Adams_operation

central_character()

Returns the central character of self.

EXAMPLES:

sage: t = SymmetricGroup(4).trivial_character()
sage: t.central_character().values()
[1, 6, 3, 8, 6]

decompose()

Returns a list of the characters that appear in the decomposition of chi.

EXAMPLES:

sage: S5 = SymmetricGroup(5)
sage: chi = ClassFunction(S5, [22, -8, 2, 1, 1, 2, -3])
sage: chi.decompose()
((3, Character of Symmetric group of order 5! as a permutation group),
 (2, Character of Symmetric group of order 5! as a permutation group))

degree()

Returns the degree of the character self.

EXAMPLES:
sage: S5 = SymmetricGroup(5)
sage: irr = S5.irreducible_characters()
sage: [x.degree() for x in irr]
[1, 4, 5, 6, 5, 4, 1]

determinant_character()

    Returns the determinant character of self.

    EXAMPLES:

    sage: t = ClassFunction(SymmetricGroup(4), [1, -1, 1, 1, -1])
sage: t.determinant_character().values()
[1, -1, 1, 1, -1]

domain()

    Returns the domain of the self.

    OUTPUT:

    The underlying group of the class function.

    EXAMPLES:

    sage: ClassFunction(SymmetricGroup(4), [1,-1,1,1,-1]).domain()
Symmetric group of order 4! as a permutation group

exterior_power(n)

    Returns the anti-symmetrized product of self with itself n times.

    INPUT:

        • n – a positive integer.

    OUTPUT:

    The n-th anti-symmetrized power of self as a ClassFunction.

    EXAMPLES:

    sage: chi = ClassFunction(SymmetricGroup(4), [3, 1, -1, 0, -1])
sage: p = chi.exterior_power(3)     # the highest anti-symmetric power for a 3-
˓→d character
sage: p
Character of Symmetric group of order 4! as a permutation group
sage: p.values()
[1, -1, 1, 1, -1]
sage: p == chi.determinant_character()
True

induct(G)

    Return the induced character.

    INPUT:

        • G – A supergroup of the underlying group of self.

    OUTPUT:

    A ClassFunction of G defined by induction. Induction is the adjoint functor to restriction, see restrict().

    EXAMPLES:
sage: G = SymmetricGroup(5)
sage: H = G.subgroup([(1,2,3), (1,2), (4,5)])
sage: xi = H.trivial_character(); xi
Character of Subgroup generated by [(4,5), (1,2), (1,2,3)] of (Symmetric group of order 5! as a permutation group)
sage: xi.induct(G)
Character of Symmetric group of order 5! as a permutation group
sage: xi.induct(G).values()
[10, 4, 2, 1, 1, 0, 0]

irreducible_constituents()
Returns a list of the characters that appear in the decomposition of chi.

EXAMPLES:

sage: S5 = SymmetricGroup(5)
sage: chi = ClassFunction(S5, [22, -8, 2, 1, 1, 2, -3])
sage: irr = chi.irreducible_constituents(); irr
(Character of Symmetric group of order 5! as a permutation group,
Character of Symmetric group of order 5! as a permutation group)
sage: list(map(list, irr))
[[4, -2, 0, 1, 1, 0, -1], [5, -1, 1, -1, -1, 1, 0]]
sage: G = GL(2,3)
sage: chi = ClassFunction(G, [-1, -1, -1, -1, -1, -1, -1, -1])
sage: chi.irreducible_constituents()
(Character of General Linear Group of degree 2 over Finite Field of size 3,)
sage: chi = ClassFunction(G, [1, 1, 1, 1, 1, 1, 1, 1])
sage: chi.irreducible_constituents()
(Character of General Linear Group of degree 2 over Finite Field of size 3,)
sage: chi = ClassFunction(G, [2, 2, 2, 2, 2, 2, 2, 2])
sage: chi.irreducible_constituents()
(Character of General Linear Group of degree 2 over Finite Field of size 3,)
sage: chi = ClassFunction(G, [-1, -1, -1, -1, 3, -1, -1, 1])
sage: ic = chi.irreducible_constituents(); ic
(Character of General Linear Group of degree 2 over Finite Field of size 3,
Character of General Linear Group of degree 2 over Finite Field of size 3)
sage: list(map(list, ic))
[[2, -1, 2, -1, 2, 0, 0, 0], [3, 0, 3, 0, -1, 1, 1, -1]]

is_irreducible()
Returns True if self cannot be written as the sum of two nonzero characters of self.

EXAMPLES:

sage: S4 = SymmetricGroup(4)
sage: irr = S4.irreducible_characters()
sage: [x.is_irreducible() for x in irr]
[True, True, True, True, True]

norm()
Returns the norm of self.

EXAMPLES:

sage: A5 = AlternatingGroup(5)
sage: [x.norm() for x in A5.irreducible_characters()]
[1, 1, 1, 1, 1]
restrict \((H)\)
Return the restricted character.

INPUT:

• \(H\) – a subgroup of the underlying group of \(self\).

OUTPUT:

A \emph{ClassFunction} of \(H\) defined by restriction.

EXAMPLES:

\begin{verbatim}
sage: G = SymmetricGroup(5)
sage: chi = ClassFunction(G, [3, -3, -1, 0, 0, -1, 3]); chi
Character of Symmetric group of order 5! as a permutation group
sage: H = G.subgroup([(1,2,3), (1,2), (4,5)])
sage: chi.restrict(H)
Character of Subgroup generated by [(4,5), (1,2), (1,2,3)] of (Symmetric group of order 5! as a permutation group)
sage: chi.restrict(H).values()
[3, -3, -3, -1, 0, 0]
\end{verbatim}

scalar_product \((other)\)
Returns the scalar product of \(self\) with \(other\).

EXAMPLES:

\begin{verbatim}
sage: S4 = SymmetricGroup(4)
sage: irr = S4.irreducible_characters()
sage: [[x.scalar_product(y) for x in irr] for y in irr]
[[1, 0, 0, 0, 0],
 [0, 1, 0, 0, 0],
 [0, 0, 1, 0, 0],
 [0, 0, 0, 1, 0],
 [0, 0, 0, 0, 1]]
\end{verbatim}

symmetric_power \((n)\)
Returns the symmetrized product of \(self\) with itself \(n\) times.

INPUT:

• \(n\) – a positive integer.

OUTPUT:

The \(n\)-th symmetrized power of \(self\) as a \emph{ClassFunction}.

EXAMPLES:

\begin{verbatim}
sage: chi = ClassFunction(SymmetricGroup(4), [3, 1, -1, 0, -1])
sage: p = chi.symmetric_power(3)
sage: p
Character of Symmetric group of order 4! as a permutation group
sage: p.values()
[10, 2, -2, 1, 0]
\end{verbatim}

tensor_product \((other)\)
EXAMPLES:
values()

Return the list of values of self on the conjugacy classes.

EXAMPLES:

```python
sage: G = GL(2,3)
sage: [x.values() for x in G.irreducible_characters()] #random
[[1, 1, 1, 1, 1, 1, 1, 1],
 [1, 1, 1, 1, -1, -1, -1, -1],
 [2, -1, 2, -1, 2, 0, 0, 0],
 [2, 1, -2, -1, 0, -zeta8^3 - zeta8, zeta8^3 + zeta8, 0],
 [2, 1, -2, -1, 0, zeta8^3 + zeta8, -zeta8^3 - zeta8, 0],
 [3, 0, 3, 0, -1, -1, -1, 1],
 [3, 0, 3, 0, -1, 1, 1, -1],
 [4, -1, -4, 1, 0, 0, 0, 0]]
```

class sage.groups.class_function.ClassFunction_libgap(G, values)

Bases: sage.structure.sage_object.SageObject

A wrapper of GAP’s ClassFunction function.

Note: It is not checked whether the given values describes a character, since GAP does not do this.

EXAMPLES:

```python
sage: G = SO(3,3)
sage: values = [1, -1, -1, 1, 2]
sage: chi = ClassFunction(G, values); chi
Character of Special Orthogonal Group of degree 3 over Finite Field of size 3
sage: loads(dumps(chi)) == chi
True
```

adams_operation(k)

Return the k-th Adams operation on self.

Let G be a finite group. The k-th Adams operation \( \Psi^k \) is given by

\[
\Psi^k(\chi)(g) = \chi(g^k).
\]

The Adams operations turn the representation ring of G into a \( \lambda \)-ring.

EXAMPLES:

```python
sage: G = GL(2,3)
sage: chars = G.irreducible_characters()
sage: [chi.adams_operation(2).values() for chi in chars]
[[1, 1, 1, 1, 1, 1, 1, 1],
 [1, 1, 1, 1, -1, -1, -1, -1],
 [2, -1, 2, -1, 2, 0, 0, 0],
 [2, 1, -2, -1, 0, -zeta8^3 - zeta8, zeta8^3 + zeta8, 0],
 [2, 1, -2, -1, 0, zeta8^3 + zeta8, -zeta8^3 - zeta8, 0],
 [3, 0, 3, 0, -1, -1, -1, 1],
 [3, 0, 3, 0, -1, 1, 1, -1],
 [4, -1, -4, 1, 0, 0, 0, 0]]
```
sage: chars[5].adams_operation(3).decompose()
((1, Character of General Linear Group of degree 2 over Finite Field of size 3),
 (1, Character of General Linear Group of degree 2 over Finite Field of size 3),
 (-1, Character of General Linear Group of degree 2 over Finite Field of size 3),
 (1, Character of General Linear Group of degree 2 over Finite Field of size 3))

REFERENCES:
- Wikipedia article Adams_operation

central_character()
Return the central character of self.

EXAMPLES:

sage: t = SymmetricGroup(4).trivial_character()
sage: t.central_character().values()
[1, 6, 3, 8, 6]

decompose()
Return a list of the characters that appear in the decomposition of self.

EXAMPLES:

sage: S5 = SymmetricGroup(5)
sage: chi = ClassFunction(S5, [22, -8, 2, 1, 1, 2, -3])
sage: chi.decompose()
((3, Character of Symmetric group of order 5! as a permutation group),
 (2, Character of Symmetric group of order 5! as a permutation group))

degree()
Return the degree of the character self.

EXAMPLES:

sage: S5 = SymmetricGroup(5)
sage: irr = S5.irreducible_characters()
sage: [x.degree() for x in irr]
[1, 4, 5, 6, 5, 4, 1]

determinant_character()
Return the determinant character of self.

EXAMPLES:

sage: t = ClassFunction(SymmetricGroup(4), [1, -1, 1, 1, -1])
sage: t.determinant_character().values()
[1, -1, 1, 1, -1]

domain()
Return the domain of self.

OUTPUT:
The underlying group of the class function.

EXAMPLES:

```python
sage: ClassFunction(SymmetricGroup(4), [1,-1,1,1,-1]).domain()
Symmetric group of order 4! as a permutation group
```

**exterior_power**(n)

Return the anti-symmetrized product of self with itself n times.

**INPUT:**
- n – a positive integer

**OUTPUT:**

The n-th anti-symmetrized power of self as a `ClassFunction`.

**EXAMPLES:**

```python
sage: chi = ClassFunction(SymmetricGroup(4), [3, 1, -1, 0, -1])
sage: p = chi.exterior_power(3)  # the highest anti-symmetric power for a 3-d character
sage: p
Character of Symmetric group of order 4! as a permutation group
sage: p.values()
[1, -1, 1, 1, -1]
sage: p == chi.determinant_character()
True
```

**gap()**

Return the underlying LibGAP element.

**EXAMPLES:**

```python
sage: G = CyclicPermutationGroup(4)
sage: values = [1, -1, 1, -1]
sage: chi = ClassFunction(G, values); chi
Character of Cyclic group of order 4 as a permutation group
sage: type(chi)
<class 'sage.groups.class_function.ClassFunction_gap'>
sage: gap(chi)
ClassFunction( CharacterTable( Group( [ (1,2,3,4) ] ) ), [ 1, -1, 1, -1 ] )
sage: type(_)
<class 'sage.interfaces.gap.GapElement'>
```

**induct**(G)

Return the induced character.

**INPUT:**
- G – A supergroup of the underlying group of self.

**OUTPUT:**

A `ClassFunction` of G defined by induction. Induction is the adjoint functor to restriction, see `restrict()`.

**EXAMPLES:**
sage: G = SymmetricGroup(5)
sage: H = G.subgroup([(1,2,3), (1,2), (4,5)])
sage: xi = H.trivial_character(); xi
Character of Subgroup generated by [(4,5), (1,2), (1,2,3)] of (Symmetric group of order 5! as a permutation group)
sage: xi.induct(G)
Character of Symmetric group of order 5! as a permutation group
sage: xi.induct(G).values()
[10, 4, 2, 1, 1, 0, 0]

irreducible_constituents()

Return a list of the characters that appear in the decomposition of self.

EXAMPLES:

sage: S5 = SymmetricGroup(5)
sage: chi = ClassFunction(S5, [22, -8, 2, 1, 1, 2, -3])
sage: irr = chi.irreducible_constituents(); irr
(Character of Symmetric group of order 5! as a permutation group, Character of Symmetric group of order 5! as a permutation group)
sage: list(map(list, irr))
[[4, -2, 0, 1, 1, 0, -1], [5, -1, 1, -1, -1, 1, 0]]
sage: G = GL(2,3)
sage: chi = ClassFunction(G, [-1, -1, -1, -1, -1, -1, -1, -1])
sage: chi.irreducible_constituents()
(Character of General Linear Group of degree 2 over Finite Field of size 3,)
sage: chi = ClassFunction(G, [1, 1, 1, 1, 1, 1, 1, 1])
sage: chi.irreducible_constituents()
(Character of General Linear Group of degree 2 over Finite Field of size 3,)
sage: chi = ClassFunction(G, [2, 2, 2, 2, 2, 2, 2, 2])
sage: chi.irreducible_constituents()
(Character of General Linear Group of degree 2 over Finite Field of size 3,)
sage: chi = ClassFunction(G, [-1, -1, -1, -1, 3, -1, -1, 1])
sage: ic = chi.irreducible_constituents(); ic
(Character of General Linear Group of degree 2 over Finite Field of size 3, Character of General Linear Group of degree 2 over Finite Field of size 3)
sage: list(map(list, ic))
[[2, -1, 2, -1, 2, 0, 0, 0], [3, 0, 3, 0, -1, 1, 1, -1]]

is_irreducible()

Return True if self cannot be written as the sum of two nonzero characters of self.

EXAMPLES:

sage: S4 = SymmetricGroup(4)
sage: irr = S4.irreducible_characters()
sage: [x.is_irreducible() for x in irr]
[True, True, True, True, True]

norm()

Return the norm of self.

EXAMPLES:

sage: A5 = AlternatingGroup(5)
sage: [x.norm() for x in A5.irreducible_characters()]
[1, 1, 1, 1, 1]
restrict \((H)\)

Return the restricted character.

**INPUT:**

- \(H\) – a subgroup of the underlying group of \(self\).

**OUTPUT:**

A `ClassFunction` of \(H\) defined by restriction.

**EXAMPLES:**

```python
sage: G = SymmetricGroup(5)
sage: chi = ClassFunction(G, [3, -3, -1, 0, 0, -1, 3]); chi
Character of Symmetric group of order 5! as a permutation group
sage: H = G.subgroup([(1,2,3), (1,2), (4,5)])
sage: chi.restrict(H)
Character of Subgroup generated by [(4,5), (1,2), (1,2,3)] of (Symmetric group of order 5! as a permutation group)
sage: chi.restrict(H).values()
[3, -3, -3, -1, 0, 0]
```

**scalar_product** \((other)\)

Return the scalar product of \(self\) with \(other\).

**EXAMPLES:**

```python
sage: S4 = SymmetricGroup(4)
sage: irr = S4.irreducible_characters()
sage: [[x.scalar_product(y) for x in irr] for y in irr]
[[1, 0, 0, 0, 0],
 [0, 1, 0, 0, 0],
 [0, 0, 1, 0, 0],
 [0, 0, 0, 1, 0],
 [0, 0, 0, 0, 1]]
```

**symmetric_power** \((n)\)

Return the symmetrized product of \(self\) with itself \(n\) times.

**INPUT:**

- \(n\) – a positive integer

**OUTPUT:**

The \(n\)-th symmetrized power of \(self\) as a `ClassFunction`.

**EXAMPLES:**

```python
sage: chi = ClassFunction(SymmetricGroup(4), [3, 1, -1, 0, -1])
sage: p = chi.symmetric_power(3)
sage: p
Character of Symmetric group of order 4! as a permutation group
sage: p.values()
[10, 2, -2, 1, 0]
```

tensor_product **\((other)\)**

Return the tensor product of \(self\) and \(other\).

**EXAMPLES:**
```python
sage: S3 = SymmetricGroup(3)
sage: chi1, chi2, chi3 = S3.irreducible_characters()
sage: chi1.tensor_product(chi3).values()
[1, -1, 1]
```

The `values()` method returns the list of values of self on the conjugacy classes.

**EXAMPLES:**

```python
sage: G = GL(2,3)
sage: [x.values() for x in G.irreducible_characters()] # random
[[1, 1, 1, 1, 1, 1, 1, 1],
 [1, 1, 1, 1, -1, -1, -1, -1],
 [2, -1, 2, -1, 2, 0, 0, 0],
 [2, 1, -2, -1, 0, -zeta8^3 - zeta8, zeta8^3 + zeta8, 0],
 [2, 1, -2, -1, 0, zeta8^3 + zeta8, -zeta8^3 - zeta8, 0],
 [3, 0, 3, 0, -1, -1, -1, 1],
 [3, 0, 3, 0, -1, 1, 1, -1],
 [4, -1, -4, 1, 0, 0, 0, 0]]
```
CONJUGACY CLASSES OF GROUPS

This module implements a wrapper of GAP’s `ConjugacyClass` function.

There are two main classes, `ConjugacyClass` and `ConjugacyClassGAP`. All generic methods should go into `ConjugacyClass`, whereas `ConjugacyClassGAP` should only contain wrappers for GAP functions. `ConjugacyClass` contains some fallback methods in case some group cannot be defined as a GAP object.

Todo:

- Implement a non-naive fallback method for computing all the elements of the conjugacy class when the group is not defined in GAP, as the one in Butler’s paper.
- Define a sage method for gap matrices so that groups of matrices can use the quicker GAP algorithm rather than the naive one.

EXAMPLES:

Conjugacy classes for groups of permutations:

```sage
sage: G = SymmetricGroup(4)
sage: g = G((1,2,3,4))
sage: G.conjugacy_class(g)
Conjugacy class of cycle type [4] in Symmetric group of order 4! as a permutation
```

Conjugacy classes for groups of matrices:

```sage
sage: F = GF(5)
sage: gens = [matrix(F,2,[1,2, -1, 1]), matrix(F,2, [1,1, 0,1])]
sage: H = MatrixGroup(gens)
sage: h = H(matrix(F,2,[1,2, -1, 1]))
sage: H.conjugacy_class(h)
Conjugacy class of [1 2]
[4 1] in Matrix group over Finite Field of size 5 with 2 generators {
[1 2] [1 1]
[4 1], [0 1]
}
```

```python
class sage.groups.conjugacy_classes.ConjugacyClass(group, element)
    Bases: sage.structure.parent.Parent

    Generic conjugacy classes for elements in a group.

    This is the default fall-back implementation to be used whenever GAP cannot handle the group.

    EXAMPLES:
```
sage: G = SymmetricGroup(4)
sage: g = G((1,2,3,4))
sage: ConjugacyClass(G,g)
Conjugacy class of (1,2,3,4) in Symmetric group of order 4! as a permutation group

**an_element()**
Return a representative of self.

**EXAMPLES:**

```
sage: G = SymmetricGroup(3)
sage: g = G((1,2,3))
sage: C = ConjugacyClass(G,g)
sage: C.an_element()
(1,2,3)
```

**is_rational()**
Check if self is rational (closed for powers).

**EXAMPLES:**

```
sage: G = SymmetricGroup(4)
sage: g = G((1,2,3,4))
sage: c = ConjugacyClass(G,g)
sage: c.is_rational()
False
```

**is_real()**
Check if self is real (closed for inverses).

**EXAMPLES:**

```
sage: G = SymmetricGroup(4)
sage: g = G((1,2,3,4))
sage: c = ConjugacyClass(G,g)
sage: c.is_real()
True
```

**list()**
Return a list with all the elements of self.

**EXAMPLES:**

Groups of permutations:

```
sage: G = SymmetricGroup(3)
sage: g = G((1,2,3))
sage: c = ConjugacyClass(G,g)
sage: L = c.list()
sage: Set(L) == Set([G((1,3,2)), G((1,2,3))])
True
```

**representative()**
Return a representative of self.

**EXAMPLES:**

```
sage: G = SymmetricGroup(3)
sage: g = G((1,2,3))
sage: C = ConjugacyClass(G,g)
sage: C.representative()
    (1,2,3)

set()

Return the set of elements of the conjugacy class.

EXAMPLES:

Groups of permutations:

sage: G = SymmetricGroup(3)
sage: g = G((1,2))
sage: C = ConjugacyClass(G,g)
sage: S = [(2,3), (1,2), (1,3)]
sage: C.set() == Set(G(x) for x in S)
    True

Groups of matrices over finite fields:

sage: F = GF(5)
sage: gens = [matrix(F,2,[1,2, -1, 1]), matrix(F,2, [1,1, 0,1])]
sage: H = MatrixGroup(gens)
sage: h = H(matrix(F,2,[1,2, -1, 1]))
sage: C = ConjugacyClass(H,h)
sage: S = [
            [[3, 2], [2, 4]], [[0, 1], [2, 2]], [[3, 4], [1, 4]],
            [0, 3], [4, 2]], [[1, 2], [4, 1]], [[2, 1], [2, 0]],
            [4, 1], [4, 3]], [[4, 4], [1, 3]], [[2, 4], [3, 0]],
            [1, 4], [2, 1]], [[3, 3], [3, 4]], [[2, 3], [4, 0]],
            [0, 2], [1, 2]], [[1, 3], [1, 1]], [[4, 3], [3, 3]],
            [4, 2], [2, 3]], [[0, 4], [3, 2]], [[1, 1], [3, 1]],
            [2, 2], [1, 0]], [[3, 1], [4, 4]]
sage: C.set() == Set(H(x) for x in S)
    True

It is not implemented for infinite groups:

sage: a = matrix(ZZ,2,[1,1,0,1])
sage: b = matrix(ZZ,2,[1,0,1,1])
sage: G = MatrixGroup([a,b])  # takes Is
sage: g = G(a)
sage: C = ConjugacyClass(G, g)
sage: C.set()
Traceback (most recent call last):
  ... NotImplementedError: Listing the elements of conjugacy classes is not implemented for infinite groups! Use the iter function instead.

class sage.groups.conjugacy_classes.ConjugacyClassGAP (group, element)

Bases: sage.groups.conjugacy_classes.ConjugacyClass

Class for a conjugacy class for groups defined over GAP.

Intended for wrapping GAP methods on conjugacy classes.

INPUT:

  • group -- the group in which the conjugacy class is taken
• element – the element generating the conjugacy class

**EXAMPLES:**

```python
sage: G = SymmetricGroup(4)
sage: g = G((1,2,3,4))
sage: ConjugacyClassGAP(G,g)
Conjugacy class of (1,2,3,4) in Symmetric group of order 4! as a permutation group
```

**cardinality()**

Return the size of this conjugacy class.

**EXAMPLES:**

```python
sage: W = WeylGroup(['C',6])
sage: cc = W.conjugacy_class(W.an_element())
sage: cc.cardinality()
3840
sage: type(cc.cardinality())
<type 'sage.rings.integer.Integer'>
```

**set()**

Return a Sage Set with all the elements of the conjugacy class.

By default attempts to use GAP construction of the conjugacy class. If GAP method is not implemented for the given group, and the group is finite, falls back to a naive algorithm.

**Warning:** The naive algorithm can be really slow and memory intensive.

**EXAMPLES:**

Groups of permutations:

```python
sage: G = SymmetricGroup(4)
sage: g = G((1,2,3,4))
sage: C = ConjugacyClassGAP(G,g)
sage: S = [(1,3,2,4), (1,4,3,2), (1,3,4,2), (1,2,3,4), (1,4,2,3), (1,2,4,3)]
sage: C.set() == Set(G(x) for x in S)
True
```


23.1 Multiplicative Abelian Groups

This module lets you compute with finitely generated Abelian groups of the form

\[ G = \mathbb{Z}^r \oplus \mathbb{Z}_{k_1} \oplus \cdots \oplus \mathbb{Z}_{k_t} \]

It is customary to denote the infinite cyclic group \( \mathbb{Z} \) as having order 0, so the data defining the Abelian group can be written as an integer vector

\[ \vec{k} = (0, \ldots, 0, k_1, \ldots, k_t) \]

where there are \( r \) zeroes and \( t \) non-zero values. To construct this Abelian group in Sage, you can either specify all entries of \( \vec{k} \) or only the non-zero entries together with the total number of generators:

\begin{verbatim}
sage: AbelianGroup([0,0,0,2,3])
Multiplicative Abelian group isomorphic to Z x Z x Z x C2 x C3

sage: AbelianGroup(5, [2,3])
Multiplicative Abelian group isomorphic to Z x Z x Z x C2 x C3
\end{verbatim}

It is also legal to specify 1 as the order. The corresponding generator will be the neutral element, but it will still take up an index in the labelling of the generators:

\begin{verbatim}
sage: G = AbelianGroup([2,1,3], names='g')
sage: G.gens()
(g0, 1, g2)
\end{verbatim}

Note that this presentation is not unique, for example \( \mathbb{Z}_6 = \mathbb{Z}_2 \times \mathbb{Z}_3 \). The orders of the generators \( \vec{k} = (0, \ldots, 0, k_1, \ldots, k_t) \) has previously been called invariants in Sage, even though they are not necessarily the (unique) invariant factors of the group. You should now use \texttt{gens_orders()} instead:

\begin{verbatim}
sage: J = AbelianGroup([2,0,3,2,4]); J
Multiplicative Abelian group isomorphic to C2 x Z x C3 x C2 x C4

sage: J.gens_orders()       # use this instead
(2, 0, 3, 2, 4)
sage: J.invariants()       # deprecated
(2, 0, 3, 2, 4)
sage: J.elementary_divisors()  # these are the "invariant factors"
(2, 2, 12, 0)
sage: for i in range(J.ngens()):  
....:     print((i, J.gen(i), J.gen(i).order()))  # or use this form
(0, f0, 2)
(1, f1, +Infinity)
\end{verbatim}

(continues on next page)
Background on invariant factors and the Smith normal form (according to section 4.1 of [C1]): An abelian group is a group \( A \) for which there exists an exact sequence \( \mathbb{Z}^k \to \mathbb{Z}^\ell \to A \to 1 \), for some positive integers \( k, \ell \) with \( k \leq \ell \). For example, a finite abelian group has a decomposition

\[ A = \langle a_1 \rangle \times \cdots \times \langle a_\ell \rangle, \]

where \( \text{ord}(a_i) = p_i^{c_i} \), for some primes \( p_i \) and some positive integers \( c_i, i = 1, \ldots, \ell \). GAP calls the list (ordered by size) of the \( p_i^{c_i} \) the abelian invariants. In Sage they will be called invariants. In this situation, \( k = \ell \) and \( \phi : \mathbb{Z}^\ell \to A \) is the map \( \phi(x_1, \ldots, x_\ell) = a_1^{x_1} \cdots a_\ell^{x_\ell} \), for \( (x_1, \ldots, x_\ell) \in \mathbb{Z}^\ell \). The matrix of relations \( M : \mathbb{Z}^k \to \mathbb{Z}^\ell \) is the matrix whose rows generate the kernel of \( \phi \) as a \( \mathbb{Z} \)-module. In other words, \( M = (M_{ij}) \) is a \( \ell \times \ell \) diagonal matrix with \( M_{ii} = p_i^{c_i} \).

Consider now the subgroup \( B \subset A \) generated by \( b_1 = a_1^{f_{1,1}} \cdots a_\ell^{f_{1,\ell}}, \ldots, b_m = a_1^{f_{m,1}} \cdots a_\ell^{f_{m,\ell}} \). The kernel of the map \( \phi_B : \mathbb{Z}^m \to B \) defined by \( \phi_B(y_1, \ldots, y_m) = b_1^{y_1} \cdots b_m^{y_m} \), for \( (y_1, \ldots, y_m) \in \mathbb{Z}^m \), is the kernel of the matrix

\[
F = \begin{pmatrix}
    f_{11} & f_{12} & \cdots & f_{1m} \\
    f_{21} & f_{22} & \cdots & f_{2m} \\
    \vdots & \ddots & \vdots \\
    f_{\ell,1} & f_{\ell,2} & \cdots & f_{\ell,m}
\end{pmatrix},
\]

regarded as a map \( \mathbb{Z}^m \to (\mathbb{Z}/p_1^{c_1}\mathbb{Z}) \times \cdots \times (\mathbb{Z}/p_\ell^{c_\ell}\mathbb{Z}) \). In particular, \( B \cong \mathbb{Z}^m/\ker(F) \). If \( B = A \) then the Smith normal form (SNF) of a generator matrix of \( \ker(F) \) and the SNF of \( M \) are the same. The diagonal entries \( s_i \) of the SNF \( S = \text{diag}(s_1, s_2, s_3, \ldots, s_r, 0, 0, \ldots, 0) \), are called determinantal divisors of \( F \). where \( r \) is the rank. The \{it invariant factors\} of \( A \) are:

\[ s_1, s_2/s_1, s_3/s_2, \ldots, s_r/s_{r-1}. \]

Sage supports multiplicative abelian groups on any prescribed finite number \( n \geq 0 \) of generators. Use the \texttt{AbelianGroup()} function to create an abelian group, and the \texttt{gen()} and \texttt{gens()} methods to obtain the corresponding generators. You can print the generators as arbitrary strings using the optional \texttt{names} argument to the \texttt{AbelianGroup()} function.

**EXAMPLE 1:**

We create an abelian group in zero or more variables; the syntax \( T(1) \) creates the identity element even in the rank zero case:

```python
sage: T = AbelianGroup(0,[])
sage: T
Trivial Abelian group
sage: T.gens()
()  
sage: T(1)
1
```

**EXAMPLE 2:**

An Abelian group uses a multiplicative representation of elements, but the underlying representation is lists of integer exponents:

```python
sage: F = AbelianGroup(5,[3,4,5,5,7],names = list("abcde"))
sage: F
Multiplicative Abelian group isomorphic to C3 x C4 x C5 x C5 x C7
```
(continued from previous page)

```python
sage: (a,b,c,d,e) = F.gens()
sage: a*b^2*e*d
a*b^2*d*e
sage: x = b^2*e*d*a^7
sage: x
a*b^2*d*e
sage: x.list()
[1, 2, 0, 1, 1]
```

REFERENCES:


**Warning:** Many basic properties for infinite abelian groups are not implemented.

AUTHORS:

- William Stein, David Joyner (2008-12): added (user requested) is_cyclic, fixed elementary_divisors.
- David Joyner (2006-03): (based on free abelian monoids by David Kohel)
- David Joyner (2006-05) several significant bug fixes
- David Joyner (2006-08) trivial changes to docs, added random, fixed bug in how invariants are recorded
- David Joyner (2006-10) added dual_group method
- David Joyner (2008-02) fixed serious bug in word_problem
- David Joyner (2008-03) fixed bug in trivial group case
- David Loeffler (2009-05) added subgroups method

```python
sage.groups.abelian_gps.abelian_group.AbelianGroup(n, gens_orders=None, names='f')
```

Create the multiplicative abelian group in \( n \) generators with given orders of generators (which need not be prime powers).

**INPUT:**

- \( n \) – integer (optional). If not specified, will be derived from \( \text{gens_orders} \).
- **gens_orders** – a list of non-negative integers in the form \([a_0, a_1, \ldots, a_{n-1}]\), typically written in increasing order. This list is padded with zeros if it has length less than \( n \). The orders of the commuting generators, with 0 denoting an infinite cyclic factor.
- **names** – (optional) names of generators

Alternatively, you can also give input in the form `AbelianGroup(gens_orders, names="f")`, where the names keyword argument must be explicitly named.

**OUTPUT:**

Abelian group with generators and invariant type. The default name for generator \( A.i \) is \( fi \), as in GAP.

**EXAMPLES:**
```
sage: F = AbelianGroup(5, [5,5,7,8,9], names='abcde')
sage: F(1)
1
sage: (a, b, c, d, e) = F.gens()
sage: mul([ a, b, a, c, b, d, c, d, F(1)]
       a^2*b^2*c^2*d^2 e^3)
sage: d * b**2 * c^3
b^2*c^3*d
sage: F = AbelianGroup(3,[2]*3); F
Multiplicative Abelian group isomorphic to C2 x C2 x C2
sage: H = AbelianGroup([2,3], names="xy"); H
Multiplicative Abelian group isomorphic to C2 x C3
sage: AbelianGroup(5)
Multiplicative Abelian group isomorphic to Z x Z x Z x Z x Z
sage: AbelianGroup(5).order()
+Infinity
```

Notice that 0’s are prepended if necessary:

```
sage: G = AbelianGroup(5, [2,3,4]); G
Multiplicative Abelian group isomorphic to Z x Z x C2 x C3 x C4
sage: G.gens_orders()
(0, 0, 2, 3, 4)
```

The invariant list must not be longer than the number of generators:

```
sage: AbelianGroup(2, [2,3,4])
Traceback (most recent call last):
...
ValueError: gens_orders (=(2, 3, 4)) must have length n (=2)
```

```
class sage.groups.abelian_gps.abelian_group.AbelianGroup_class(generator_orders, names)
    Bases: sage.structure.unique_representation.UniqueRepresentation, sage.groups.group.AbelianGroup

The parent for Abelian groups with chosen generator orders.

**Warning:** You should use `AbelianGroup()` to construct Abelian groups and not instantiate this class directly.

**INPUT:**

- `names` – names of the group generators (optional).

**EXAMPLES:**

```
sage: Z2xZ3 = AbelianGroup([2,3])
sage: Z6 = AbelianGroup([6])
sage: Z2xZ3 is Z2xZ3, 26 is 26
(True, True)
sage: Z2xZ3 is 26
False
sage: Z2xZ3 == 26
```
```
Element

alias of \texttt{sage.groups.abelian_gps.abelian_group_element.AbelianGroupElement}

cardinality()

Return the order of this group.

**EXAMPLES:**

\begin{verbatim}
sage: G = AbelianGroup([2],[2,3])
sage: G.order()
6
sage: G = AbelianGroup([3],[2,3,0])
sage: G.order()
+Infinity
\end{verbatim}

dual_group\texttt{(names='X', base\_ring=None)}

Return the dual group.

**INPUT:**

- \texttt{names} – string or list of strings. The generator names for the dual group.
- \texttt{base\_ring} – the base ring. If \texttt{None} (default), then a suitable cyclotomic field is picked automatically.

**OUTPUT:**

The \texttt{~sage.groups.abelian_gps.dual_abelian_group.DualAbelianGroup_class}

**EXAMPLES:**

\begin{verbatim}
sage: G = AbelianGroup([2])
sage: G.dual_group()
Dual of Abelian Group isomorphic to Z/2Z over Cyclotomic Field of order 2 and degree 1
\end{verbatim}

\begin{verbatim}
sage: G.dual_group().gens()
(X,)
sage: G.dual_group(names='Z').gens()
(Z,)
sage: G.dual_group(base\_ring=QQ)
Dual of Abelian Group isomorphic to Z/2Z over Rational Field
\end{verbatim}

elementary_divisors()

This returns the elementary divisors of the group, using Pari.
Note: Here is another algorithm for computing the elementary divisors \( d_1, d_2, d_3, \ldots \), of a finite abelian group (where \( d_1 \mid d_2 \mid d_3 \mid \ldots \) are composed of prime powers dividing the invariants of the group in a way described below). Just factor the invariants \( a_i \) that define the abelian group. Then the biggest \( d_i \) is the product of the maximum prime powers dividing some \( a_j \). In other words, the largest \( d_i \) is the product of \( p^v \), where \( v = \max(\text{ord}_p(a_j) \text{forall} j) \). Now divide out all those \( p^v \)'s into the list of invariants \( a_i \), and get a new list of “smaller invariants”\( a' \). Repeat the above procedure on these “smaller invariants”\( a' \) to compute \( d_{i-1} \), and so on. (Thanks to Robert Miller for communicating this algorithm.)

OUTPUT:
A tuple of integers.

EXAMPLES:

```python
sage: G = AbelianGroup(2, [2, 3])
sage: G.elementary_divisors()
(6,)
sage: G = AbelianGroup(1, [6])
sage: G.elementary_divisors()
(6,)
sage: G = AbelianGroup(2, [2, 6])
sage: G
Multiplicative Abelian group isomorphic to C2 x C6
sage: G.gens_orders()
(2, 6)
sage: G.elementary_divisors()
(2, 6)
sage: J = AbelianGroup([1, 3, 5, 12])
sage: J.elementary_divisors()
(3, 60)
sage: G = AbelianGroup(2, [0, 6])
sage: G.elementary_divisors()
(6, 0)
sage: AbelianGroup([3, 4, 5]).elementary_divisors()
(60,)
```

**exponent()**
Return the exponent of this abelian group.

EXAMPLES:

```python
sage: G = AbelianGroup([2, 3, 7]); G
Multiplicative Abelian group isomorphic to C2 x C3 x C7
sage: G.exponent()
42
sage: G = AbelianGroup([2, 4, 6]); G
Multiplicative Abelian group isomorphic to C2 x C4 x C6
sage: G.exponent()
12
```

**gen(i=0)**
The \( i \)-th generator of the abelian group.

EXAMPLES:

```python
sage: F = AbelianGroup(5, [], names='a')
sage: F.gen(0)
```

(continues on next page)
a0
sage: F.2

a2
sage: F gens_orders()
(0, 0, 0, 0, 0)

sage: G = AbelianGroup([2,1,3])
sage: G gens()
(f0, 1, f2)

gens()  
Return the generators of the group.

OUTPUT:
A tuple of group elements. The generators according to the chosen \( \text{gens_orders}() \).

EXAMPLES:

sage: F = AbelianGroup(5,[3,2],names='abcde')
sage: F. gens()
(a, b, c, d, e)
sage: [ g.order() for g in F.gens() ]
[+Infinity, +Infinity, +Infinity, 3, 2]

gens_orders()  
Return the orders of the cyclic factors that this group has been defined with.

Use \( \text{elementary_divisors}() \) if you are looking for an invariant of the group.

OUTPUT:
A tuple of integers.

EXAMPLES:

sage: Z2xZ3 = AbelianGroup([2,3])
sage: Z2xZ3 gens_orders()
(2, 3)
sage: Z2xZ3. elementary_divisors()
(6, )
sage: Z6 = AbelianGroup([6])
sage: Z6 gens_orders()
(6, )
sage: Z6. elementary_divisors()
(6, )
sage: Z2xZ3 is_isomorphic(Z6)
True
sage: Z2xZ3 is 26
False

identity()  
Return the identity element of this group.

EXAMPLES:
sage: G = AbelianGroup([2,2])
sage: e = G.identity()
sage: e
1
sage: g = G.gen(0)
sage: g*e
f0
sage: e*g
f0

\textbf{invariants()}

Return the orders of the cyclic factors that this group has been defined with.

For historical reasons this has been called invariants in Sage, even though they are not necessarily the invariant factors of the group. Use \texttt{gens_orders()} instead:

\begin{verbatim}sage: J = AbelianGroup([2,0,3,2,4]); J
Multiplicative Abelian group isomorphic to C2 x Z x C3 x C2 x C4
sage: J.invariants() # deprecated
(2, 0, 3, 2, 4)
sage: J.gens_orders() # use this instead
(2, 0, 3, 2, 4)
sage: for i in range(J.ngens()):
   ....: print((i, J.gen(i), J.gen(i).order())) # or this
(0, f0, 2)
(1, f1, +Infinity)
(2, f2, 3)
(3, f3, 2)
(4, f4, 4)
\end{verbatim}

Use \texttt{elementary_divisors()} if you are looking for an invariant of the group.

\textbf{OUTPUT:}

A tuple of integers. Zero means infinite cyclic factor.

\textbf{EXAMPLES:}

\begin{verbatim}sage: J = AbelianGroup([2,3])
sage: J.invariants()
(2, 3)
sage: J.elementary_divisors()
(6,)
\end{verbatim}

\textbf{is_commutative()}

Return True since this group is commutative.

\textbf{EXAMPLES:}

\begin{verbatim}sage: G = AbelianGroup([2,3,5, 0])
sage: G.is_commutative()
True
sage: G.is_abelian()
True
\end{verbatim}

\textbf{is_cyclic()}

Return True if the group is a cyclic group.

\textbf{EXAMPLES:}
is_isomorphic(left, right)
Check whether left and right are isomorphic

INPUT:

* right – anything.

OUTPUT:
Boolean. Whether left and right are isomorphic as abelian groups.

EXAMPLES:

```sage
sage: G1 = AbelianGroup([2,3,4,5])
sage: G2 = AbelianGroup([2,3,4,5,1])
sage: G1.is_isomorphic(G2)
True
```

is_subgroup(left, right)
Test whether left is a subgroup of right.

EXAMPLES:
sage: G = AbelianGroup([2,3,4,5])
sage: G.is_subgroup(G)
True

sage: H = G.subgroup([G.1])
sage: H.is_subgroup(G)
True

sage: G.<a, b> = AbelianGroup(2)
sage: H.<c> = AbelianGroup(1)
sage: H < G
False

```
is_trivial()

Return whether the group is trivial

A group is trivial if it has precisely one element.

EXAMPLES:

```
sage: AbelianGroup([2, 3]).is_trivial()
False

sage: AbelianGroup([1, 1]).is_trivial()
True

```

```
list()

Return tuple of all elements of this group.

EXAMPLES:

```
sage: G = AbelianGroup([2,3], names = "ab")
sage: G.list()
(1, b, b^2, a, a*b, a*b^2)

sage: G = AbelianGroup([]); G
Trivial Abelian group
sage: G.list()
(1,)

```

```
gens()

The number of free generators of the abelian group.

EXAMPLES:

```
sage: F = AbelianGroup(10000)
sage: F.ngens()
10000

```

```
order()

Return the order of this group.

EXAMPLES:

```
sage: G = AbelianGroup(2,[2,3])
sage: G.order()
6

sage: G = AbelianGroup(3,[2,3,0])
sage: G.order()
Infinity

```

Chapter 23. Abelian Groups
**permutation_group()**

Return the permutation group isomorphic to this abelian group.

If the invariants are $q_1, \ldots, q_n$ then the generators of the permutation will be of order $q_1, \ldots, q_n$, respectively.

**EXAMPLES:**

```
sage: G = AbelianGroup(2, [2,3]); G
Multiplicative Abelian group isomorphic to C2 x C3
sage: G.permutation_group()
Permutation Group with generators [(3,4,5), (1,2)]
```

**random_element()**

Return a random element of this group.

**EXAMPLES:**

```
sage: G = AbelianGroup([2,3,9])
sage: G.random_element()
f1^2
```

**subgroup(gensH, names='f')**

Create a subgroup of this group. The “big” group must be defined using “named” generators.

**INPUT:**

- **gensH** – list of elements which are products of the generators of the ambient abelian group $G = self$

**EXAMPLES:**

```
sage: G.<a,b,c> = AbelianGroup(3, [2,3,4]); G
Multiplicative Abelian group isomorphic to C2 x C3 x C4
sage: H = G.subgroup([a*b,a]); H
Multiplicative Abelian subgroup isomorphic to C2 x C3 generated by {a*b, a}
sage: H < G
True
sage: F = G.subgroup([a,b^2])
sage: F
Multiplicative Abelian subgroup isomorphic to C2 x C3 generated by {a, b^2}
sage: F.gens()
(a, b^2)
sage: F = AbelianGroup(5,[30,64,729],names = list("abcde"))
sage: a,b,c,d,e = F.gens()
sage: F.subgroup([a,b])
Multiplicative Abelian subgroup isomorphic to Z x Z generated by {a, b}
sage: F.subgroup([c,e])
Multiplicative Abelian subgroup isomorphic to C2 x C3 x C5 x C729 generated by {c, e}
```

**subgroup_reduced(els, verbose=False)**

Given a list of lists of integers (corresponding to elements of self), find a set of independent generators for the subgroup generated by these elements, and return the subgroup with these as generators, forgetting the original generators.

This is used by the **subgroups** routine.

An error will be raised if the elements given are not linearly independent over QQ.

**EXAMPLES:**

## 23.1. Multiplicative Abelian Groups
sage: G = AbelianGroup([4,4])
sage: G.subgroup( [ G([1,0]), G([1,2]) ])
Multiplicative Abelian subgroup isomorphic to C2 x C4
generated by {f0, f0*f1^2}
sage: AbelianGroup([4,4]).subgroup_reduced( [ [1,0], [1,2] ])
Multiplicative Abelian subgroup isomorphic to C2 x C4
generated by {f1^2, f0}

subgroups (check=False)
Compute all the subgroups of this abelian group (which must be finite).

Todo: This is many orders of magnitude slower than Magma.

INPUT:

• check: if True, performs the same computation in GAP and checks that the number of subgroups generated is the same. (I don’t know how to convert GAP’s output back into Sage, so we don’t actually compare the subgroups).

ALGORITHM:

If the group is cyclic, the problem is easy. Otherwise, write it as a direct product A x B, where B is cyclic. Compute the subgroups of A (by recursion).

Now, for every subgroup C of A x B, let G be its projection onto A and H its intersection with B. Then there is a well-defined homomorphism f: G -> B/H that sends a in G to the class mod H of b, where (a,b) is any element of C lifting a; and every subgroup C arises from a unique triple (G, H, f).

EXAMPLES:

sage: AbelianGroup([2,3]).subgroups()
[Multiplicative Abelian subgroup isomorphic to C2 x C3 generated by {f0*f1^2},
 Multiplicative Abelian subgroup isomorphic to C2 generated by {f0},
 Multiplicative Abelian subgroup isomorphic to C3 generated by {f1},
 Trivial Abelian subgroup]
sage: len(AbelianGroup([2,4,8]).subgroups())
81

class sage.groups.abelian_gps.abelian_group.AbelianGroup_subgroup (ambient, gens, names='f')

Bases: sage.groups.abelian_gps.abelian_group.AbelianGroup_class

Subgroup subclass of AbelianGroup_class, so instance methods are inherited.

Todo: There should be a way to coerce an element of a subgroup into the ambient group.

ambient_group ()
Return the ambient group related to self.

OUTPUT:
A multiplicative Abelian group.

EXAMPLES:
sage: G.<a,b,c> = AbelianGroup([2,3,4])
sage: H = G.subgroup([a, b^2])
sage: H.ambient_group() is G
True

equals (left, right)
Check whether left and right are the same (sub)group.

INPUT:
- right – anything.

OUTPUT:
Boolean. If right is a subgroup, test whether left and right are the same subset of the ambient group. If right is not a subgroup, test whether they are isomorphic groups, see is_isomorphic().

EXAMPLES:

sage: G = AbelianGroup(3, [2,3,4], names="abc"); G
Multiplicative Abelian group isomorphic to C2 x C3 x C4
sage: a,b,c = G.gens()
sage: F = G.subgroup([a,b^2]); F
Multiplicative Abelian subgroup isomorphic to C2 x C3 generated by {a, b^2}
sage: F<G
True
sage: A = AbelianGroup(1, [6])
sage: A.subgroup(list(A.gens())) == A
True
sage: G.<a,b> = AbelianGroup(2)
sage: A = G.subgroup([a])
sage: B = G.subgroup([b])
sage: A.equals(B)
False
sage: A == B # same as A.equals(B)
False
sage: A.is_isomorphic(B)
True

gen (n)
Return the nth generator of this subgroup.

EXAMPLES:

sage: G.<a,b> = AbelianGroup(2)
sage: A = G.subgroup([a])
sage: A.gen(0)
a

gens ()
Return the generators for this subgroup.

OUTPUT:
A tuple of group elements generating the subgroup.

EXAMPLES:
sage: G.<a,b> = AbelianGroup(2)
sage: A = G.subgroup([a])
sage: G.gens()
(a, b)
sage: A.gens()
(a,)

```
sage.groups.abelian_gps.abelian_group.is_AbelianGroup(x)
Return True if x is an Abelian group.
```

EXAMPLES:

```
sage: from sage.groups.abelian_gps.abelian_group import is_AbelianGroup
sage: F = AbelianGroup(5,[5,5,7,8,9],names = list("abcde")); F
Multiplicative Abelian group isomorphic to C5 x C5 x C7 x C8 x C9
sage: is_AbelianGroup(F)
True
sage: is_AbelianGroup(AbelianGroup(7,[3]*7))
True
```

```
sage.groups.abelian_gps.abelian_group.word_problem(words, g, verbose=False)
G and H are abelian, g in G, H is a subgroup of G generated by a list (words) of elements of G. If g is in H, return the expression for g as a word in the elements of (words).

The ‘word problem’ for a finite abelian group G boils down to the following matrix-vector analog of the Chinese remainder theorem.

Problem: Fix integers $1 < n_1 \leq n_2 \leq \ldots \leq n_k$ (indeed, these $n_i$ will all be prime powers), fix a generating set $g_i = (a_{i1}, \ldots, a_{ik})$ (with $a_{ij} \in \mathbb{Z}/n_j\mathbb{Z}$), for $1 \leq i \leq \ell$, for the group G, and let $d = (d_1, \ldots, d_k)$ be an element of the direct product $\mathbb{Z}/n_1\mathbb{Z} \times \ldots \times \mathbb{Z}/n_k\mathbb{Z}$. Find, if they exist, integers $c_1, \ldots, c_\ell$ such that $c_1 g_1 + \ldots + c_\ell g_\ell = d$. In other words, solve the equation $cA = d$ for $c \in \mathbb{Z}^\ell$, where $A$ is the matrix whose rows are the $g_i$’s. Of course, it suffices to restrict the $c_i$’s to the range $0 \leq c_i \leq N-1$, where $N$ denotes the least common multiple of the integers $n_1, \ldots, n_k$.

This function does not solve this directly, as perhaps it should. Rather (for both speed and as a model for a similar function valid for more general groups), it pushes it over to GAP, which has optimized (non-deterministic) algorithms for the word problem. Essentially, this function is a wrapper for the GAP function ‘Factorization’.

EXAMPLES:

```
sage: G.<a,b,c> = AbelianGroup(3,[2,3,4]); G
Multiplicative Abelian group isomorphic to C2 x C3 x C4
sage: w = word_problem([a*b,a*c], b*c); w #random
[[a*b, 1], [a*c, 1]]
sage: prod([x^i for x,i in w]) == b*c
True
sage: w = word_problem([a*c,c],a); w #random
[[a*c, 1], [c, -1]]
sage: prod([x^i for x,i in w]) == a
True
sage: word_problem([a*c,c],a,verbose=True) #random
a = (a*c)^1*(c)^-1
[[a*c, 1], [c, -1]]
```

```
sage: A.<a,b,c,d,e> = AbelianGroup(5,[4, 5, 7, 8])
sage: b1 = a^3*b*c*d^2*e^5
sage: b2 = a^2*b*c^2*d^3*e^3
sage: b3 = a^7*b^3*c^5*d^4*e^4
```

(continues on next page)
23.2 Finitely generated abelian groups with GAP.

This module provides a python wrapper for abelian groups in GAP.

EXAMPLES:

```sage
sage: from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
sage: AbelianGroupGap([3,5])
Abelian group with gap, generator orders (3, 5)
```

For infinite abelian groups we use the GAP package Polycyclic:

```sage
sage: AbelianGroupGap([3,0])  # optional - gap_packages
Abelian group with gap, generator orders (3, 0)
```

AUTHORS:

- Simon Brandhorst (2018-01-17): initial version

```sage
class sage.groups.abelian_gps.abelian_group_gap.AbelianGroupElement_gap (parent, x, check=True)
Bases: sage.groups.libgap_wrapper.ElementLibGAP
```

An element of an abelian group via libgap.

EXAMPLES:

```sage
sage: from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
sage: G = AbelianGroupGap([3,6])
sage: G.gens()
(e1, e2)
```

`exponents()`

Return the tuple of exponents of this element.
OUTPUT:

- a tuple of integers

EXAMPLES:

```python
from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
G = AbelianGroupGap([4, 7, 9])
gens = G.gens()
g = gens[0]^2 * gens[1]^4 * gens[2]^8
g.exponents()
(2, 4, 8)
S = G.subgroup(G.gens()[:1])
s = S.gens()[0]
s.exponents()
(1,)
```

It can handle quite large groups too:

```python
G = AbelianGroupGap([2^10, 5^10])
f1, f2 = G.gens()
g = f1^123*f2^789
g.exponents()
(123, 789)
```

**Warning:** Crashes for very large groups.

**Todo:** Make exponents work for very large groups. This could be done by using Pcgs in gap.

```python
order()
```

Return the order of this element.

OUTPUT:

- an integer or infinity

EXAMPLES:

```python
from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
G = AbelianGroupGap([4])
g = G.gens()[0]
g.order()
4
G = AbelianGroupGap([0])
g.order()
+Infinity
```

```
class sage.groups.abelian_gps.abelian_group_gap.AbelianGroupElement_polycyclic (parent, x, check=True)

Bases: sage.groups.abelian_gps.abelian_group_gap.AbelianGroupElement_gap

An element of an abelian group using the GAP package Polycyclic.
```
exponents()  
Return the tuple of exponents of self.

OUTPUT:
• a tuple of integers

EXAMPLES:

```python
sage: from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
sage: G = AbelianGroupGap([4, 7, 0])  # optional - gap_packages
sage: gens = G.gens()  # optional - gap_packages
sage: g.exponents()  # optional - gap_packages
(2, 4, 8)
```

Efficiently handles very large groups:

```python
sage: G = AbelianGroupGap([2^30, 5^30, 0])  # optional - gap_packages
sage: f1, f2, f3 = G.gens()  # optional - gap_packages
sage: (f1^12345*f2^123456789).exponents()  # optional - gap_packages
(12345, 123456789, 0)
```

## AbelianGroupGap

**class** sage.groups.abelian_gps.abelian_group_gap.AbelianGroupGap(generator_orders)

**Bases:** sage.groups.abelian_gps.abelian_group_gap.AbelianGroup_gap

Abelian groups implemented using GAP.

**INPUT:**
• generator_orders – a list of nonnegative integers where 0 gives a factor isomorphic to \( \mathbb{Z} \)

**OUTPUT:**
• an abelian group

**EXAMPLES:**

```python
sage: from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
sage: AbelianGroupGap([3, 6])
Abelian group with gap, generator orders (3, 6)
```

**Warning:** Needs the GAP package Polycyclic in case the group is infinite.

## AbelianGroupSubgroup_gap

**class** sage.groups.abelian_gps.abelian_group_gap.AbelianGroupSubgroup_gap(ambient, gens)

**Bases:** sage.groups.abelian_gps.abelian_group_gap.AbelianGroup_gap

Subgroups of abelian groups with GAP.

**INPUT:**
• ambient – the ambient group
• gens – generators of the subgroup
Note: Do not construct this class directly. Instead use subgroup().

EXAMPLES:

```python
sage: from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
sage: G = AbelianGroupGap([2,3,4,5])
sage: gen = G.gens()[:2]
sage: S = G.subgroup(gen)
```

```python
class sage.groups.abelian_gps.abelian_group_gap.AbelianGroup_gap(G, category=None, ambient=None)
Bases: sage.structure.unique_representation.UniqueRepresentation, sage.groups.libgap_mixin.GroupMixinLibGAP, sage.groups.libgap_wrapper.ParentLibGAP, sage.groups.group.AbelianGroup

Finitely generated abelian groups implemented in GAP.

Needs the gap package Polycyclic in case the group is infinite.

INPUT:

• G – a GAP group
• category – a category
• ambient – (optional) an AbelianGroupGap

EXAMPLES:

```python
sage: from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
sage: G = AbelianGroupGap([3, 2, 5])
sage: G
Abelian group with gap, generator orders (3, 2, 5)
```
```
element alias of AbelianGroupElement_gap

all_subgroups()
Return the list of all subgroups of this group.

EXAMPLES:

```python
sage: from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
sage: G = AbelianGroupGap([2, 3])
sage: G.all_subgroups()
[Subgroup of Abelian group with gap, generator orders (2, 3) generated by (), Subgroup of Abelian group with gap, generator orders (2, 3) generated by (f1, →), Subgroup of Abelian group with gap, generator orders (2, 3) generated by (f2, →), Subgroup of Abelian group with gap, generator orders (2, 3) generated by (f2, → f1)]
```

aut()
Return the group of automorphisms of self.

EXAMPLES:
sage: from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
sage: G = AbelianGroupGap([2, 3])
sage: G.aut()
Full group of automorphisms of Abelian group with gap, generator orders (2, 3)

automorphism_group()
Return the group of automorphisms of self.

EXAMPLES:

sage: from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
sage: G = AbelianGroupGap([2, 3])
sage: G.aut()
Full group of automorphisms of Abelian group with gap, generator orders (2, 3)

elementary_divisors()
Return the elementary divisors of this group.

See sage.groups.abelian_gps.abelian_group_gap.elementary_divisors().

EXAMPLES:

sage: from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
sage: G = AbelianGroupGap([2,3,4,5])
sage: G.elementary_divisors()
(2, 60)

exponent()
Return the exponent of this abelian group.

EXAMPLES:

sage: from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
sage: G = AbelianGroupGap([2,3,7])
sage: G
Abelian group with gap, generator orders (2, 3, 7)
sage: G = AbelianGroupGap([2,4,6])
sage: G
Abelian group with gap, generator orders (2, 4, 6)
sage: G.exponent()
12

gens_orders()
Return the orders of the generators.

Use elementary_divisors() if you are looking for an invariant of the group.

OUTPUT:
• a tuple of integers

EXAMPLES:

sage: from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
sage: 2x2x3 = AbelianGroupGap([2,3])
sage: 2x2x3.gens_orders()
(2, 3)
sage: 2x2x3.elementary_divisors()
(6,)
sage: 26 = AbelianGroupGap([6])
sage: Z6.gens_orders()
(6,)
sage: Z6.elementary_divisors()
(6,)
sage: 2*Z2xZ3.is_isomorphic(Z6)
True
sage: 2*Z2xZ3 is Z6
False

identity()
Return the identity element of this group.

EXAMPLES:

```python
sage: from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
sage: G = AbelianGroupGap([4,10])
sage: G.identity()
1
```

is_subgroup_of(G)
Return if self is a subgroup of G considered in the same ambient group.

EXAMPLES:

```python
sage: from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
sage: G = AbelianGroupGap([2,3,4,5])
sage: gen = G.gens()[0:2]
sage: S1 = G.subgroup(gen)
sage: S1.is_subgroup_of(G)
True
sage: S2 = G.subgroup(G.gens()[1:])
sage: S2.is_subgroup_of(S1)
False
```

is_trivial()
Return True if this group is the trivial group.

EXAMPLES:

```python
sage: from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
sage: G = AbelianGroupGap([[]])
sage: G
Abelian group with gap, generator orders ()
sage: G.is_trivial()
True
sage: AbelianGroupGap([1]).is_trivial()
True
sage: AbelianGroupGap([1,1,1]).is_trivial()
True
sage: AbelianGroupGap([2]).is_trivial()
False
sage: AbelianGroupGap([2,1]).is_trivial()
False
```

subgroup(gens)
Return the subgroup of this group generated by gens.

INPUT:
• gens – a list of elements coercible into this group

OUTPUT:

• a subgroup

EXAMPLES:

```
sage: from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
sage: G = AbelianGroupGap([2,3,4,5])
sage: gen = G.gens()[:2]
sage: S = G.subgroup(gen)
sage: S
Subgroup of Abelian group with gap, generator orders (2, 3, 4, 5) generated by (f1, f2)
sage: g = G.an_element()
sage: s = S.an_element()
sage: g * s
f2^2*f3*f5
sage: G = AbelianGroupGap([3,4,0,2])  # optional - gap_packages
sage: gen = G.gens()[:2]  # optional - gap_packages
sage: S = G.subgroup(gen)  # optional - gap_packages
sage: g = G.an_element()  # optional - gap_packages
sage: s = S.an_element()  # optional - gap_packages
sage: g * s  # optional - gap_packages
g1^2*g2^2*g3*g4
```

23.3 Automorphisms of abelian groups

This implements groups of automorphisms of abelian groups.

EXAMPLES:

```
sage: from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
sage: G = AbelianGroupGap([2,6])
sage: autG = G.aut()

Automorphisms act on the elements of the domain:

sage: g = G.an_element()
sage: f = autG.an_element()
sage: f
Pcgs([ f1, f2, f3 ]) -> [ f1, f1*f2*f3^2, f3^2 ]
sage: (g, f(g))
(f1*f2, f2*f3^2)
```

Or anything coercible into its domain:

```
sage: A = AbelianGroup([2,6])
sage: a = A.an_element()
sage: (a, f(a))
(f0*f1, f2*f3^2)
sage: A = AdditiveAbelianGroup([2,6])
sage: a = A.an_element()
sage: (a, f(a))
((1, 0), f1)
```

(continues on next page)
We can compute conjugacy classes:

```
sage: autG.conjugacy_classes_representatives()
```

```
(1, Pcgs([ f1, f2, f3 ]) -> [ f2*f3, f1*f2, f3 ],
 Pcgs([ f1, f2, f3 ]) -> [ f1*f2*f3, f2*f3^2, f3^2 ],
 [ f3^2, f1*f2*f3, f1 ] -> [ f3^2, f1, f1*f2*f3 ],
 Pcgs([ f1, f2, f3 ]) -> [ f2*f3, f1*f2*f3^2, f3^2 ],
 [ f1*f2*f3, f1, f3^2 ] -> [ f1*f2*f3, f1, f3 ])}
```

the group order:

```
sage: autG.order()
```

```
12
```

or create subgroups and do the same for them:

```
sage: S = autG.subgroup(autG.gens()[:1])
sage: S
```

Subgroup of automorphisms of Abelian group with gap, generator orders (2, 6)

Only automorphism groups of finite abelian groups are supported:

```
sage: G = AbelianGroupGap([0,2])  # optional gap_packages
sage: autG = G.aut()  # optional gap_packages
```

Traceback (most recent call last):
...
ValueError: only finite abelian groups are supported

AUTHORS:

- Simon Brandhorst (2018-02-17): initial version

```
class sage.groups.abelian_gps.abelian_aut.AbelianGroupAutomorphism(parent, x,
check=True)
```

Automorphisms of abelian groups with gap.

INPUT:

- \(x\) – a libgap element
- \(\text{parent}\) – the parent \texttt{AbelianGroupAutomorphismGroup} gap
- \(\text{check}\) – bool (default: True) checks if \(x\) is an element of the group

EXAMPLES:

```
sage: from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
sage: G = AbelianGroupGap([2,3,4,5])
sage: F = G.aut().an_element()
```

```
matrix()
```

Return the matrix defining \(self\).
The $i$-th row is the exponent vector of the image of the $i$-th generator.

**OUTPUT:**
- a square matrix over the integers

**EXAMPLES:**

```python
sage: from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
sage: G = AbelianGroupGap([2,3,4])
sage: f = G.aut().an_element()
sage: f
Pcgs([ f1, f2, f3, f4 ]) -> [ f1*f4, f2^2, f1*f3, f4 ]
sage: f.matrix()
[1 0 2]
[0 2 0]
[1 0 1]
```

Compare with the exponents of the images:

```python
sage: f(G.gens()[0]).exponents()
(1, 0, 2)
sage: f(G.gens()[1]).exponents()
(0, 2, 0)
sage: f(G.gens()[2]).exponents()
(1, 0, 1)
```

**class** `sage.groups.abelian_gps.abelian_aut.AbelianGroupAutomorphismGroup(AbelianGroupGap)`

Bases: `sage.groups.abelian_gps.abelian_aut.AbelianGroupAutomorphismGroup_gap`

The full automorphism group of a finite abelian group.

**INPUT:**
- `AbelianGroupGap` – an instance of `AbelianGroup_gap`

**EXAMPLES:**

```python
sage: from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
sage: from sage.groups.abelian_gps.abelian_aut import AbelianGroupAutomorphismGroup
sage: G = AbelianGroupGap([2,3,4,5])
sage: aut = G.aut()
sage: aut1 = AbelianGroupAutomorphismGroup(G)
sage: aut is aut1
True
```

Equivalently:

```python
sage: aut1 = AbelianGroupAutomorphismGroup(G)
sage: aut is aut1
True
```

**Element**

alias of `AbelianGroupAutomorphism`

**class** `sage.groups.abelian_gps.abelian_aut.AbelianGroupAutomorphismGroup_gap(domain, gap_group, category, ambient=None)`
Bases:  
sage.structure.unique_representation.UniqueRepresentation,  
sage.groups.libgap_mixin.GroupMixinLibGAP,  
sage.groups.group.Group,  
sage.groups.libgap_wrapper.ParentLibGAP

Base class for groups of automorphisms of abelian groups.
Do not construct this directly.

INPUT:

• domain – AbelianGroup_gap

• libgap_parent – the libgap element that is the parent in GAP

• category – a category

• ambient – an instance of a derived class of ParentLibGAP or None (default); the ambient group if libgap_parent has been defined as a subgroup

EXAMPLES:

```python
sage: from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
sage: domain = AbelianGroupGap([2,3,4,5])
sage: aut = domain.gap().AutomorphismGroupAbelianGroup()
sage: AbelianGroupAutomorphismGroup_gap(domain, aut, Groups().Finite())
<group with 6 generators>
```

Element

alias of AbelianGroupAutomorphism

covering_matrix_ring()

Return the covering matrix ring of this group.

This is the ring of \(n \times n\) matrices over \(\mathbb{Z}\) where \(n\) is the number of (independent) generators.

EXAMPLES:

```python
sage: G = AbelianGroupGap([2,3,4,5])
sage: aut = G.aut()
sage: aut.covering_matrix_ring()
Full MatrixSpace of 4 by 4 dense matrices over Integer Ring
```

domain()

Return the domain of this group of automorphisms.

EXAMPLES:

```python
sage: G = AbelianGroupGap([2,3,4,5])
sage: aut = G.aut()
sage: aut.domain()
```

is_subgroup_of(G)

Return if self is a subgroup of G considered in the same ambient group.

EXAMPLES:
```python
sage: from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
sage: G = AbelianGroupGap([2,3,4,5])
sage: aut = G.aut()
sage: gen = aut.gens()
```

```python
sage: S1 = aut.subgroup(gen[:2])
sage: S1.is_subgroup_of(aut)
True
sage: S2 = aut.subgroup(aut.gens()[1:])
sage: S2.is_subgroup_of(S1)
False
```

```python
class sage.groups.abelian_gps.abelian_aut.AbelianGroupAutomorphismGroup_subgroup(ambient, generators)

Bases: sage.groups.abelian_gps.abelian_aut.AbelianGroupAutomorphismGroup_gap

Groups of automorphisms of abelian groups.

They are subgroups of the full automorphism group.

Note: Do not construct this class directly; instead use sage.groups.abelian_gps.abelian_group_gap.AbelianGroup_gap.subgroup().

```
```

INPUT:

- ambient – the ambient group
- generators – a tuple of gap elements of the ambient group

EXAMPLES:

```python
sage: from sage.groups.abelian_gps.abelian_group_gap import AbelianGroupGap
sage: from sage.groups.abelian_gps.abelian_aut import AbelianGroupAutomorphismGroup_subgroup
sage: G = AbelianGroupGap([2,3,4,5])
sage: aut = G.aut()
sage: gen = aut.gens()
sage: AbelianGroupAutomorphismGroup_subgroup(aut, gen)
Subgroup of automorphisms of Abelian group with gap, generator orders (2, 3, 4, 5)
generated by 6 automorphisms

Element

alias of AbelianGroupAutomorphism
```

## 23.4 Multiplicative Abelian Groups With Values

Often, one ends up with a set that forms an Abelian group. It would be nice if one could return an Abelian group class to encapsulate the data. However, AbelianGroup() is an abstract Abelian group defined by generators and relations. This module implements AbelianGroupWithValues that allows the group elements to be decorated with values.

An example where this module is used is the unit group of a number field, see sage.rings.number_field.unit_group. The units form a finitely generated Abelian group. We can think of the elements either as abstract
Abelian group elements or as particular numbers in the number field. The `AbelianGroupWithValues()` keeps track of these associated values.

**Warning:** Really, this requires a group homomorphism from the abstract Abelian group to the set of values. This is only checked if you pass the `check=True` option to `AbelianGroupWithValues()`.

**EXAMPLES:**

Here is \( \mathbb{Z}_6 \) with value \(-1\) assigned to the generator:

```python
sage: Z6 = AbelianGroupWithValues([-1], [6], names='g')
sage: g = Z6.gen(0)
sage: g.value()
-1
sage: g^2
1
sage: for i in range(7):
    ....: print((i, g^i, (g^i).value()))
(0, 1, 1)
(1, g, -1)
(2, g^2, 1)
(3, g^3, -1)
(4, g^4, 1)
(5, g^5, -1)
(6, 1, 1)
```

The elements come with a coercion embedding into the `values_group()`, so you can use the group elements instead of the values:

```python
sage: CF3.<zeta> = CyclotomicField(3)
sage: Z3.<g> = AbelianGroupWithValues([zeta], [3])
sage: Z3.values_group()
Cyclotomic Field of order 3 and degree 2
sage: g.value()
zeta
sage: CF3(g)
zeta
sage: g + zeta
2*zeta
sage: zeta + g
2*zeta
```

Construct an Abelian group with values associated to the generators.

**INPUT:**

- `values` – a list/tuple/iterable of values that you want to associate to the generators.
- `n` – integer (optional). If not specified, will be derived from `gens_orders`.
- `gens_orders` – a list of non-negative integers in the form \([a_0, a_1, \ldots, a_{n-1}]\), typically written in increasing order. This list is padded with zeros if it has length less than \(n\). The orders of the commuting generators, with \(0\) denoting an infinite cyclic factor.
• names – (optional) names of generators

• values_group – a parent or None (default). The common parent of the values. This might be a group, but can also just contain the values. For example, if the values are units in a ring then the values_group would be the whole ring. If None it will be derived from the values.

EXAMPLES:

```python
sage: G = AbelianGroupWithValues([-1], [6])
```

```python
g = G.gen(0)
```

```python
for i in range(7):
    print((i, g^i, (g^i).value()))
```

```
(0, 1, 1)
(1, f, -1)
(2, f^2, 1)
(3, f^3, -1)
(4, f^4, 1)
(5, f^5, -1)
(6, 1, 1)
```

```python
sage: G.values_group()
```

```
Integer Ring
```

The group elements come with a coercion embedding into the values_group(), so you can use them like their value()

```python
sage: G.values_embedding()
```

```
Generic morphism:
  From: Multiplicative Abelian group isomorphic to C6
  To:   Integer Ring
```

```python
g.value()
```

```
-1
```

```python
0 + g
```

```
-1
```

```python
1 + 2*g
```

```
-1
```

```python
class sage.groups.abelian_gps.values.AbelianGroupWithValuesElement
    Bases: sage.groups.abelian_gps.abelian_group_element.AbelianGroupElement

An element of an Abelian group with values assigned to generators.

INPUT:

• exponents – tuple of integers. The exponent vector defining the group element.

• parent – the parent.

• value – the value assigned to the group element or None (default). In the latter case, the value is computed as needed.

EXAMPLES:

```python
sage: F = AbelianGroupWithValues([1,-1], [2,4])
```

```python
a,b = F.gens()
```

```python
TestSuite(a+b).run()
```

```python
inverse()
```

Return the inverse element.

EXAMPLES:
sage: G.<a,b> = AbelianGroupWithValues([2,-1], [0,4])

sage: a.inverse()

a^-1

sage: a.inverse().value()

1/2

sage: a.__invert__().value()

1/2

sage: (~a).value()

1/2

sage: (a*b).value()

-2

sage: (a*b).inverse().value()

-1/2

value()

Return the value of the group element.

OUTPUT:

The value according to the values for generators, see gens_values().

EXAMPLES:

sage: G = AbelianGroupWithValues([5], 1)

sage: G.0.value()

5

class sage.groups.abelian_gps.values.AbelianGroupWithValuesEmbedding(domain, codomain)

Bases: sage.categories.morphism.Morphism

The morphism embedding the Abelian group with values in its values group.

INPUT:

- domain – a [AbelianGroupWithValues_class]

- codomain – the values group (need not be in the category of groups, e.g. symbolic ring).

EXAMPLES:

sage: Z4.<g> = AbelianGroupWithValues([I], [4])

sage: embedding = Z4.values_embedding(); embedding

Generic morphism:

  From: Multiplicative Abelian group isomorphic to C4
  To: Symbolic Ring

sage: embedding(l)

1

sage: embedding(g)

I

sage: embedding(g^2)

-1

class sage.groups.abelian_gps.values.AbelianGroupWithValues_class(generator_orders, names, values, values_group)

Bases: sage.groups.abelian_gps.abelian_group.AbelianGroup_class

The class of an Abelian group with values associated to the generator.

INPUT:
• generator_orders – tuple of integers. The orders of the generators.
• names – string or list of strings. The names for the generators.
• values – Tuple the same length as the number of generators. The values assigned to the generators.
• values_group – the common parent of the values.

EXAMPLES:

```python
sage: G.<a,b> = AbelianGroupWithValues([2,-1], [0,4])
sage: TestSuite(G).run()
```

Element

alias of `AbelianGroupWithValuesElement`

`gen(i=0)`
The `i`-th generator of the abelian group.

**INPUT:**

• `i` – integer (default: 0). The index of the generator.

**OUTPUT:**

A group element.

**EXAMPLES:**

```python
sage: F = AbelianGroupWithValues([1,2,3,4,5], 5,[],names='a')
sage: F.0
a0
sage: F.0.value()
1
sage: F.2
a2
sage: F.2.value()
3
sage: G = AbelianGroupWithValues([-1,0,1], [2,1,3])
sage: G.gens()
(f0, 1, f2)
```

gens_values()

Return the values associated to the generators.

**OUTPUT:**

A tuple.

**EXAMPLES:**

```python
sage: G = AbelianGroupWithValues([-1,0,1], [2,1,3])
sage: G.gens_values()
(-1, 0, 1)
```

values_embedding()

Return the embedding of `self` in `values_group()`.

**OUTPUT:**

A morphism.
EXAMPLES:

```
sage: Z4 = AbelianGroupWithValues([I], [4])
sage: Z4.values_embedding()
Generic morphism:
  From: Multiplicative Abelian group isomorphic to C4
  To:  Symbolic Ring

values_group()

The common parent of the values.

The values need to form a multiplicative group, but can be embedded in a larger structure. For example, if
the values are units in a ring then the values_group() would be the whole ring.

OUTPUT:

The common parent of the values, containing the group generated by all values.

EXAMPLES:

```
sage: G = AbelianGroupWithValues([-1,0,1], [2,1,3])
sage: G.values_group()
Integer Ring

sage: Z4 = AbelianGroupWithValues([I], [4])
sage: Z4.values_group()
Symbolic Ring
```

### 23.5 Dual groups of Finite Multiplicative Abelian Groups

The basic idea is very simple. Let $G$ be an abelian group and $G^*$ its dual (i.e., the group of homomorphisms from $G$ to $\mathbb{C}^\times$). Let $g_j, j = 1, \ldots, n$, denote generators of $G^*$ say $g_j$ is of order $m_j > 1$. There are generators $X_j, j = 1, \ldots, n,$ of $G^*$ for which $X_j(g_j) = \exp(2\pi i/m_j)$ and $X_i(g_j) = 1$ if $i \neq j$. These are used to construct $G^*$.

Sage supports multiplicative abelian groups on any prescribed finite number $n > 0$ of generators. Use `AbelianGroup()` function to create an abelian group, the dual_group() method to create its dual, and then the gen() and gens() methods to obtain the corresponding generators. You can print the generators as arbitrary strings using the optional names argument to the dual_group() method.

EXAMPLES:

```
sage: F = AbelianGroup(5, [2,5,7,8,9], names='abcde')
sage: (a, b, c, d, e) = F.gens()
sage: Fd = F.dual_group(names='ABCDE')
sage: Fd.base_ring()
Cyclotomic Field of order 2520 and degree 576
sage: A,B,C,D,E = Fd.gens()
sage: A(a)
-1
sage: A(b), A(c), A(d), A(e)
(1, 1, 1, 1)
sage: Fd = F.dual_group(names='ABCDE', base_ring=CC)
sage: A,B,C,D,E = Fd.gens()
sage: A(a)  # abs tol 1e-8
-1.00000000000000 + 0.000000000000000*I
```

(continues on next page)
AUTHORS:

- David Joyner (2006-08) (based on abelian_groups)
- David Joyner (2006-10) modifications suggested by William Stein

class sage.groups.abelian_gps.dual_abelian_group.DualAbelianGroup_class(G, names, base_ring)

Bases: sage.structure.unique_representation.UniqueRepresentation, sage.groups.group.AbelianGroup

Dual of abelian group.

EXAMPLES:

```sage
sage: F = AbelianGroup(5,[3,5,7,8,9], names="abcde")
sage: F.dual_group()
Dual of Abelian Group isomorphic to Z/3Z x Z/5Z x Z/7Z x Z/8Z x Z/9Z over Cyclotomic Field of order 2520 and degree 576
sage: F = AbelianGroup(4,[15,7,8,9], names="abcd")
sage: F.dual_group(base_ring=CC)
Dual of Abelian Group isomorphic to Z/15Z x Z/7Z x Z/8Z x Z/9Z over Complex Field with 53 bits of precision
```

Element alias of sage.groups.abelian_gps.dual_abelian_group_element.DualAbelianGroupElement

base_ring()
Return the scalars over which the group is dualized.

EXAMPLES:

```sage
sage: F = AbelianGroup(3,[5,64,729], names=list("abc"))
sage: Fd = F.dual_group(base_ring=CC)
sage: Fd.base_ring()
Complex Field with 53 bits of precision
```

gen(i=0)
The i-th generator of the abelian group.

EXAMPLES:

```sage
sage: F = AbelianGroup(3,[1,2,3],names='a')
sage: Fd = F.dual_group(names='A')
sage: Fd.0
1
sage: Fd.1
A1
sage: Fd.gens_orders()
(1, 2, 3)
```
**gens()**

Return the generators for the group.

**OUTPUT:**

A tuple of group elements generating the group.

**EXAMPLES:**

```sage
def main():
    F = AbelianGroup([7,11]).dual_group()
    print(F.gens())
main()
```

```
(X0, X1)
```

**gens_orders()**

The orders of the generators of the dual group.

**OUTPUT:**

A tuple of integers.

**EXAMPLES:**

```sage
def main():
    F = AbelianGroup([5]*1000)
    Fd = F.dual_group()
    print(Fd.gens_orders())
    print(len(Fd.gens_orders()))
main()
```

```
(1000,)
1000
```

**group()**

Return the group that self is the dual of.

**EXAMPLES:**

```sage
def main():
    F = AbelianGroup(3,[5,64,729], names=list("abc"))
    Fd = F.dual_group(base_ring=CC)
    print(Fd.group())
main()
```

```
True
```

**invariants()**

The invariants of the dual group.

You should use **gens_orders()** instead.

**EXAMPLES:**

```sage
def main():
    F = AbelianGroup([5]*1000)
    Fd = F.dual_group()
    print(Fd.gens_orders())
    print(len(Fd.gens_orders()))
main()
```

```
(1000,)
1000
```

**is_commutative()**

Return True since this group is commutative.

**EXAMPLES:**

```sage
def main():
    G = AbelianGroup([2,3,9])
    Gd = G.dual_group()
    print(Gd.is_commutative())
    print(Gd.is_abelian())
main()
```

```
True
True
```
list()
Return tuple of all elements of this group.

EXAMPLES:

```python
sage: G = AbelianGroup([2,3], names="ab")
sage: Gd = G.dual_group(names="AB")
sage: Gd.list()
```

ngens()
The number of generators of the dual group.

EXAMPLES:

```python
sage: F = AbelianGroup([7]*100)
sage: Fd = F.dual_group()
sage: Fd.ngens()
100
```

order()
Return the order of this group.

EXAMPLES:

```python
sage: G = AbelianGroup([2,3,9])
sage: Gd = G.dual_group()
sage: Gd.order()
54
```

random_element()
Return a random element of this dual group.

EXAMPLES:

```python
sage: G = AbelianGroup([2,3,9])
sage: Gd = G.dual_group(base_ring=CC)
sage: Gd.random_element()
X1^2
sage: N = 43^2-1
sage: G = AbelianGroup([N],names="a")
sage: Gd = G.dual_group(names="A", base_ring=CC)
sage: a, = G.gens()
sage: A, = Gd.gens()
sage: x = a^(N/4); y = a^(N/3); z = a^(N/14)
sage: X = A*Gd.random_element(); X
A^615
sage: len([a for a in [x,y,z] if abs(X(a)-1)>10^(-8)])
2
```

sage.groups.abelian_gps.dual_abelian_group.is_DualAbelianGroup(x)
Return True if x is the dual group of an abelian group.

EXAMPLES:

```python
sage: from sage.groups.abelian_gps.dual_abelian_group import is_DualAbelianGroup
sage: F = AbelianGroup([5,[3,5,7,8,9], names=list("abcde"))
sage: Fd = F.dual_group()
```
### 23.6 Base class for abelian group elements

This is the base class for both `abelian_group_element` and `dual_abelian_group_element`. As always, elements are immutable once constructed.

```python
sage: F = AbelianGroup(3, [1, 2, 3], names='a')
sage: Fd = F.dual_group()
sage: Fd.gens()
(1, X1, X2)
sage: F.gens()
(1, a1, a2)
```

**class** `sage.groups.abelian_gps.element_base.AbelianGroupElementBase(parent, exponents)`

Base class for abelian group elements

The group element is defined by a tuple whose i-th entry is an integer in the range from 0 (inclusively) to `G.gen(i).order()` (exclusively) if the i-th generator is of finite order, and an arbitrary integer if the i-th generator is of infinite order.

**INPUT:**

- `exponents` – 1 or a list/tuple/iterable of integers. The exponent vector (with respect to the parent generators) defining the group element.
- `parent` – Abelian group. The parent of the group element.

**EXAMPLES:**

```python
sage: F.<a,b,c,f> = AbelianGroup([7,8,9])
sage: Fd = F.dual_group(names="ABC")
sage: A, B, C = Fd.gens()
sage: A*B^-1 in Fd
True
```

**exponents()**

The exponents of the generators defining the group element.

**OUTPUT:**

A tuple of integers for an abelian group element. The integer can be arbitrary if the corresponding generator has infinite order. If the generator is of finite order, the integer is in the range from 0 (inclusive) to the order (exclusive).

**EXAMPLES:**

```python
sage: (a^3*b^2*c).exponents()
(3, 2, 1, 0)
sage: F([3, 2, 1, 0])
a^3*b^2*c
sage: (c^42).exponents()
(28, 0, 0)
```

(continues on next page)
inverse()

Returns the inverse element.

EXAMPLES:

```python
sage: G.<a,b> = AbelianGroup([0,5])
sage: a.inverse()
a^-1
sage: a.__invert__()
a^-1
sage: a^-1
a^-1
sage: ~a
a^-1
sage: (a*b).exponents()
(1, 1)
sage: (a*b).inverse().exponents()
(-1, 4)
```

is_trivial()

Test whether self is the trivial group element $1$.

OUTPUT:

Boolean.

EXAMPLES:

```python
sage: G.<a,b> = AbelianGroup([0,5])
sage: (a^5).is_trivial()  # False
sage: (b^5).is_trivial()  # True
```

list()

Return a copy of the exponent vector.

Use `exponents()` instead.

OUTPUT:

The underlying coordinates used to represent this element. If this is a word in an abelian group on $n$ generators, then this is a list of nonnegative integers of length $n$.

EXAMPLES:

```python
sage: F = AbelianGroup(5,[2, 3, 5, 7, 8], names="abcde")
sage: a,b,c,d,e = F.gens()
sage: Ad = F.dual_group(names="ABCDE")
sage: A,B,C,D,E = Ad gens()
sage: (A+B+C^2*D^20+E^65).exponents()
(1, 1, 2, 6, 1)
sage: X = A*B*C^2*D^2*E^-6
sage: X.exponents()
(1, 1, 2, 2, 2)
```
**multiplicative_order()**

Return the order of this element.

**OUTPUT:**

An integer or infinity.

**EXAMPLES:**

```python
sage: F = AbelianGroup(3,[7,8,9])
sage: Fd = F.dual_group()
sage: A,B,C = Fd.gens()
sage: (B*C).order()
72

sage: F = AbelianGroup(3,[7,8,9]); F
Multiplicative Abelian group isomorphic to C7 x C8 x C9
sage: F.gens()[2].order()
9
sage: a,b,c = F.gens()
sage: (b*c).order()
72
sage: G = AbelianGroup(3,[7,8,9])
sage: type((G.0 * G.1).order())==Integer
True
```

**order()**

Return the order of this element.

**OUTPUT:**

An integer or infinity.

**EXAMPLES:**

```python
sage: F = AbelianGroup(3,[7,8,9])
sage: Fd = F.dual_group()
sage: A,B,C = Fd.gens()
sage: (B*C).order()
72

sage: F = AbelianGroup(3,[7,8,9]); F
Multiplicative Abelian group isomorphic to C7 x C8 x C9
sage: F.gens()[2].order()
9
sage: a,b,c = F.gens()
sage: (b*c).order()
72
sage: G = AbelianGroup(3,[7,8,9])
sage: type((G.0 * G.1).order())==Integer
True
```

### 23.7 Abelian group elements

**AUTHORS:**

- David Joyner (2006-02); based on free_abelian_monoid_element.py, written by David Kohel.
- David Joyner (2006-05); bug fix in order
• David Joyner (2006-08): bug fix+new method in pow for negatives+fixed corresponding examples.
• David Joyner (2009-02): Fixed bug in order.
• Volker Braun (2012-11) port to new Parent base. Use tuples for immutables.

EXAMPLES:

Recall an example from abelian groups:

```python
sage: F = AbelianGroup(5, [4,5,5,7,8], names = list("abcde"))
sage: (a,b,c,d,e) = F.gens()
sage: x = a*b^2*c*d^20*e^12
sage: x
a*b^2*d^6*e^5
sage: x = a^10*b^12*c^13*d^20*e^12
sage: x
a^2*b^2*c^3*d^6*e^4
sage: y = a^13*b^19*c^23*d^27*e^72
sage: y
a*b^4*c^3*d^6
sage: x*y
a^3*b*c*d^5*e^4
sage: x.list()
[2, 2, 3, 6, 4]
```

```python
class sage.groups.abelian_gps.abelian_group_element.AbelianGroupElement

Bases: sage.groups.abelian_gps.element_base.AbelianGroupElementBase

Elements of an AbelianGroup

INPUT:

• x – list/tuple/iterable of integers (the element vector)
• parent – the parent AbelianGroup

EXAMPLES:

```python
sage: F = AbelianGroup(5, [3,4,5,8,7], 'abcde')
sage: a, b, c, d, e = F.gens()
sage: a^2 * b^3 * a^2 * b^-4
a*b^3
sage: b^-11
b
sage: a^-11
a
sage: a*b in F
True

as_permutation()

Return the element of the permutation group G (isomorphic to the abelian group A) associated to a in A.

EXAMPLES:

```python
sage: G = AbelianGroup(3, [2,3,4], names="abc"); G
Multiplicative Abelian group isomorphic to C2 x C3 x C4
sage: a,b,c=G.gens()
```
word_problem(words)

TODO - this needs a rewrite - see stuff in the matrix_grp directory.

G and H are abelian groups, g in G, H is a subgroup of G generated by a list (words) of elements of G. If self is in H, return the expression for self as a word in the elements of (words).

This function does not solve the word problem in Sage. Rather it pushes it over to GAP, which has optimized (non-deterministic) algorithms for the word problem.

Warning: Don’t use E (or other GAP-reserved letters) as a generator name.

EXAMPLES:

```python
sage: G = AbelianGroup(2, [2, 3], names="xy")
sage: x, y = G.gens()
sage: x.word_problem([x, y])
[[x, 1]]
sage: y.word_problem([x, y])
[[y, 1]]
sage: v = (y*x).word_problem([x, y]); v #random
[[x, 1], [y, 1]]
sage: prod([x^i for x, i in v]) == y*x
True
```

sage.groups.abelian_gps.abelian_group_element.is_AbelianGroupElement(x)

Return true if x is an abelian group element, i.e., an element of type AbelianGroupElement.

EXAMPLES: Though the integer 3 is in the integers, and the integers have an abelian group structure, 3 is not an AbelianGroupElement:

```python
sage: from sage.groups.abelian_gps.abelian_group_element import is_
       ...AbelianGroupElement
sage: is_AbelianGroupElement(3)
False
sage: F = AbelianGroup(5, [3,4,5,8,7], 'abcde')
sage: is_AbelianGroupElement(F.0)
True
```

23.8 Elements (characters) of the dual group of a finite Abelian group.

To obtain the dual group of a finite Abelian group, use the dual_group() method:

```python
sage: F = AbelianGroup([2,3,5,7,8], names="abcde")
sage: F
```

(continues on next page)
Multiplicative Abelian group isomorphic to $C_2 \times C_3 \times C_5 \times C_7 \times C_8$

```
sage: Fd = F.dual_group(names="ABCDE")
sage: Fd
Dual of Abelian Group isomorphic to $Z/2Z \times Z/3Z \times Z/5Z \times Z/7Z \times Z/8Z$
over Cyclotomic Field of order 840 and degree 192
```

The elements of the dual group can be evaluated on elements of the original group:

```
sage: a,b,c,d,e = F.gens()
sage: A,B,C,D,E = Fd.gens()
sage: A*B^2*D^7
A*B^2
sage: A(a)
-1
sage: B(b)
zeta840^140 - 1
sage: CC(_)
# abs tol 1e-8
-0.499999999999995 + 0.866025403784447*I
sage: A(a*b)
-1
(1, 1, 2, 6, 1)
sage: B^(-1)
B^2
```

AUTHORS:

- David Joyner (2006-07); based on abelian_group_element.py.
- David Joyner (2006-10); modifications suggested by William Stein.

```
class sage.groups.abelian_gps.dual_abelian_group_element.DualAbelianGroupElement

Bases: sage.groups.abelian_gps.element_base.AbelianGroupElementBase

Base class for abelian group elements

word_problem(words, display=True)
```

This is a rather hackish method and is included for completeness.

The word problem for an instance of DualAbelianGroup as it can for an AbelianGroup. The reason why is that word problem for an instance of AbelianGroup simply calls GAP (which has abelian groups implemented) and invokes “EpimorphismFromFreeGroup” and “PreImagesRepresentative”. GAP does not have duals of abelian groups implemented. So, by using the same name for the generators, the method below converts the problem for the dual group to the corresponding problem on the group itself and uses GAP to solve that.

EXAMPLES:

```
sage: G = AbelianGroup(5,[3, 5, 5, 7, 8],names="abcde")
sage: Gd = G.dual_group(names="abcde")
sage: a,b,c,d,e = Gd.gens()
sage: u = a^3*b*c*d^2*e^5
sage: v = a^2*b*c^2*d^20*E^65
```

(continues on next page)
The command `e.word_problem([u,v,w,x,y],display=False)` returns the same list but also prints $e = (b^2 * c^2 * d^3 * e^5) ^ {245}$.

This was in `sage.misc.misc` but commented out. Needed to add lists of strings in the `word_problem` method below.

Return the sum of the elements of `x`. If `x` is empty, return `z`.

**INPUT:**
- `x` – iterable
- `z` – the 0 that will be returned if `x` is empty.

**OUTPUT:**
The sum of the elements of `x`.

**EXAMPLES:**

```python
sage: from sage.groups.abelian_gps.dual_abelian_group_element import add_strings
sage: add_strings([], z='empty')
'empty'
sage: add_strings(['a', 'b', 'c'])
'abc'
```

Test whether `x` is a dual Abelian group element.

**INPUT:**
- `x` – anything.

**OUTPUT:**
Boolean.

**EXAMPLES:**

```python
sage: from sage.groups.abelian_gps.dual_abelian_group_element import is_DualAbelianGroupElement
sage: F = AbelianGroup([5,5,7,8,9],names = list("abcde")).dual_group()
sage: is_DualAbelianGroupElement(F.an_element())
False
sage: is_DualAbelianGroupElement(F.an_element())
True
```

### 23.9 Homomorphisms of abelian groups

Todo:
• there must be a homspace first
• there should be hom and Hom methods in abelian group

AUTHORS:
• David Joyner (2006-03-03): initial version

```python
class sage.groups.abelian_gps.abelian_group_morphism.AbelianGroupMap(parent)
    Bases: sage.categories.morphism.Morphism

    A set-theoretic map between AbelianGroups.

class sage.groups.abelian_gps.abelian_group_morphism.AbelianGroupMorphism(G, H, genss, imgss)
    Bases: sage.categories.morphism.Morphism

    Some python code for wrapping GAP's GroupHomomorphismByImages function for abelian groups. Returns “fail” if gens does not generate self or if the map does not extend to a group homomorphism, self - other.

    EXAMPLES:

    sage: G = AbelianGroup(3,[2,3,4],names="abc"); G
    Multiplicative Abelian group isomorphic to C2 x C3 x C4
    sage: a,b,c = G.gens()
    sage: H = AbelianGroup(2,[2,3],names="xy"); H
    Multiplicative Abelian group isomorphic to C2 x C3
    sage: x,y = H.gens()

    sage: from sage.groups.abelian_gps.abelian_group_morphism import *
    ->AbelianGroupMorphism
    sage: phi = AbelianGroupMorphism(H,G,[x,y],[a,b])
```

AUTHORS:
• David Joyner (2006-02)

```python
image(S)
    Return the image of the subgroup S by the morphism.
    This only works for finite groups.

    INPUT:
    • S – a subgroup of the domain group G

    EXAMPLES:

    sage: G = AbelianGroup(2,[2,3],names="xy")
    sage: x,y = G.gens()
    sage: subG = G.subgroup([x])
    sage: H = AbelianGroup(3,[2,3,4],names="abc")
    sage: a,b,c = H.gens()
    sage: phi = AbelianGroupMorphism(H,G,[x,y],[a,b])
    sage: phi.image(subG)
    Multiplicative Abelian subgroup isomorphic to C2 generated by {a}
```

```python
kernel()
    Only works for finite groups.
```
**Todo:** not done yet; returns a gap object but should return a Sage group.

**EXAMPLES:**

```python
sage: H = AbelianGroup(3,[2,3,4],names="abc"); H
Multiplicative Abelian group isomorphic to C2 x C3 x C4
sage: a,b,c = H.gens()
sage: G = AbelianGroup(2,[2,3],names="xy"); G
Multiplicative Abelian group isomorphic to C2 x C3
sage: x,y = G.gens()
sage: phi = AbelianGroupMorphism(G,H,[x,y],[a,b])
sage: phi.kernel()
'Group([  ])'
sage: H = AbelianGroup(3,[2,2,2],names="abc")
sage: a,b,c = H.gens()
sage: G = AbelianGroup(2,[2,2],names="x")
sage: x,y = G.gens()
sage: phi = AbelianGroupMorphism(G,H,[x,y],[a,a])
sage: phi.kernel()
'Group([ f1*f2 ])'
```

sage.groups.abelian_gps.abelian_group_morphism.is_AbelianGroupMorphism(f)

## 23.10 Additive Abelian Groups

Additive abelian groups are just modules over \( \mathbb{Z} \). Hence the classes in this module derive from those in the module sage.modules.fg_pid. The only major differences are in the way elements are printed.

```python
sage.groups.additive_abelian.additive_abelian_group.AdditiveAbelianGroup(invs, remember_generators=True)
```

Construct a finitely-generated additive abelian group.

**INPUT:**
- \( \text{invs} \) (list of integers): the invariants. These should all be greater than or equal to zero.
- \( \text{remember generators} \) (boolean): whether or not to fix a set of generators (corresponding to the given invariants, which need not be in Smith form).

**OUTPUT:**
The abelian group \( \bigoplus_i \mathbb{Z}/n_i\mathbb{Z} \), where \( n_i \) are the invariants.

**EXAMPLES:**

```python
sage: AdditiveAbelianGroup([0, 2, 4])
Additive abelian group isomorphic to Z + Z/2 + Z/4
```

An example of the \text{remember generators} switch:

```python
sage: G = AdditiveAbelianGroup([0, 2, 3]); G
Additive abelian group isomorphic to Z + Z/2 + Z/3
sage: G.gens()
```

(continues on next page)
There are several ways to create elements of an additive abelian group. Realize that there are two sets of generators: the “obvious” ones composed of zeros and ones, one for each invariant given to construct the group, the other being a set of minimal generators. Which set is the default varies with the use of the `remember_generators` switch.

First with “obvious” generators. Note that a raw list will use the minimal generators and a vector (a module element) will use the generators that pair up naturally with the invariants. We create the same element repeatedly.

```sage
sage: H=AdditiveAbelianGroup([3,2,0], remember_generators=True)
sage: H.gens()
((1, 0, 0), (0, 1, 0), (0, 0, 1))
sage: [H.0, H.1, H.2]
[(1, 0, 0), (0, 1, 0), (0, 0, 1)]
sage: p=H.0+H.1+6*H.2; p
(1, 1, 6)
sage: H.smith_form_gens()
((2, 1, 0), (0, 0, 1))
sage: q=H.linear_combination_of_smith_form_gens([5,6]); q
(1, 1, 6)
sage: p==q
True
sage: r=H(vector([1,1,6])); r
(1, 1, 6)
sage: p==r
True
sage: s=H(p)
sage: p==s
True
```

Again, but now where the generators are the minimal set. Coercing a list or a vector works as before, but the default generators are different.

```sage
sage: G=AdditiveAbelianGroup([3,2,0], remember_generators=False)
sage: G.gens()
((2, 1, 0), (0, 0, 1))
sage: [G.0, G.1]
[(2, 1, 0), (0, 0, 1)]
sage: p=5*G.0+6*G.1; p
(1, 1, 6)
sage: H.smith_form_gens()
((2, 1, 0), (0, 0, 1))
sage: q=G.linear_combination_of_smith_form_gens([5,6]); q
(1, 1, 6)
sage: p==q
True
```
sage: r=G(vector([1,1,6])); r
(1, 1, 6)
sage: p==r
True
sage: s=H(p)
sage: p==s
True

class sage.groups.additive_abelian.additive_abelian_group.AdditiveAbelianGroupElement(parent, x, check=True)

Bases: sage.modules.fg_pid.fgp_element.FGP_Element

An element of an AdditiveAbelianGroup_class.

class sage.groups.additive_abelian.additive_abelian_group.AdditiveAbelianGroup_class(cover, relations)

Bases: sage.modules.fg_pid.fgp_module.FGP_Module_class, sage.groups.old.AbelianGroup

An additive abelian group, implemented using the \(\mathbb{Z}\)-module machinery.

**INPUT:**

- **cover** – the covering group as \(\mathbb{Z}\)-module.
- **relations** – the relations as submodule of cover.

**Element**

alias of AdditiveAbelianGroupElement

**exponent()**

Return the exponent of this group (the smallest positive integer \(N\) such that \(Nx = 0\) for all \(x\) in the group). If there is no such integer, return 0.

**EXAMPLES:**

```
sage: AdditiveAbelianGroup([2,4]).exponent()
4
sage: AdditiveAbelianGroup([0, 2,4]).exponent()
0
sage: AdditiveAbelianGroup([]).exponent()
1
```

**is_cyclic()**

Returns True if the group is cyclic.

**EXAMPLES:**

With no common factors between the orders of the generators, the group will be cyclic.

```
sage: G=AdditiveAbelianGroup([6, 7, 55])
sage: G.is_cyclic()
True
```

Repeating primes in the orders will create a non-cyclic group.
sage: G = AdditiveAbelianGroup([6, 15, 21, 33])
sage: G.is_cyclic()
False

A trivial group is trivially cyclic.

sage: T = AdditiveAbelianGroup([1])
sage: T.is_cyclic()
True

**is_multiplicative()**
Return False since this is an additive group.

**EXAMPLES:**

sage: AdditiveAbelianGroup([0]).is_multiplicative()
False

**order()**
Return the order of this group (an integer or infinity)

**EXAMPLES:**

sage: AdditiveAbelianGroup([2, 4]).order()
8
sage: AdditiveAbelianGroup([0, 2, 4]).order()
+Infinity
sage: AdditiveAbelianGroup([]).order()
1

**short_name()**
Return a name for the isomorphism class of this group.

**EXAMPLES:**

sage: AdditiveAbelianGroup([0, 2, 4]).short_name()
'Z + Z/2 + Z/4'
sage: AdditiveAbelianGroup([0, 2, 3]).short_name()
'Z + Z/2 + Z/3'

**class** sage.groups.additive_abelian.additive_abelian_group.AdditiveAbelianGroup_fixed_gens(cover, rels, gens) (**sage.groups.additive_abelian.additive_abelian_group.AdditiveAbelianGroup_class**)
A variant which fixes a set of generators, which need not be in Smith form (or indeed independent).

**gens()**
Return the specified generators for self (as a tuple). Compare `self.smithform_gens()`.

**EXAMPLES:**

sage: G = AdditiveAbelianGroup([2, 3])
sage: G.gens()
((1, 0), (0, 1))
sage: G.smith_form_gens()
((1, 2),)
identity()  
Return the identity (zero) element of this group.

EXAMPLES:

```sage
G = AdditiveAbelianGroup([2, 3])
sage: G.identity()
(0, 0)
```

permutation_group()  
Return the permutation group attached to this group.

EXAMPLES:

```sage
G = AdditiveAbelianGroup([2, 3])
sage: G.permutation_group()
Permutation Group with generators [(3,4,5), (1,2)]
```

sage.groups.additive_abelian.additive_abelian_group.cover_and_relations_from_invariants()  
A utility function to construct modules required to initialize the super class.

Given a list of integers, this routine constructs the obvious pair of free modules such that the quotient of the two free modules over \( \mathbb{Z} \) is naturally isomorphic to the corresponding product of cyclic modules (and hence isomorphic to a direct sum of cyclic groups).

EXAMPLES:

```sage
from sage.groups.additive_abelian.additive_abelian_group import cover_and_relations_from_invariants as cr
sage: cr([0,2,3])
(Ambient free module of rank 3 over the principal ideal domain Integer Ring, Free module of degree 3 and rank 2 over Integer Ring
Echelon basis matrix:
[0 2 0]
[0 0 3])
```

## 23.11 Wrapper class for abelian groups

This class is intended as a template for anything in Sage that needs the functionality of abelian groups. One can create an AdditiveAbelianGroupWrapper object from any given set of elements in some given parent, as long as an \_add\_ method has been defined.

EXAMPLES:

We create a toy example based on the Mordell-Weil group of an elliptic curve over \( \mathbb{Q} \):

```sage
E = EllipticCurve('30a2')
sage: pts = [E(4,-7,1), E(7/4, -11/8, 1), E(3, -2, 1)]
sage: M = AdditiveAbelianGroupWrapper(pts[0].parent(), pts, [3, 2, 2])
sage: M
Additive abelian group isomorphic to Z/3 + Z/2 + Z/2 embedded in Abelian group of points on Elliptic Curve defined by y^2 + x*y + y = x^3 - 19*x + 26 over Rational Field
sage: M.gens()
((4 : -7 : 1), (7/4 : -11/8 : 1), (3 : -2 : 1))
sage: 3*M.0
(0 : 1 : 0)
```
We check that ridiculous operations are being avoided:

```
sage: set_verbose(2, 'additive_abelian_wrapper.py')
sage: 300001 * M.0
verbose 1 (...: additive_abelian_wrapper.py, _discrete_exp) Calling discrete exp on
   (1, 0, 0)
   (4 : -7 : 1)
sage: set_verbose(0, 'additive_abelian_wrapper.py')
```

```
 TODO:
  • Implement proper black-box discrete logarithm (using baby-step giant-step). The discrete_exp function can also
    potentially be speeded up substantially via caching.
  • Think about subgroups and quotients, which probably won’t work in the current implementation – some fiddly
    adjustments will be needed in order to be able to pass extra arguments to the subquotient’s init method.

```
class sage.groups.additive_abelian.additive_abelian_wrapper.AdditiveAbelianGroupWrapper

Bases: sage.groups.additive_abelian.additive_abelian_group.AdditiveAbelianGroup_fixed_gens

The parent of AdditiveAbelianGroupWrapperElement

Element

    alias of AdditiveAbelianGroupWrapperElement

    generator_orders()

    The orders of the generators with which this group was initialised. (Note that these are not necessarily
    a minimal set of generators.) Generators of infinite order are returned as 0. Compare self.
    invariants(), which returns the orders of a minimal set of generators.

EXAMPLES:

```
sage: V = Zmod(6)**2
sage: G = AdditiveAbelianGroupWrapper(V, [2*V.0, 3*V.1], [3, 2])
sage: G.generator_orders()
(3, 2)
sage: G.invariants()
(6,)
```

```
universe()

    The ambient group in which this abelian group lives.

EXAMPLES:

```
sage: G = AdditiveAbelianGroupWrapper(QQbar, [sqrt(QQbar(2)), sqrt(QQbar(3))],
        -> [0, 0])
sage: G.universe()
Algebraic Field
```

23.11. Wrapper class for abelian groups
class sage.groups.additive_abelian.additive_abelian_wrapper.AdditiveAbelianGroupWrapperElement

Bases: sage.groups.additive_abelian.additive_abelian_group.AdditiveAbelianGroupElement

An element of an AdditiveAbelianGroupWrapper.

element()
    Return the underlying object that this element wraps.

EXAMPLES:

    sage: T = EllipticCurve('65a').torsion_subgroup().gen(0)
    sage: T; type(T)
    (0 : 0 : 1)
    <class 'sage.schemes.elliptic_curves.ell_torsion.EllipticCurveTorsionSubgroup_→with_category.element_class'>
    sage: T.element(); type(T.element())
    (0 : 0 : 1)
    <class 'sage.schemes.elliptic_curves.ell_point.EllipticCurvePoint_number_field_→'>

class sage.groups.additive_abelian.additive_abelian_wrapper.UnwrappingMorphism(domain)

Bases: sage.categories.morphism.Morphism

    The embedding into the ambient group. Used by the coercion framework.
24.1 Catalog of permutation groups

Type `groups.permutation.<tab>` to access examples of groups implemented as permutation groups.

24.2 Permutation groups

A permutation group is a finite group $G$ whose elements are permutations of a given finite set $X$ (i.e., bijections $X \rightarrow X$) and whose group operation is the composition of permutations. The number of elements of $X$ is called the degree of $G$.

In Sage, a permutation is represented as either a string that defines a permutation using disjoint cycle notation, or a list of tuples, which represent disjoint cycles. That is:

$$(a, \ldots, b)(c, \ldots, d)\ldots(e, \ldots, f) \leftrightarrow [(a, \ldots, b), (c, \ldots, d), \ldots, (e, \ldots, f)]$$

$() = \text{identity} \leftrightarrow []$

You can make the “named” permutation groups (see `permgp_named.py`) and use the following constructions:

- permutation group generated by elements,
- `direct_product_permgroups`, which takes a list of permutation groups and returns their direct product.


24.2.1 Index of methods

Here are the method of a `PermutationGroup()`

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>as_finitely_presented()</code></td>
<td>Return a finitely presented group isomorphic to self.</td>
</tr>
<tr>
<td><code>blocks_all()</code></td>
<td>Returns the list of block systems of imprimitivity.</td>
</tr>
<tr>
<td><code>cardinality()</code></td>
<td>Return the number of elements of this group. See also: G.degree()</td>
</tr>
<tr>
<td><code>center()</code></td>
<td>Return the subgroup of elements that commute with every element of this group.</td>
</tr>
<tr>
<td><code>centralizer()</code></td>
<td>Returns the centralizer of g in self.</td>
</tr>
<tr>
<td><code>character()</code></td>
<td>Returns a group character from values, where values is a list of the values of the character evaluated on the conjugacy classes.</td>
</tr>
<tr>
<td><code>character_table()</code></td>
<td>Returns the matrix of values of the irreducible characters of a permutation group $G$ at the conjugacy classes of $G$.</td>
</tr>
</tbody>
</table>
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<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
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<tbody>
<tr>
<td>cohomology()</td>
<td>Computes the group cohomology $H^n(G, F)$, where $F = \mathbb{Z}$ if $p = 0$ and $F = \mathbb{Z}/p\mathbb{Z}$ if $p &gt; 0$ is a prime.</td>
</tr>
<tr>
<td>cohomology_part()</td>
<td>Computes the $p$-part of the group cohomology $H^n(G, F)$, where $F = \mathbb{Z}$ if $p = 0$ and $F = \mathbb{Z}/p\mathbb{Z}$ if $p &gt; 0$ is a prime.</td>
</tr>
<tr>
<td>commutator()</td>
<td>Returns the commutator subgroup of a group, or of a pair of groups.</td>
</tr>
<tr>
<td>composition_series()</td>
<td>Return the composition series of this group as a list of permutation groups.</td>
</tr>
<tr>
<td>conjugacy_class()</td>
<td>Return the conjugacy class of $g$ inside the group $self$.</td>
</tr>
<tr>
<td>conjugacy_classes()</td>
<td>Return a list with all the conjugacy classes of $self$.</td>
</tr>
<tr>
<td>conjugacy_classes_representatives()</td>
<td>Returns a complete list of representatives of conjugacy classes in a permutation group $G$.</td>
</tr>
<tr>
<td>conjugacy_classes_subgroups()</td>
<td>Returns a complete list of representatives of conjugacy classes of subgroups in a permutation group $G$.</td>
</tr>
<tr>
<td>conjugate()</td>
<td>Returns the group formed by conjugating $self$ with $g$.</td>
</tr>
<tr>
<td>construction()</td>
<td>Return the construction of $self$.</td>
</tr>
<tr>
<td>cosets()</td>
<td>Returns a list of the cosets of $S$ in $self$.</td>
</tr>
<tr>
<td>degree()</td>
<td>Returns the degree of this permutation group.</td>
</tr>
<tr>
<td>derived_series()</td>
<td>Return the derived series of this group as a list of permutation groups.</td>
</tr>
<tr>
<td>direct_product()</td>
<td>Wraps GAP’s DirectProduct, Embedding, and Projection.</td>
</tr>
<tr>
<td>domain()</td>
<td>Returns the underlying set that this permutation group acts on.</td>
</tr>
<tr>
<td>exponent()</td>
<td>Computes the exponent of the group.</td>
</tr>
<tr>
<td>fitting_subgroup()</td>
<td>Returns the Fitting subgroup of $self$.</td>
</tr>
<tr>
<td>fixed_points()</td>
<td>Return the list of points fixed by $self$, i.e., the subset of $domain()$ not moved by any element of $self$.</td>
</tr>
<tr>
<td>frattini_subgroup()</td>
<td>Returns the Frattini subgroup of $self$.</td>
</tr>
<tr>
<td>gen()</td>
<td>Returns the $i$-th generator of $self$; that is, the $i$-th element of the list $self$.</td>
</tr>
<tr>
<td>gens()</td>
<td>Return tuple of generators of this group. These need not be minimal, as they are the generators used in defining this group.</td>
</tr>
<tr>
<td>gens_small()</td>
<td>For this group, returns a generating set which has few elements. As neither irredundancy nor minimal length is proven, it is fast.</td>
</tr>
<tr>
<td>group_id()</td>
<td>Return the ID code of this group, which is a list of two integers.</td>
</tr>
<tr>
<td>group_primitive_id()</td>
<td>Return the index of this group in the GAP database of primitive groups.</td>
</tr>
<tr>
<td>has_element()</td>
<td>Returns boolean value of item in self - however ignores parentage.</td>
</tr>
<tr>
<td>holomorph()</td>
<td>The holomorph of a group as a permutation group.</td>
</tr>
<tr>
<td>homology()</td>
<td>Computes the group homology $H_n(G, F)$, where $F = \mathbb{Z}$ if $p = 0$ and $F = \mathbb{Z}/p\mathbb{Z}$ if $p &gt; 0$ is a prime. Wraps HAP’s GroupHomology function, written by Graham Ellis.</td>
</tr>
<tr>
<td>homology_part()</td>
<td>Computes the $p$-part of the group homology $H_n(G, F)$, where $F = \mathbb{Z}$ if $p = 0$ and $F = \mathbb{Z}/p\mathbb{Z}$ if $p &gt; 0$ is a prime. Wraps HAP’s Homology function, written by Graham Ellis, applied to the $p$-Sylow subgroup of $G$.</td>
</tr>
<tr>
<td>id()</td>
<td>(Same as $self.group_id()$) Return the ID code of this group, which is a list of two integers.</td>
</tr>
<tr>
<td>identity()</td>
<td>Return the identity element of this group.</td>
</tr>
<tr>
<td>intersection()</td>
<td>Returns the permutation group that is the intersection of $self$ and $other$.</td>
</tr>
<tr>
<td>irreducible_characters()</td>
<td>Returns a list of the irreducible characters of $self$.</td>
</tr>
<tr>
<td>is_cyclic()</td>
<td>Return True if this group is cyclic.</td>
</tr>
<tr>
<td>is_elementary_abelian()</td>
<td>Return True if this group is elementary abelian. An elementary abelian group is a finite abelian group, where every nontrivial element has order $p$, where $p$ is a prime.</td>
</tr>
<tr>
<td>is_isomorphic()</td>
<td>Return True if the groups are isomorphic.</td>
</tr>
</tbody>
</table>

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<table>
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<tr>
<th>Function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>is_monomial()</code></td>
<td>Returns True if the group is monomial. A finite group is monomial if every</td>
</tr>
<tr>
<td></td>
<td>irreducible complex character is induced from a linear character of a subgroup.</td>
</tr>
<tr>
<td><code>is_nilpotent()</code></td>
<td>Return True if this group is nilpotent.</td>
</tr>
<tr>
<td><code>is_normal()</code></td>
<td>Return True if this group is a normal subgroup of <code>other</code>.</td>
</tr>
<tr>
<td><code>is_perfect()</code></td>
<td>Return True if this group is perfect. A group is perfect if it equals its derived subgroup.</td>
</tr>
<tr>
<td><code>is_pgroup()</code></td>
<td>Returns True if this group is a $p$-group. A finite group is a $p$-group if its order is of the form $p^n$ for a prime integer $p$ and a nonnegative integer $n$.</td>
</tr>
<tr>
<td><code>is_polycyclic()</code></td>
<td>Return True if this group is polycyclic. A group is polycyclic if it has a subnormal series with cyclic factors. (For finite groups, this is the same as if the group is solvable - see <code>is_solvable</code>).</td>
</tr>
<tr>
<td><code>is_primitive()</code></td>
<td>Returns True if <code>self</code> acts primitively on <code>domain</code>. A group $G$ acts primitively on a set $S$ if</td>
</tr>
<tr>
<td></td>
<td><code>is_regular()</code> Return True if <code>self</code> acts regularly on <code>domain</code>. A group $G$ acts regularly on a set $S$ if</td>
</tr>
<tr>
<td><code>is_semi_regular()</code></td>
<td>Returns True if <code>self</code> acts semi-regularly on <code>domain</code>. A group $G$ acts semi-regularly on a set $S$ if the point stabilizers of $S$ in $G$ are trivial.</td>
</tr>
<tr>
<td><code>is_simple()</code></td>
<td>Returns True if the group is simple. A group is simple if it has no proper normal subgroups.</td>
</tr>
<tr>
<td><code>is_solvable()</code></td>
<td>Returns True if the group is solvable.</td>
</tr>
<tr>
<td><code>is_subgroup()</code></td>
<td>Returns True if <code>self</code> is a subgroup of <code>other</code>.</td>
</tr>
<tr>
<td><code>is_supersolvable()</code></td>
<td>Returns True if the group is supersolvable. A finite group is supersolvable if it has a normal series with cyclic factors.</td>
</tr>
<tr>
<td><code>is_transitive()</code></td>
<td>Returns True if <code>self</code> acts transitively on <code>domain</code>. A group $G$ acts transitively on a set $S$ if for all $x,y \in S$ there is some $g \in G$ such that $x^g = y$.</td>
</tr>
<tr>
<td><code>isomorphism_to()</code></td>
<td>Return an isomorphism from <code>self</code> to <code>right</code> if the groups are isomorphic, otherwise None.</td>
</tr>
<tr>
<td><code>isomorphism_type_info_simple_group()</code></td>
<td>If the group is simple, then this returns the name of the group.</td>
</tr>
<tr>
<td><code>iteration()</code></td>
<td>Return an iterator over the elements of this group.</td>
</tr>
<tr>
<td><code>largest_moved_point()</code></td>
<td>Return the largest point moved by a permutation in this group.</td>
</tr>
<tr>
<td><code>list()</code></td>
<td>Return list of all elements of this group.</td>
</tr>
<tr>
<td><code>lower_central_series()</code></td>
<td>Return the lower central series of this group as a list of permutation groups.</td>
</tr>
<tr>
<td><code>minimal_generating_set()</code></td>
<td>Return a minimal generating set</td>
</tr>
<tr>
<td><code>molien_series()</code></td>
<td>Return the Molien series of a permutation group. The function</td>
</tr>
<tr>
<td><code>ngens()</code></td>
<td>Return the number of generators of <code>self</code>.</td>
</tr>
<tr>
<td><code>non_fixed_points()</code></td>
<td>Return the list of points not fixed by <code>self</code>, i.e., the subset of <code>self</code>.</td>
</tr>
<tr>
<td></td>
<td><code>domain()</code> moved by some element of <code>self</code>.</td>
</tr>
<tr>
<td><code>normal_subgroups()</code></td>
<td>Return the normal subgroups of this group as a (sorted in increasing order) list of permutation groups.</td>
</tr>
<tr>
<td><code>normalizer()</code></td>
<td>Returns the normalizer of <code>g</code> in <code>self</code>.</td>
</tr>
<tr>
<td><code>normalizes()</code></td>
<td>Returns True if the group <code>other</code> is normalized by <code>self</code>. Wraps GAP’s <code>IsNormal</code> function.</td>
</tr>
<tr>
<td><code>poincare_series()</code></td>
<td>Return the Poincaré series of $G$ mod $p$ ($p \geq 2$ must be a prime), for $n$ large.</td>
</tr>
<tr>
<td><code>random_element()</code></td>
<td>Return a random element of this group.</td>
</tr>
<tr>
<td><code>representative_action()</code></td>
<td>Return an element of <code>self</code> that maps $x$ to $y$ if it exists.</td>
</tr>
<tr>
<td><code>semidirect_product()</code></td>
<td>The semidirect product of <code>self</code> with <code>N</code>.</td>
</tr>
<tr>
<td><code>socle()</code></td>
<td>Returns the socle of <code>self</code>. The socle of a group $G$ is the subgroup generated by all minimal normal subgroups.</td>
</tr>
<tr>
<td><code>solvable_radical()</code></td>
<td>Returns the solvable radical of <code>self</code>. The solvable radical (or just radical) of a group $G$ is the largest solvable normal subgroup of $G$.</td>
</tr>
</tbody>
</table>

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<tr>
<th>Method</th>
<th>Description</th>
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<tbody>
<tr>
<td><code>stabilizer()</code></td>
<td>Return the subgroup of <code>self</code> which stabilize the given position. <code>self</code> and its stabilizers must have same degree.</td>
</tr>
<tr>
<td><code>strong_generating_system()</code></td>
<td>Return a Strong Generating System of <code>self</code> according the given base for the right action of <code>self</code> on itself.</td>
</tr>
<tr>
<td><code>structure_description()</code></td>
<td>Return a string that tries to describe the structure of <code>G</code>.</td>
</tr>
<tr>
<td><code>subgroup()</code></td>
<td>Wraps the <code>PermutationGroup_subgroup</code> constructor. The argument <code>gens</code> is a list of elements of <code>self</code>.</td>
</tr>
<tr>
<td><code>subgroups()</code></td>
<td>Returns a list of all the subgroups of <code>self</code>.</td>
</tr>
<tr>
<td><code>sylow_subgroup()</code></td>
<td>Returns a Sylow $p$-subgroup of the finite group $G$, where $p$ is a prime. This is a $p$-subgroup of $G$ whose index in $G$ is coprime to $p$.</td>
</tr>
<tr>
<td><code>transversals()</code></td>
<td>If $G$ is a permutation group acting on the set $X = {1, 2, \ldots, n}$ and $H$ is the stabilizer subgroup of $&lt;\text{integer}&gt;$, a right (respectively left) transversal is a set containing exactly one element from each right (respectively left) coset of $H$. This method returns a right transversal of <code>self</code> by the stabilizer of <code>self</code> on $&lt;\text{integer}&gt;$ position.</td>
</tr>
<tr>
<td><code>trivial_character()</code></td>
<td>Returns the trivial character of <code>self</code>.</td>
</tr>
<tr>
<td><code>upper_central_series()</code></td>
<td>Returns the upper central series of this group as a list of permutation groups.</td>
</tr>
</tbody>
</table>

AUTHORS:

- David Joyner (2005-10-14): first version
- David Joyner (2005-11-17)
- William Stein (2005-11-26): rewrite to better wrap Gap
- David Joyner (2005-12-21)
- William Stein and David Joyner (2006-01-04): added conjugacy_class_representatives
- David Joyner (2006-03): reorganization into subdirectory perm_gps; added __contains__, has_element; fixed __cmp__; added subgroup class+methods, PGL,PSL,PSp, PSU classes,
- David Joyner (2006-06): added PGU, functionality to SymmetricGroup, AlternatingGroup, direct_product_permgroups
- David Joyner (2006-08): added degree, ramification_module_decomposition_modular_curve and ramification_module_decomposition_hurwitz_curve methods to PSL(2,q), MathieuGroup, is_isomorphic
- Bobby Moretti (2006-10): Added KleinFourGroup, fixed bug in DihedralGroup
- David Joyner (2006-10): added is_subgroup (fixing a bug found by Kiran Kedlaya), is_solvable, normalizer, is_normal_subgroup, Suzuki
- David Kohel (2007-02): fixed __contains__ to not enumerate group elements, following the convention for __call__
- David Harvey, Mike Hansen, Nick Alexander, William Stein (2007-02,03,04,05): Various patches
- Nathan Dunfield (2007-05): added orbits
- David Joyner (2007-06): added subgroup method (suggested by David Kohel), composition_series, lower_central_series, upper_central_series, cayley_table, quotient_group, sylow_subgroup, is_cyclic, homology, homology_part, cohomology, cohomology_part, poincare_series, molien_series, is_simple, is_monomial, is_supersolvable, is_nilpotent, is_perfect, is_poly cyclic, is_elementary_abelian, is_pgroup, gens_small, isomorphism_type_info_simple_group. moved all the"named" groups to a new file.
- Nick Alexander (2007-07): move is_isomorphic to isomorphism_to, add from_gap_list
- William Stein (2007-07): put is_isomorphic back (and make it better)
• David Joyner (2007-08): fixed bugs in composition_series, upper/lower_central_series, derived_series,
• David Joyner (2008-06): modified is_normal (reported by W. J. Palenstijn), and added normalizes
• David Joyner (2008-08): Added example to docstring of cohomology.
• Simon King (2009-04): __cmp__ methods for PermutationGroup_generic and PermutationGroup_subgroup
• Nicolas Borie (2009): Added orbit, transversals, stabiliser and strong_generating_system methods
• Christopher Swenson (2012): Added a special case to compute the order efficiently. (This patch Copyright 2012
  Google Inc. All Rights Reserved. )
• Javier Lopez Pena (2013): Added conjugacy classes.
• Sebastian Oehms (2018): added _coerce_map_from_ in order to use isomorphism coming up with
  as_permutation_group method (Trac #25706)
• Christian Stump (2018): Added alternative implementation of strong_generating_system directly using GAP.
• Sebastian Oehms (2018): Added PermutationGroup_generic._Hom_() to use sage.groups.
  libgap_morphism.GroupHomset_libgap and PermutationGroup_generic.gap() and
  PermutationGroup_generic._subgroup_constructor() (for compatibility to libgap frame-
  work, see trac ticket #26750

REFERENCES:

Note: Though Suzuki groups are okay, Ree groups should not be wrapped as permutation groups - the construction
is too slow - unless (for small values or the parameter) they are made using explicit generators.

sage.groups.perm_gps.permgroup.PermutationGroup(gens=None, gap_group=None, domain=None, canonicalize=True, category=None)

Return the permutation group associated to \( x \) (typically a list of generators).

INPUT:
• gens - list of generators (default: None)
• gap_group - a gap permutation group (default: None)
• canonicalize - bool (default: True); if True, sort generators and remove duplicates

OUTPUT:
• A permutation group.

EXAMPLES:

```python
sage: G = PermutationGroup([[1,2,3],[4,5]],[(3,4)])
sage: G
Permutation Group with generators [(3,4), (1,2,3)(4,5)]
```

We can also make permutation groups from PARI groups:
We can also create permutation groups whose generators are Gap permutation objects:

```python
sage: p = gap('(1,2)(3,7)(4,6)(5,8)'); p
(1,2)(3,7)(4,6)(5,8)
sage: PermutationGroup([p])
Permutation Group with generators [(1,2)(3,7)(4,6)(5,8)]
```

Permutation groups can work on any domain. In the following examples, the permutations are specified in list notation, according to the order of the elements of the domain:

```python
sage: list(PermutationGroup([[b,'c','a']], domain=['a','b','c']))
[(), ('a','c','b'), ('a','b','c')]
sage: list(PermutationGroup([[b,'c','a']], domain=['b','c','a']))
[()]
sage: list(PermutationGroup([[b,'c','a']], domain=['a','c','b']))
[(), ('a','b')]
```

There is an underlying gap object that implements each permutation group:

```python
sage: G = PermutationGroup([[1,2,3,4]])
sage: G._gap_()
Group( [ (1,2,3,4) ] )
sage: gap(G)
Group( [ (1,2,3,4) ] )
sage: gap(G) is G._gap_()
True
sage: G = PermutationGroup([[1,2,3),(4,5)],[(3,4)])
sage: current_randstate().set_seed_gap()
sage: G._gap_().DerivedSeries()
[ Group( [ (3,4), (1,2,3)(4,5) ] ), Group( [ (1,5)(3,4), (1,5)(2,4), (1,3,5) ] ) ]
```

class `sage.groups.perm_gps.permgroup.PermutationGroup_generic`(*gens=None*, *gap_group=None*, *canonicalize=True*, *domain=None*, *category=None*)

Bases: `sage.groups.group.FiniteGroup`

A generic permutation group.

**EXAMPLES:**

```python
sage: G = PermutationGroup([[1,2,3),(4,5)],[(3,4)])
sage: G
Permutation Group with generators [(3,4), (1,2,3)(4,5)]
sage: G.center()
Subgroup generated by [()] of (Permutation Group with generators [(3,4), (1,2,3)(4,5)])
sage: G.group_id()
```

(continues on next page)
Element class alias of `sage.groups.perm_gps.permgroup_element.PermutationGroupElement`.

**as_finitely_presented_group**(`reduced=False`)

Returns a finitely presented group isomorphic to `self`.

This method acts as wrapper for the GAP function `IsomorphismFpGroupByGenerators`, which yields an isomorphism from a given group to a finitely presented group.

**INPUT:**

- `reduced` – Default `False`, if `True` `FinitelyPresentedGroup.simplified` is called, attempting to simplify the presentation of the finitely presented group to be returned.

**OUTPUT:**

Finite presentation of `self`, obtained by taking the image of the isomorphism returned by the GAP function `IsomorphismFpGroupByGenerators`.

**ALGORITHM:**

Uses GAP.

**EXAMPLES:**

```python
sage: CyclicPermutationGroup(50).as_finitely_presented_group()
Finitely presented group < a | a^50 >
sage: DihedralGroup(4).as_finitely_presented_group()
Finitely presented group < a, b | b^2, a^4, (b*a)^2 >
sage: GeneralDihedralGroup([2,2]).as_finitely_presented_group()
Finitely presented group < a, b, c | a^2, b^2, c^2, (c*b)^2, (c*a)^2, (b*a)^2 >
```

GAP algorithm is not guaranteed to produce minimal or canonical presentation:

```python
sage: G = PermutationGroup(["(1,2,3,4,5)", "(1,5)(2,4)"])
sage: G.is_isomorphic(DihedralGroup(5))
True
sage: K = G.as_finitely_presented_group(); K
Finitely presented group < a, b | b^2, (b*a)^2, b*a^-3*b*a^2 >
sage: K.as_permutation_group().is_isomorphic(DihedralGroup(5))
True
```

We can attempt to reduce the output presentation:

```python
sage: PermutationGroup(["(1,2,3,4,5)", "(1,3,5,2,4)"]).as_finitely_presented_group()
Finitely presented group < a, b | b^-2*a^-1, b*a^-2 >
sage: PermutationGroup(["(1,2,3,4,5)", "(1,3,5,2,4)"]).as_finitely_presented_group(reduced=True)
Finitely presented group < a | a^5 >
```

**AUTHORS:**

24.2. Permutation groups
base (seed=None)
Returns a (minimum) base of this permutation group. A base $B$ of a permutation group is a subset of the
domain of the group such that the only group element stabilizing all of $B$ is the identity.

The argument $seed$ is optional and must be a subset of the domain of $base$. When used, an attempt to
create a base containing all or part of $seed$ will be made.

EXAMPLES:

```python
sage: G = PermutationGroup([(1,2,3),(6,7,8)])
sage: G.base()
[1, 6]
sage: G.base([2])
[2, 6]

sage: H = PermutationGroup([('a','b','c'), ('a','y')])
sage: H.base()
['a', 'b', 'c']

sage: S = SymmetricGroup(13)
sage: S.base()
[1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12]

sage: S = MathieuGroup(12)
sage: S.base()
[1, 2, 3, 4, 5]
sage: S.base([1,3,5,7,9,11])  # create a base for M12 with only odd integers
[1, 3, 5, 7, 9]
```

blocks_all (representatives=True)
Returns the list of block systems of imprimitivity.

For more information on primitivity, see the Wikipedia article on primitive group actions.

INPUT:

- representative (boolean) – whether to return all possible block systems of imprimitivity or only
  one of their representatives (the block can be obtained from its representative set $S$ by computing the
  orbit of $S$ under self).

  This parameter is set to True by default (as it is GAP’s default behaviour).

OUTPUT:

This method returns a description of all block systems. Hence, the output is a “list of lists of lists” or a
“list of lists” depending on the value of representatives. A bit more clearly, output is:

- A list of length (#number of different block systems) of
  - block systems, each of them being defined as
    * If representatives = True: a list of representatives of each set of the block system
    * If representatives = False: a partition of the elements defining an imprimitivity
      block.

See also:

- isPrimitive()
EXAMPLES:

Picking an interesting group:

```
sage: g = graphs.DodecahedralGraph()
sage: g.is_vertex_transitive()
True
sage: ag = g.automorphism_group()
sage: ag.is_primitive()
False
```

Computing its blocks representatives:

```
sage: ag.blocks_all()
[[0, 15]]
```

Now the full block:

```
sage: sorted(ag.blocks_all(representatives = False)[0])
[[0, 15], [1, 16], [2, 12], [3, 13], [4, 9], [5, 10], [6, 11], [7, 18], [8, 17], [14, 19]]
```

cardinality()  
Return the number of elements of this group. See also: G.degree()

EXAMPLES:

```
sage: G = PermutationGroup([[(1,2,3),(4,5)], [(1,2)]])
sage: G.order()
12
sage: G = PermutationGroup([()])
sage: G.order()
1
```

cardinality is just an alias:

```
sage: PermutationGroup([[(1,2,3)]]).cardinality()
3
```

center()  
Return the subgroup of elements that commute with every element of this group.

EXAMPLES:

```
sage: G = PermutationGroup([[(1,2,3,4)]]
sage: G.center()
Subgroup generated by [(1,2,3,4)] of (Permutation Group with generators [(1,2,3,4)])
sage: G = PermutationGroup([[(1,2,3,4)], [(1,2)]]
sage: G.center()
Subgroup generated by [] of (Permutation Group with generators [(1,2), (1,2,3,4)])
```

centralizer(g)  
Returns the centralizer of g in self.

EXAMPLES:
sage: G = PermutationGroup([(1,2),(3,4), (1,2,3,4)])
sage: g = G([(1,3)])
sage: G.centralizer(g)
Subgroup generated by [(2,4), (1,3)] of (Permutation Group with generators [(1,2)(3,4), (1,2,3,4)])

sage: g = G([(1,2,3,4)])
sage: G.centralizer(g)
Subgroup generated by [(1,2,3,4)] of (Permutation Group with generators [(1,2)(3,4), (1,2,3,4)])

sage: H = G.subgroup([G([(1,2,3,4)])])
sage: G.centralizer(H)
Subgroup generated by [(1,2,3,4)] of (Permutation Group with generators [(1,2)(3,4), (1,2,3,4)])

**character** *(values)*

Returns a group character from values, where values is a list of the values of the character evaluated on the conjugacy classes.

**EXAMPLES:**

```
sage: G = AlternatingGroup(4)
sage: n = len(G.conjugacy_classes_representatives())
sage: G.character([1]*n)
Character of Alternating group of order 4!/2 as a permutation group
```

**character_table**

Returns the matrix of values of the irreducible characters of a permutation group $G$ at the conjugacy classes of $G$.

The columns represent the conjugacy classes of $G$ and the rows represent the different irreducible characters in the ordering given by GAP.

**EXAMPLES:**

```
sage: G = PermutationGroup([(1,2),(3,4), (1,2,3)])
sage: G.order()
12
sage: G.character_table()
[ 1  1  1  1  1]
[ 1 -zeta3 - 1 zeta3  1]
[ 1 zeta3 -zeta3 - 1  1]
[ 3  0  0  0 -1]
sage: CT = gap(G).CharacterTable()
Type print(gap.eval("Display(%s)"%CT.name())) to display this nicely.
```

```
sage: G = PermutationGroup([(1,2),(3,4), (1,2,3,4)])
sage: G.order()
8
sage: G.character_table()
[ 1  1  1  1]
[ 1 -1 -1  1]
[ 1 -1  1 -1]
[ 1  1 -1 -1]
[ 2  0  0 -2]
sage: CT = gap(G).CharacterTable()
Again, type print(gap.eval("Display(%s)"%CT.name())) to display this nicely.
```
Suppose that you have a class function \( f(g) \) on \( G \) and you know the values \( v_1, \ldots, v_n \) on the conjugacy class elements in \( \text{conjugacy_classes_representatives}(G) = \{g_1, \ldots, g_n\} \). Since the irreducible characters \( \rho_1, \ldots, \rho_n \) of \( G \) form an \( E \)-basis of the space of all class functions (\( E \) a “sufficiently large” cyclotomic field), such a class function is a linear combination of these basis elements, \( f = c_1 \rho_1 + \cdots + c_n \rho_n \). To find the coefficients \( c_i \), you simply solve the linear system \( \text{character_table_values}(G) \begin{pmatrix} v_1, \ldots, v_n \end{pmatrix} = \begin{pmatrix} c_1, \ldots, c_n \end{pmatrix} \), where \( \text{character_table_values}(G) = \begin{pmatrix} v_1, \ldots, v_n \end{pmatrix} \).

AUTHORS:
- David Joyner and William Stein (2006-01-04)

**cohomology** \((n, p=0)\)

Computes the group cohomology \( H^n(G, F) \), where \( F = \mathbb{Z} \) if \( p = 0 \) and \( F = \mathbb{Z}/p\mathbb{Z} \) if \( p > 0 \) is a prime.

Wraps HAP’s `GroupHomology` function, written by Graham Ellis.

REQUIRES: GAP package HAP (in gap_packages-*-spkg).

EXAMPLES:

```
sage: G = SymmetricGroup(4)
sage: G.cohomology(1,2)  # optional - gap_packages
Multiplicative Abelian group isomorphic to C2
sage: G = SymmetricGroup(3)
sage: G.cohomology(5)  # optional - gap_packages
Trivial Abelian group
sage: G.cohomology(5,2)  # optional - gap_packages
Multiplicative Abelian group isomorphic to C2
sage: G.homology(5,3)  # optional - gap_packages
Trivial Abelian group
sage: G.homology(5,4)  # optional - gap_packages
Traceback (most recent call last):
...
ValueError: p must be 0 or prime
```

This computes \( H^4(S_3, \mathbb{Z}) \) and \( H^4(S_3, \mathbb{Z}/2\mathbb{Z}) \), respectively.

AUTHORS:
• David Joyner and Graham Ellis

REFERENCES:

cohomology_part \((n, p=0)\)
Compute the p-part of the group cohomology \(H^n(G, F)\), where \(F = \mathbb{Z}\) if \(p = 0\) and \(F = \mathbb{Z}/p\mathbb{Z}\) if \(p > 0\) is a prime.
Wraps HAP’s Homology function, written by Graham Ellis, applied to the \(p\)-Sylow subgroup of \(G\).
REQUIRES: GAP package HAP (in gap_packages-*.spkg).
EXAMPLES:

```
sage: G = SymmetricGroup(5)
sage: G.cohomology_part(7,2)  # optional - gap_packages
Multiplicative Abelian group isomorphic to C2 x C2 x C2
sage: G = SymmetricGroup(3)
sage: G.cohomology_part(2,3)  # optional - gap_packages
Multiplicative Abelian group isomorphic to C3
```

AUTHORS:
• David Joyner and Graham Ellis

commutator \((other=None)\)
Returns the commutator subgroup of a group, or of a pair of groups.

INPUT:
• other - default: None - a permutation group.

OUTPUT:
Let \(G\) denote self. If other is None then this method returns the subgroup of \(G\) generated by the set of commutators,
\[
\{[g_1, g_2]|g_1, g_2 \in G\} = \{g_1^{-1}g_2^{-1}g_1g_2|g_1, g_2 \in G\}
\]
Let \(H\) denote other, in the case that it is not None. Then this method returns the group generated by the set of commutators,
\[
\{[g, h]|g \in G \ h \in H\} = \{g^{-1}h^{-1}gh|g \in G \ h \in H\}
\]
The two groups need only be permutation groups, there is no notion of requiring them to explicitly be subgroups of some other group.

Note: For the identical statement, the generators of the returned group can vary from one execution to the next.

EXAMPLES:
sage: G = DiCyclicGroup(4)
sage: G.commutator()
Permutation Group with generators [(1,3,5,7)(2,4,6,8)(9,11,13,15)(10,12,14,16)]

sage: G = SymmetricGroup(5)
sage: H = CyclicPermutationGroup(5)
sage: C = G.commutator(H)
sage: C.is_isomorphic(AlternatingGroup(5))
True

An abelian group will have a trivial commutator.

sage: G = CyclicPermutationGroup(10)
sage: G.commutator()
Permutation Group with generators [()]

The quotient of a group by its commutator is always abelian.

sage: G = DihedralGroup(20)
sage: C = G.commutator()
sage: Q = G.quotient(C)
sage: Q.is_abelian()
True

When forming commutators from two groups, the order of the groups does not matter.

sage: D = DihedralGroup(3)
sage: S = SymmetricGroup(2)
sage: C1 = D.commutator(S); C1
Permutation Group with generators [(1,2,3)]
sage: C2 = S.commutator(D); C2
Permutation Group with generators [(1,3,2)]
sage: C1 == C2
True

This method calls two different functions in GAP, so this tests that their results are consistent. The commutator groups may have different generators, but the groups are equal.

sage: G = DiCyclicGroup(3)
sage: C = G.commutator(); C
Permutation Group with generators [(5,7,6)]
sage: CC = G.commutator(G); CC
Permutation Group with generators [(5,6,7)]
sage: C == CC
True

The second group is checked.

sage: G = SymmetricGroup(2)
sage: G.commutator('junk')
Traceback (most recent call last):
...
TypeError: junk is not a permutation group

**composition_series()**

Return the composition series of this group as a list of permutation groups.
EXAMPLES:

These computations use pseudo-random numbers, so we set the seed for reproducible testing.

```python
sage: set_random_seed(0)
sage: G = PermutationGroup([(1,2,3),(4,5)], [(3,4)])
sage: G.composition_series()  # random output
[Permutation Group with generators [(1,2,3)(4,5), (3,4)], Permutation Group with generators [(1,5)(3,4), (1,5)(2,3), (1,5,4)], Permutation Group with generators [()]]
sage: G = PermutationGroup([(1,2,3),(4,5)], [(1,2)])
sage: CS = G.composition_series()
sage: CS[3]
Subgroup generated by [()] of (Permutation Group with generators [(1,2), (1,2,3)(4,5)])
```

`conjugacy_class(g)`

Return the conjugacy class of `g` inside the group `self`.

**INPUT:**

- `g` – an element of the permutation group `self`

**OUTPUT:**

The conjugacy class of `g` in the group `self`. If `self` is the group denoted by `G`, this method computes the set `\{x^{-1}gx \mid x \in G\}`

**EXAMPLES:**

```python
sage: G = DihedralGroup(3)
sage: g = G.gen(0)
sage: G.conjugacy_class(g)
Conjugacy class of (1,2,3) in Dihedral group of order 6 as a permutation group
```

`conjugacy_classes()`

Return a list with all the conjugacy classes of `self`.

**EXAMPLES:**

```python
sage: G = DihedralGroup(3)
sage: G.conjugacy_classes()
[Conjugacy class of () in Dihedral group of order 6 as a permutation group,
Conjugacy class of (2,3) in Dihedral group of order 6 as a permutation group,
Conjugacy class of (1,2,3) in Dihedral group of order 6 as a permutation group]
```

`conjugacy_classes_representatives()`

Returns a complete list of representatives of conjugacy classes in a permutation group `G`.

The ordering is that given by GAP.

**EXAMPLES:**

```python
sage: G = PermutationGroup([(1,2),(3,4)], [(1,2,3,4)])
sage: cl = G.conjugacy_classes_representatives(); cl
[(1, 2, 3)(4, 5), (1, 2)(3, 4), (1, 3)(2, 4)]
sage: cl[3] in G
True
```
sage: G = SymmetricGroup(5)
sage: G.conjugacy_classes_representatives()
[(), (1,2), (1,2)(3,4), (1,2,3), (1,2,3)(4,5), (1,2,3,4), (1,2,3,4,5)]

sage: S = SymmetricGroup(['a','b','c'])
sage: S.conjugacy_classes_representatives()
[(), ('a','b'), ('a','b','c')]

AUTHORS:
• David Joyner and William Stein (2006-01-04)

conjugacy_classes_subgroups()  
Returns a complete list of representatives of conjugacy classes of subgroups in a permutation group \( G \).

The ordering is that given by GAP.

EXAMPLES:

sage: G = PermutationGroup([[(1,2),(3,4)], [(1,2,3,4)]]

sage: cl = G.conjugacy_classes_subgroups()
sage: cl
[Subgroup generated by [()] of (Permutation Group with generators [(1,2)(3,4),
(1,2,3,4)]),
Subgroup generated by [(1,2)(3,4)] of (Permutation Group with generators [(1,
→2)(3,4), (1,2,3,4)]),
Subgroup generated by [(1,3)(2,4)] of (Permutation Group with generators [(1,
→2)(3,4), (1,2,3,4)]),
Subgroup generated by [(2,4)] of (Permutation Group with generators [(1,2)(3,
→4), (1,2,3,4)]),
Subgroup generated by [(1,2)(3,4), (1,4)(2,3)] of (Permutation Group with
generators [(1,2)(3,4), (1,2,3,4)]),
Subgroup generated by [(2,4), (1,2,3)] of (Permutation Group with
generators [(1,2)(3,4), (1,2,3,4)]),
Subgroup generated by [(2,4), (1,3)(2,4)] of (Permutation Group with
generators [(1,2)(3,4), (1,2,3,4)]),
Subgroup generated by [(1,2), (1,2)(3,4), (1,4)(2,3)] of (Permutation Group
together with generators [(1,2)(3,4), (1,2,3,4)]]]

sage: G = SymmetricGroup(3)
sage: G.conjugacy_classes_subgroups()
[Subgroup generated by [()] of (Symmetric group of order 3! as a permutation
→group),
Subgroup generated by [(2,3)] of (Symmetric group of order 3! as a
→permutation group),
Subgroup generated by [(1,2,3)] of (Symmetric group of order 3! as a
→permutation group),
Subgroup generated by [(2,3), (1,2,3)] of (Symmetric group of order 3! as a
→permutation group)]

AUTHORS:
• David Joyner (2006-10)

conjugate\( (g) \)

Returns the group formed by conjugating \( \text{self} \) with \( g \).

INPUT:
- \texttt{g} - a permutation group element, or an object that converts to a permutation group element, such as a list of integers or a string of cycles.

\textbf{OUTPUT:}

If \texttt{self} is the group denoted by \( H \), then this method computes the group

\[ g^{-1}Hg = \{g^{-1}hg \mid h \in H\} \]

which is the group \( H \) conjugated by \( g \).

There are no restrictions on \texttt{self} and \texttt{g} belonging to a common permutation group, and correspondingly, there is no relationship (such as a common parent) between \texttt{self} and the output group.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: G = DihedralGroup(6)
sage: a = PermutationGroupElement("(1,2,3,4)")
sage: G.conjugate(a)
Permutation Group with generators [(1,4)(2,6)(3,5), (1,5,6,2,3,4)]
\end{verbatim}

The element performing the conjugation can be specified in several ways.

\begin{verbatim}
sage: G = DihedralGroup(6)
sage: strng = "(1,2,3,4)"
sage: G.conjugate(strng)
Permutation Group with generators [(1,4)(2,6)(3,5), (1,5,6,2,3,4)]
sage: G = DihedralGroup(6)
sage: lst = [2,3,4,1]
sage: G.conjugate(lst)
Permutation Group with generators [(1,4)(2,6)(3,5), (1,5,6,2,3,4)]
sage: G = DihedralGroup(6)
sage: cycles = [(1,2,3,4)]
sage: G.conjugate(cycles)
Permutation Group with generators [(1,4)(2,6)(3,5), (1,5,6,2,3,4)]
\end{verbatim}

Conjugation is a group automorphism, so conjugate groups will be isomorphic.

\begin{verbatim}
sage: G = DiCyclicGroup(6)
sage: G.degree()
11
sage: cycle = [i+1 for i in range(1,11)] + [1]
sage: C = G.conjugate(cycle)
sage: G.is_isomorphic(C)
True
\end{verbatim}

The conjugating element may be from a symmetric group with larger degree than the group being conjugated.

\begin{verbatim}
sage: G = AlternatingGroup(5)
sage: G.degree()
5
sage: g = "(1,3)(5,6,7)"
sage: H = G.conjugate(g); H
Permutation Group with generators [(1,4,6,3,2), (1,4,6)]
sage: H.degree()
6
\end{verbatim}

The conjugating element is checked.
**sage:** G = SymmetricGroup(3)
**sage:** G.conjugate("junk")
Traceback (most recent call last):
  ...
**TypeError:** junk does not convert to a permutation group element

**construction()**

Return the construction of self.

**EXAMPLES:**

```python
**sage:** P1 = PermutationGroup([[(1,2)]]
**sage:** P1.construction()
(PermutationGroupFunctor[(1,2)], Permutation Group with generators [()])
**sage:** PermutationGroup([]).construction() is None
True
```

This allows us to perform computations like the following:

```python
**sage:** P1 = PermutationGroup([[(1,2)]]); p1 = P1.gen()
**sage:** P2 = PermutationGroup([[(1,3)]]); p2 = P2.gen()
**sage:** p = p1*p2; p
(1,2,3)
**sage:** p.parent()
Permutation Group with generators [(1,2), (1,3)]
**sage:** p.parent().domain()
{1, 2, 3}
```

Note that this will merge permutation groups with different domains:

```python
**sage:** g1 = PermutationGroupElement([(1,2),(3,4,5)])
**sage:** g2 = PermutationGroup([(['a','b'])), domain=[['a', 'b']]].gens()[0]
**sage:** g2
(['a','b'])
**sage:** p = g1*g2; p
(1,2) (3,4,5)('a','b')
```

**cosets (S, side='right')**

Returns a list of the cosets of $S$ in self.

**INPUT:**

- $S$ - a subgroup of self. An error is raised if $S$ is not a subgroup.
- side - default: ‘right’ - determines if right cosets or left cosets are returned. side refers to where the representative is placed in the products forming the cosets and thus allowable values are only ‘right’ and ‘left’.

**OUTPUT:**

A list of lists. Each inner list is a coset of the subgroup in the group. The first element of each coset is the smallest element (based on the ordering of the elements of self) of all the group elements that have not yet appeared in a previous coset. The elements of each coset are in the same order as the subgroup elements used to build the coset’s elements.

As a consequence, the subgroup itself is the first coset, and its first element is the identity element. For each coset, the first element listed is the element used as a representative to build the coset. These representatives form an increasing sequence across the list of cosets, and within a coset the representative is the smallest element of its coset (both orderings are based on the ordering of elements of self).
In the case of a normal subgroup, left and right cosets should appear in the same order as part of the outer list. However, the list of the elements of a particular coset may be in a different order for the right coset versus the order in the left coset. So, if you check to see if a subgroup is normal, it is necessary to sort each individual coset first (but not the list of cosets, due to the ordering of the representatives). See below for examples of this.

**Note:** This is a naive implementation intended for instructional purposes, and hence is slow for larger groups. Sage and GAP provide more sophisticated functions for working quickly with cosets of larger groups.

**EXAMPLES:**

The default is to build right cosets. This example works with the symmetry group of an 8-gon and a normal subgroup. Notice that a straight check on the equality of the output is not sufficient to check normality, while sorting the individual cosets is sufficient to then simply test equality of the list of lists. Study the second coset in each list to understand the need for sorting the elements of the cosets.

```
sage: G = DihedralGroup(8)
sage: quarter_turn = G('(1,3,5,7)(2,4,6,8)'); quarter_turn
(1,3,5,7)(2,4,6,8)
sage: S = G.subgroup([quarter_turn])
sage: rc = G.cosets(S, side='right'); rc
[[()], (1,3,5,7)(2,4,6,8), (1,5)(2,6)(3,7)(4,8), (1,7,5,3)(2,8,6,4)],
[(2,8)(3,7)(4,6), (1,7)(2,6)(3,5), (1,5)(2,4)(6,8), (1,3)(4,8)(5,7)],
[(1,2)(3,8)(4,7)(5,6), (1,8)(2,7)(3,6)(4,5), (1,6)(2,5)(3,4)(7,8), (1,4)(2,8)(3,5)(6,7)],
[(1,2,3,4,5,6,7,8), (1,4,7,2,5,8,3,6), (1,6,3,8,5,2,7,4), (1,8,7,6,5,4,3,2)]
sage: lc = G.cosets(S, side='left'); lc
[[()], (1,3,5,7)(2,4,6,8), (1,5)(2,6)(3,7)(4,8), (1,7,5,3)(2,8,6,4)],
[(2,8)(3,7)(4,6), (1,7)(2,6)(3,5), (1,5)(2,4)(6,8), (1,3)(4,8)(5,7)],
[(1,2)(3,8)(4,7)(5,6), (1,4)(2,3)(5,8)(6,7), (1,6)(2,5)(3,4)(7,8), (1,8)(2,7)(3,5)(6,4)],
[(1,2,3,4,5,6,7,8), (1,4,7,2,5,8,3,6), (1,6,3,8,5,2,7,4), (1,8,7,6,5,4,3,2)]
sage: S.is_normal(G)
True
sage: rc == lc
False
sage: rc_sorted = [sorted(c) for c in rc]
sage: lc_sorted = [sorted(c) for c in lc]
sage: rc_sorted == lc_sorted
True
```

An example with the symmetry group of a regular tetrahedron and a subgroup that is not normal. Thus, the right and left cosets are different (and so are the representatives). With each individual coset sorted, a naive test of normality is possible.

```
sage: A = AlternatingGroup(4)
sage: face_turn = A('(1,2,3)'); face_turn
(1,2,3)
sage: stabilizer = A.subgroup([face_turn])
sage: rc = A.cosets(stabilizer, side='right'); rc
[[()], (1,2,3), (1,3,2)],
[(2,3,4), (1,3)(2,4), (1,4,2)],
[(2,4,3), (1,4,3), (1,2)(3,4)],
[(1,2,4), (1,4)(2,3), (1,3,4)]
```

(continues on next page)
\begin{verbatim}
sage: lc = A.cosets(stabilizer, side='left'); lc
[[(), (1,2,3), (1,3,2)],
 [ (2,3,4), (1,2)(3,4), (1,3,4) ],
 [ (2,4,3), (1,2,4), (1,3)(2,4) ],
 [ (1,4,2), (1,4,3), (1,4)(2,3) ]

sage: stabilizer.is_normal(A)
False
sage: rc_sorted = [sorted(c) for c in rc]
sage: lc_sorted = [sorted(c) for c in lc]
sage: rc_sorted == lc_sorted
False
\end{verbatim}

AUTHOR:

• Rob Beezer (2011-01-31)

degree()

Returns the degree of this permutation group.

EXAMPLES:

\begin{verbatim}
sage: S = SymmetricGroup(['a','b','c'])
sage: S.degree()
3
sage: G = PermutationGroup([(1,3),(4,5)])
sage: G.degree()
5
\end{verbatim}

Note that you can explicitly specify the domain to get a permutation group of smaller degree:

\begin{verbatim}
sage: G = PermutationGroup([(1,3),(4,5)], domain=[1,3,4,5])
sage: G.degree()
4
\end{verbatim}

derived_series()

Return the derived series of this group as a list of permutation groups.

EXAMPLES:

These computations use pseudo-random numbers, so we set the seed for reproducible testing.

\begin{verbatim}
sage: set_random_seed(0)
sage: G = PermutationGroup([[(1,2,3),(4,5)],[(3,4)]])
sage: G.derived_series() # random output
[Permutation Group with generators [(1,2,3)(4,5), (3,4)], Permutation Group
 with generators [(1,5)(3,4), (1,5)(2,4), (2,4)(3,5)]]
\end{verbatim}

direct_product (other, maps=True)

Wraps GAP's DirectProduct, Embedding, and Projection.

Sage calls GAP's DirectProduct, which chooses an efficient representation for the direct product. The direct product of permutation groups will be a permutation group again. For a direct product \( D \), the GAP operation Embedding \((D,i)\) returns the homomorphism embedding the \(i\)-th factor into \(D\). The GAP operation Projection \((D,i)\) gives the projection of \(D\) onto the \(i\)-th factor. This method returns a 5-tuple: a permutation group and 4 morphisms.

INPUT:

• self, other - permutation groups
OUTPUT:

- **D** - a direct product of the inputs, returned as a permutation group as well
- **iota1** - an embedding of `self` into `D`
- **iota2** - an embedding of `other` into `D`
- **pr1** - the projection of `D` onto `self` (giving a splitting `1 - other - D - self - 1`)
- **pr2** - the projection of `D` onto `other` (giving a splitting `1 - self - D - other - 1`)

EXAMPLES:

```python
sage: G = CyclicPermutationGroup(4)
sage: D = G.direct_product(G,False)
sage: D
Permutation Group with generators [(5,6,7,8), (1,2,3,4)]
sage: D, iota1, iota2, pr1, pr2 = G.direct_product(G)
sage: D; iota1; iota2; pr1; pr2
Permutation Group with generators [(5,6,7,8), (1,2,3,4)]
Permutation group morphism:
  From: Cyclic group of order 4 as a permutation group
  To:   Permutation Group with generators [(5,6,7,8), (1,2,3,4)]
  Defn: Embedding( Group( [ (1,2,3,4), (5,6,7,8) ] ), 1 )
Permutation group morphism:
  From: Cyclic group of order 4 as a permutation group
  To:   Permutation Group with generators [(5,6,7,8), (1,2,3,4)]
  Defn: Embedding( Group( [ (1,2,3,4), (5,6,7,8) ] ), 2 )
Permutation group morphism:
  From: Permutation Group with generators [(5,6,7,8), (1,2,3,4)]
  To:   Cyclic group of order 4 as a permutation group
  Defn: Projection( Group( [ (1,2,3,4), (5,6,7,8) ] ), 1 )
Permutation group morphism:
  From: Permutation Group with generators [(5,6,7,8), (1,2,3,4)]
  To:   Cyclic group of order 4 as a permutation group
  Defn: Projection( Group( [ (1,2,3,4), (5,6,7,8) ] ), 2 )
sage: g=D([(1,3),(2,4)]); g
(1,3)(2,4)
sage: d=D([(1,4,3,2),(5,7),(6,8)]); d
(1,4,3,2)(5,7)(6,8)
sage: iota1(g); iota2(g); pr1(d); pr2(d)
(1,3)(2,4)
(5,7)(6,8)
(1,4,3,2)
(1,3)(2,4)
```

domain()  
Returns the underlying set that this permutation group acts on.

EXAMPLES:

```python
sage: P = PermutationGroup([(1,2),(3,5)])
sage: P.domain()
{1, 2, 3, 4, 5}
sage: S = SymmetricGroup(['a', 'b', 'c'])
sage: S.domain()
{'a', 'b', 'c'}
```

exponent()  
Computes the exponent of the group.
The exponent $e$ of a group $G$ is the LCM of the orders of its elements, that is, $e$ is the smallest integer such that $g^e = 1$ for all $g \in G$.

**EXAMPLES:**

```python
sage: G = AlternatingGroup(4)
sage: G.exponent()
6
```

**fitting_subgroup()**

Returns the Fitting subgroup of self.

The Fitting subgroup of a group $G$ is the largest nilpotent normal subgroup of $G$.

**EXAMPLES:**

```python
sage: G=PermutationGroup([[(1,2,3,4)],[(2,4)]]
sage: G.fitting_subgroup()
Subgroup generated by [(2,4), (1,2,3,4), (1,3)] of (Permutation Group with generators [(2,4), (1,2,3,4)])
sage: G=PermutationGroup([[(1,2,3,4)],[(1,2)]]
sage: G.fitting_subgroup()
Subgroup generated by [(1,2)(3,4), (1,3)(2,4)] of (Permutation Group with generators [(1,2), (1,2,3,4)])
```

**fixed_points()**

Return the list of points fixed by self, i.e., the subset of .domain() not moved by any element of self.

**EXAMPLES:**

```python
sage: G = PermutationGroup([[(1,2,3)]]
sage: G.fixed_points()
[]
sage: G = PermutationGroup([[(1,2,3),(5,6)]]
sage: G.fixed_points()
[4]
sage: G = PermutationGroup([[(1,4,7)],[(4,3),(6,7)]]
sage: G.fixed_points()
[2, 5]
```

**frattini_subgroup()**

Returns the Frattini subgroup of self.

The Frattini subgroup of a group $G$ is the intersection of all maximal subgroups of $G$.

**EXAMPLES:**

```python
sage: G=PermutationGroup([[(1,2,3,4)],[(2,4)]]
sage: G.frattini_subgroup()
Subgroup generated by [(1,3)(2,4)] of (Permutation Group with generators [(2,4), (1,2,3,4)])
sage: G=SymmetricGroup(4)
sage: G.frattini_subgroup()
Subgroup generated by [(1,2)] of (Symmetric group of order 4! as a permutation group)
```

**gap()**

this method from sage.groups.libgap_wrapper.ParentLibGAP is added in order to achieve
compatibility and have `sage.groups.libgap_morphism.GroupHomset_libgap` work for permutation groups, as well

OUTPUT:

an instance of `sage.libs.gap.element.GapElement` representing this group

EXAMPLES:

```python
sage: P8=PSp(8,3)
sage: P8.gap()
<permutation group of size 65784756654489600 with 2 generators>
sage: gap(P8) == P8.gap()
False
sage: S3 = SymmetricGroup(3)
sage: S3.gap()
Sym( [ 1 .. 3 ] )
sage: gap(S3) == S3.gap()
False
```

`gen(i=None)`

Returns the i-th generator of self; that is, the i-th element of the list `self.gens()`.

The argument `i` may be omitted if there is only one generator (but this will raise an error otherwise).

EXAMPLES:

We explicitly construct the alternating group on four elements:

```python
sage: A4 = PermutationGroup([[(1,2,3)],[(2,3,4)]]); A4
Permutation Group with generators [(2,3,4), (1,2,3)]
sage: A4.gens()
[(2,3,4), (1,2,3)]
sage: A4.gen(0)
(2,3,4)
sage: A4.gen(1)
(1,2,3)
sage: A4.gens()[0]; A4.gens()[1]
(2,3,4)
(1,2,3)
sage: P1 = PermutationGroup([[(1,2)]]); P1.gen()
(1,2)
```

gens()

Return tuple of generators of this group. These need not be minimal, as they are the generators used in defining this group.

EXAMPLES:

```python
sage: G = PermutationGroup([[(1,2,3)], [(1,2)]])
sage: G.gens()
[(1,2,3), (1,2,3)]
```

Note that the generators need not be minimal, though duplicates are removed:

```python
sage: G = PermutationGroup([[(1,2)], [(1,3)], [(2,3)], [(1,2)]])
sage: G.gens()
[(2,3), (1,2), (1,3)]
```

We can use index notation to access the generators returned by `self.gens`:
sage: G = PermutationGroup([[(1,2,3,4), (5,6)], [(1,2)]])
sage: g = G.gens()
sage: g[0]
(1,2)
sage: g[1]
(1,2,3,4)(5,6)

sage: G = PermutationGroup([R,L,U,F,B,D])
sage: len(G.gens_small())
2
The output may be unpredictable, due to the use of randomized algorithms in GAP. Note that both the following answers are equally valid.

sage: G = PermutationGroup([[(1,2,3),(4,5)], [(1,5),(2,4)]]

sage: G.group_id()
[12, 4]

sage: G = PermutationGroup([[(1,2,3,4,5)], [(1,5),(2,4)]]

sage: G.group_primitive_id()
From the information of the degree and the identification number, you can recover the isomorphism class of your group in the GAP database:

```python
sage: H = PrimitiveGroup(5,2)
sage: G == H
False
sage: G.is_isomorphic(H)
True
```

**has_element** *(item)*

Returns boolean value of item in self - however ignores parentage.

**EXAMPLES:**

```python
sage: G = CyclicPermutationGroup(4)
sage: gens = G.gens()
sage: H = DihedralGroup(4)
sage: g = G([(1,2,3,4)]); g
(1,2,3,4)
sage: G.has_element(g)
True
sage: h = H([(1,2),(3,4)]); h
(1,2)(3,4)
sage: G.has_element(h)
False
```

**has_regular_subgroup** *(return_group=False)*

Return whether the group contains a regular subgroup.

**INPUT:**

- `return_group` (boolean) – If `return_group = True`, a regular subgroup is returned if there is one, and `None` if there isn’t. When `return_group = False` (default), only a boolean indicating whether such a group exists is returned instead.

**EXAMPLES:**

The symmetric group on 4 elements has a regular subgroup:

```python
sage: S4 = groups.permutation.Symmetric(4)
sage: S4.has_regular_subgroup()
True
sage: S4.has_regular_subgroup(return_group = True) # random
Subgroup of (Symmetric group of order 4! as a permutation group) generated by
\[
\{(1,3)(2,4), (1,4)(2,3)\}
```

But the automorphism group of Petersen’s graph does not:

```python
sage: G = graphs.PetersenGraph().automorphism_group()
sage: G.has_regular_subgroup()
False
```

**holomorph**

The holomorph of a group as a permutation group.
The holomorph of a group $G$ is the semidirect product $G \rtimes_{id} \text{Aut}(G)$, where $id$ is the identity function on $\text{Aut}(G)$, the automorphism group of $G$.

See Wikipedia article Holomorph (mathematics)

OUTPUT:

Returns the holomorph of a given group as permutation group via a wrapping of GAP’s semidirect product function.

EXAMPLES:

Thomas and Wood’s ‘Group Tables’ (Shiva Publishing, 1980) tells us that the holomorph of $C_5$ is the unique group of order 20 with a trivial center.

```
sage: C5 = CyclicPermutationGroup(5)
sage: A = C5.holomorph()
sage: A.order()
20
sage: A.is_abelian()
False
sage: A.center()
Subgroup generated by [()] of (Permutation Group with generators [(5,6,7,8,9), (1,2,4,3)(6,7,9,8)])
sage: A
Permutation Group with generators [(5,6,7,8,9), (1,2,4,3)(6,7,9,8)]
```

Noting that the automorphism group of $D_4$ is itself $D_4$, it can easily be shown that the holomorph is indeed an internal semidirect product of these two groups.

```
sage: D4 = DihedralGroup(4)
sage: H = D4.holomorph()
sage: H.gens()
[(3,8)(4,7), (2,3,5,8), (2,5)(3,8), (1,4,6,7)(2,3,5,8), (1,8)(2,7)(3,6)(4,5)]
sage: G = H.subgroup([H.gens()[0],H.gens()[1],H.gens()[2]])
sage: N = H.subgroup([H.gens()[3],H.gens()[4]])
sage: N.is_normal(H)
True
sage: G.is_isomorphic(D4)
True
sage: N.is_isomorphic(D4)
True
sage: G.intersection(N)
Permutation Group with generators [()]
sage: L = [H(x)*H(y) for x in G for y in N]; L.sort()
sage: L1 = H.list(); L1.sort()
sage: L == L1
True
```

Author:

- Kevin Halasz (2012-08-14)

**homology** $(n, p=0)$

Computes the group homology $H_n(G, F)$, where $F = \mathbb{Z}$ if $p = 0$ and $F = \mathbb{Z}/p\mathbb{Z}$ if $p > 0$ is a prime.

Wraps HAP’s GroupHomology function, written by Graham Ellis.

REQUIRES: GAP package HAP (in gap_packages-*.spkg).

AUTHORS:

- David Joyner and Graham Ellis
The example below computes $H_7(S_5, \mathbb{Z})$, $H_7(S_5, \mathbb{Z}/2\mathbb{Z})$, $H_7(S_5, \mathbb{Z}/3\mathbb{Z})$, and $H_7(S_5, \mathbb{Z}/5\mathbb{Z})$, respectively. To compute the 2-part of $H_7(S_5, \mathbb{Z})$, use the `homology_part` function.

**EXAMPLES:**

```python
sage: G = SymmetricGroup(5)
sage: G.homology(7) # optional - gap_packages
Multiplicative Abelian group isomorphic to C2 x C2 x C4 x C3 x C5
sage: G.homology(7,2) # optional - gap_packages
Multiplicative Abelian group isomorphic to C2 x C2 x C2 x C2 x C2
sage: G.homology(7,3) # optional - gap_packages
Multiplicative Abelian group isomorphic to C3
sage: G.homology(7,5) # optional - gap_packages
Multiplicative Abelian group isomorphic to C5
```

**REFERENCES:**


**homology_part** $(n, p=0)$

Computes the $p$-part of the group homology $H_n(G, F)$, where $F = \mathbb{Z}$ if $p = 0$ and $F = \mathbb{Z}/p\mathbb{Z}$ if $p > 0$ is a prime. Wraps HAP’s `Homology` function, written by Graham Ellis, applied to the $p$-Sylow subgroup of $G$.

REQUIRES: GAP package HAP (in gap_packages-* .spkg).

**EXAMPLES:**

```python
sage: G = SymmetricGroup(5)
sage: G.homology_part(7,2) # optional - gap_packages
Multiplicative Abelian group isomorphic to C2 x C2 x C2 x C2 x C4
```

**AUTHORS:**

- David Joyner and Graham Ellis

**id()**

( Same as `self.group_id()`.) Return the ID code of this group, which is a list of two integers.

**EXAMPLES:**

```python
sage: G = PermutationGroup([[1,2,3],[4,5]],[1,2]])
sage: G.group_id()
[12, 4]
```

**identity()**

Return the identity element of this group.

**EXAMPLES:**

```python
sage: G = PermutationGroup([[1,2,3],[4,5]])
sage: e = G.identity()
sage: e()
sage: g = G.gen(0)
sage: g*e
```

(continues on next page)
intersection (other)

Returns the permutation group that is the intersection of self and other.

INPUT:

- other - a permutation group.

OUTPUT:

A permutation group that is the set-theoretic intersection of self with other. The groups are viewed as subgroups of a symmetric group big enough to contain both group’s symbol sets. So there is no strict notion of the two groups being subgroups of a common parent.

EXAMPLES:

```python
sage: H = DihedralGroup(4)
sage: K = CyclicPermutationGroup(4)
sage: H.intersection(K)
Permutation Group with generators [(1,2,3,4)]
sage: L = DihedralGroup(5)
sage: H.intersection(L)
Permutation Group with generators [(1,4)(2,3)]
sage: M = PermutationGroup(["()")
sage: H.intersection(M)
Permutation Group with generators [()]
```

Some basic properties.

```python
sage: H = DihedralGroup(4)
sage: L = DihedralGroup(5)
sage: H.intersection(L) == L.intersection(H)
True
sage: H.intersection(H) == H
True
```

The group other is verified as such.

```python
sage: H = DihedralGroup(4)
sage: H.intersection('junk')
Traceback (most recent call last):
  ... TypeError: junk is not a permutation group
```

irreducible_characters ()

Returns a list of the irreducible characters of self.

EXAMPLES:
sage: irr = SymmetricGroup(3).irreducible_characters()
sage: [x.values() for x in irr]
[[1, -1, 1], [2, 0, -1], [1, 1, 1]]

is_abelian()
Return True if this group is abelian.

EXAMPLES:

sage: G = PermutationGroup(['(1,2,3)(4,5)', '(1,2,3,4,5)'])
sage: G.is_abelian()
False
sage: G = PermutationGroup(['(1,2,3)(4,5)'])
sage: G.is_abelian()
True

is_commutative()
Return True if this group is commutative.

EXAMPLES:

sage: G = PermutationGroup(['(1,2,3)(4,5)', '(1,2,3,4,5)'])
sage: G.is_commutative()
False
sage: G = PermutationGroup(['(1,2,3)(4,5)'])
sage: G.is_commutative()
True

is_cyclic()
Return True if this group is cyclic.

EXAMPLES:

sage: G = PermutationGroup(['(1,2,3)(4,5)', '(1,2,3,4,5)'])
sage: G.is_cyclic()
False
sage: G = PermutationGroup(['(1,2,3)(4,5)'])
sage: G.is_cyclic()
True

is_elementary_abelian()
Return True if this group is elementary abelian. An elementary abelian group is a finite abelian group, where every nontrivial element has order \( p \), where \( p \) is a prime.

EXAMPLES:

sage: G = PermutationGroup(['(1,2,3)(4,5)', '(1,2,3,4,5)'])
sage: G.is_elementary_abelian()
False
sage: G = PermutationGroup(['(1,2,3)', '(4,5,6)'])
sage: G.is_elementary_abelian()
True

is_isomorphic(right)
Return True if the groups are isomorphic.

INPUT:

- self - this group
• right - a permutation group

OUTPUT:

• boolean; True if self and right are isomorphic groups; False otherwise.

EXAMPLES:

```python
sage: v = ['(1,2,3)(4,5)', '(1,2,3,4,5)']
sage: G = PermutationGroup(v)
sage: H = PermutationGroup(['(1,2,3)(4,5)'])
sage: G.is_isomorphic(H)
False
sage: G.is_isomorphic(G)
True
sage: G.is_isomorphic(PermutationGroup(list(reversed(v))))
True
```

**is_monomial()**

Returns True if the group is monomial. A finite group is monomial if every irreducible complex character is induced from a linear character of a subgroup.

EXAMPLES:

```python
sage: G = PermutationGroup(['(1,2,3)(4,5)'])
sage: G.is_monomial()
True
```

**is_nilpotent()**

Return True if this group is nilpotent.

EXAMPLES:

```python
sage: G = PermutationGroup(['(1,2,3)(4,5)', '(1,2,3,4,5)'])
sage: G.is_nilpotent()
False
sage: G = PermutationGroup(['(1,2,3)(4,5)'])
sage: G.is_nilpotent()
True
```

**is_normal**(other)

Return True if this group is a normal subgroup of other.

EXAMPLES:

```python
sage: AlternatingGroup(4).is_normal(SymmetricGroup(4))
True
sage: H = PermutationGroup(['(1,2,3)(4,5)'])
sage: G = PermutationGroup(['(1,2,3)(4,5)', '(1,2,3,4,5)'])
sage: H.is_normal(G)
False
```

**is_perfect()**

Return True if this group is perfect. A group is perfect if it equals its derived subgroup.

EXAMPLES:

```python
sage: G = PermutationGroup(['(1,2,3)(4,5)', '(1,2,3,4,5)'])
sage: G.is_perfect()
False
```

(continues on next page)
sage: G = PermutationGroup(['(1,2,3)(4,5)'])
sage: G.is_perfect()
False

is_pgroup()
Returns True if this group is a p-group. A finite group is a p-group if its order is of the form \( p^n \) for a prime integer \( p \) and a nonnegative integer \( n \).

EXAMPLES:

sage: G = PermutationGroup(['(1,2,3,4,5)'])
sage: G.is_pgroup()
True

is_polycyclic()
Return True if this group is polycyclic. A group is polycyclic if it has a subnormal series with cyclic factors. (For finite groups, this is the same as if the group is solvable - see is_solvable.)

EXAMPLES:

sage: G = PermutationGroup(['(1,2,3) (4,5)', '(1,2,3,4,5)'])
sage: G.is_polycyclic()
False
sage: G = PermutationGroup(['(1,2,3) (4,5)'])
sage: G.is_polycyclic()
True

is_primitive(domain=None)
Returns True if self acts primitively on domain. A group \( G \) acts primitively on a set \( S \) if

1. \( G \) acts transitively on \( S \) and
2. the action induces no non-trivial block system on \( S \).

INPUT:

• domain (optional)

See also:

• blocks_all()

EXAMPLES:

By default, test for primitivity of self on its domain:

sage: G = PermutationGroup([[1,2,3,4],[1,2]])
sage: G.is_primitive()
True
sage: G = PermutationGroup([[1,2,3,4],[2,4]])
sage: G.is_primitive()
False

You can specify a domain on which to test primitivity:

sage: G = PermutationGroup([[1,2,3,4],[2,4]])
sage: G.is_primitive([1..4])
False
sage: G.isPrimitive([1,2,3])
True
sage: G = PermutationGroup([[3,4,5,6],[3,4]]) # S_4 on [3..6]
G = PermutationGroup([[(3,4,5,6)],[(3,4)]])
G.isPrimitive(G.non_fixed_points())
True

### is_regular\( (\text{domain}=\text{None}) \)

Returns True if self acts regularly on domain. A group \( G \) acts regularly on a set \( S \) if

1. \( G \) acts transitively on \( S \) and
2. \( G \) acts semi-regularly on \( S \).

**EXAMPLES:**

```python
sage: G = PermutationGroup([[1,2,3,4]])
sage: G.is_regular()
True
sage: G = PermutationGroup([[1,2,3,4],[5,6]])
sage: G.is_regular()
False
```

You can pass in a domain on which to test regularity:

```python
sage: G = PermutationGroup([[1,2,3,4],[5,6]])
sage: G.is_regular([1..4])
True
sage: G.is_regular(G.non_fixed_points())
False
```

### is_semi_regular\( (\text{domain}=\text{None}) \)

Returns True if self acts semi-regularly on domain. A group \( G \) acts semi-regularly on a set \( S \) if the point stabilizers of \( S \) in \( G \) are trivial.

**EXAMPLES:**

```python
sage: G = PermutationGroup([[1,2,3,4]])
sage: G.is_semi_regular()
True
sage: G = PermutationGroup([[1,2,3,4],[5,6]])
sage: G.is_semi_regular()
False
```

You can pass in a domain to test semi-regularity:

```python
sage: G = PermutationGroup([[1,2,3,4],[5,6]])
sage: G.is_semi_regular([1..4])
True
sage: G.is_semi_regular(G.non_fixed_points())
False
```

### is_simple\()

Returns True if the group is simple. A group is simple if it has no proper normal subgroups.

**EXAMPLES:**

```python
sage: G = PermutationGroup([[1,2,3,4],[5,6]])
sage: G.is_semi_regular([1..4])
True
sage: G.is_semi_regular(G.non_fixed_points())
False
```
sage: G = PermutationGroup(['(1,2,3)(4,5)'])
sage: G.is_simple()
False

\textbf{is\_solvable}()
\hspace{1em} Returns True if the group is solvable.

EXAMPLES:

sage: G = PermutationGroup(['(1,2,3)(4,5)'])
sage: G.is_solvable()
True

\textbf{is\_subgroup} (other)
\hspace{1em} Returns True if \texttt{self} is a subgroup of \texttt{other}.

EXAMPLES:

sage: G = AlternatingGroup(5)
sage: H = SymmetricGroup(5)
sage: G.is_subgroup(H)
True

\textbf{is\_supersolvable}()
\hspace{1em} Returns True if the group is supersolvable. A finite group is supersolvable if it has a normal series with cyclic factors.

EXAMPLES:

sage: G = PermutationGroup(['(1,2,3)(4,5)'])
sage: G.is_supersolvable()
True

\textbf{is\_transitive} (domain=None)
\hspace{1em} Returns True if \texttt{self} acts transitively on \texttt{domain}. A group \(G\) acts transitively on set \(S\) if for all \(x, y \in S\) there is some \(g \in G\) such that \(x^g = y\).

EXAMPLES:

sage: G = SymmetricGroup(5)
sage: G.is_transitive()
True

sage: G = PermutationGroup(['(1,2)(3,4)(5,6)'])
sage: G.is_transitive()
False

sage: G = PermutationGroup([[(1,2,3,4,5)],[(1,2)]]);
#S_5 on [1..5]
sage: G.is_transitive([4,5])
True

sage: G.is_transitive([2,6])
False

sage: G.is_transitive(G.non_fixed_points())
True

sage: H = PermutationGroup([[(1,2,3)],[4,5,6]])
sage: H.is_transitive(H.non_fixed_points())
False

Note that this differs from the definition in GAP, where \texttt{IsTransitive} returns whether the group is transitive on the set of points moved by the group.
sage: G = PermutationGroup([(2,3)])
sage: G.is_transitive()
False
sage: gap(G).IsTransitive()
true

**isomorphism_to(right)**

Return an isomorphism from self to right if the groups are isomorphic, otherwise None.

**INPUT:**

- **self** - this group
- **right** - a permutation group

**OUTPUT:**

- None or a morphism of permutation groups.

**EXAMPLES:**

```python
sage: G = PermutationGroup(['(1,2,3)(4,5)', '(1,2,3,4,5)'])
sage: H = PermutationGroup(['(1,2,3)(4,5)'])
sage: G.isomorphism_to(H)  # not tested, see below
Permutation group morphism:
  From: Permutation Group with generators [(2,3), (1,2,3)]
  To:     Permutation Group with generators [(1,2,4), (1,4)]
  Defn:  [(2,3), (1,2,3)] -> [(2,4), (1,2,4)]
```

**isomorphism_type_info_simple_group()**

If the group is simple, then this returns the name of the group.

**EXAMPLES:**

```python
sage: G = CyclicPermutationGroup(5)
sage: G.isomorphism_type_info_simple_group()
rec(
    name := "Z(5)",
    parameter := 5,
    series := "Z",
    shortname := "C5"
)
```

**iteration(algorithm='SGS')**

Return an iterator over the elements of this group.

**INPUT:**

- **algorithm** - (default: "SGS") either
  - "SGS" - using strong generating system
  - "BFS" - a breadth first search on the Cayley graph with respect to self.gens()
  - "DFS" - a depth first search on the Cayley graph with respect to self.gens()
Note: In general, the algorithm "SGS" is faster. Yet, for small groups, "BFS" and "DFS" might be faster.

Note: The order in which the iterator visits the elements differs in the algorithms.

EXAMPLES:

```
sage: G = PermutationGroup([(1,2), (2,3)])
sage: list(G.iteration())
[(), (1,2,3), (1,3,2), (2,3), (1,2), (1,3)]
sage: list(G.iteration(algorithm="BFS"))
[(), (2,3), (1,2), (1,3,2), (1,2,3), (1,3)]
sage: list(G.iteration(algorithm="DFS"))
[(), (1,2), (1,3,2), (1,3), (1,2,3), (2,3)]
```

```
largest_moved_point()

Return the largest point moved by a permutation in this group.

EXAMPLES:

```
sage: G = PermutationGroup([(1,2),(3,4)], [(1,2,3,4)])
sage: G.largest_moved_point()
4
```

```
sage: G = PermutationGroup([(1,2),(3,4)], [(1,2,3,4,10)])
sage: G.largest_moved_point()
10
```

```
sage: G = PermutationGroup([('a','b','c'), ('d','e')])
sage: G.largest_moved_point()
'e'
```

Warning: The name of this function is not good; this function should be deprecated in term of degree:

```
sage: P = PermutationGroup([(1,2,3,4)])
sage: P.largest_moved_point()
4
```

```
sage: P.cardinality()
1
```

```
list()

Return list of all elements of this group.

EXAMPLES:

```
sage: G = PermutationGroup([(1,2,3,4)], [(1,2)])
sage: G.list()
[(), (1,4)(2,3), (1,2)(3,4), (1,3)(2,4), (2,4,3), (1,4,2),
 (1,2,3), (1,3,4), (2,3,4), (1,4,3), (1,2,4), (1,3,2), (3,4),
 (1,4,2,3), (1,2), (1,3,2,4), (2,4), (1,4,3,2), (1,2,3,4),
(continues on next page)
```
lower_central_series()

Return the lower central series of this group as a list of permutation groups.

EXAMPLES:

These computations use pseudo-random numbers, so we set the seed for reproducible testing.

sage: set_random_seed(0)
sage: G = PermutationGroup([(1,2,3),(4,5)], [(3,4)])
sage: G.lower_central_series()  # random output
[Permutation Group with generators [(1,2,3)(4,5), (3,4)], Permutation Group with generators [(1,5)(3,4), (1,5)(2,3), (1,3)(2,4)]]

minimal_generating_set()

Return a minimal generating set.

EXAMPLES:

sage: g = graphs.CompleteGraph(4)
sage: g.relabel(['a','b','c','d'])
sage: mgs = g.automorphism_group().minimal_generating_set(); len(mgs)
2
sage: mgs  # random
[['b','d','c'], ['a','c','b','d']]

molien_series()

Return the Molien series of a permutation group. The function

\[ M(x) = \frac{1}{|G|} \sum_{g \in G} \det(1 - x \cdot g)^{-1} \]

is sometimes called the “Molien series” of \( G \). GAP’s MolienSeries is associated to a character of a group \( G \). How are these related? A group \( G \), given as a permutation group on \( n \) points, has a “natural” representation of dimension \( n \), given by permutation matrices. The Molien series of \( G \) is the one associated to that permutation representation of \( G \) using the above formula. Character values then count fixed points of the corresponding permutations.

EXAMPLES:

sage: G = SymmetricGroup(5)
sage: G.molien_series()
-1/(x^15 - x^14 - x^13 + x^10 + x^9 + x^8 - x^7 - x^6 - x^5 + x^2 + x - 1)
sage: G = SymmetricGroup(3)
sage: G.molien_series()
-1/(x^6 - x^5 - x^4 + x^2 + x - 1)

Some further tests (after trac ticket #15817):

sage: G = PermutationGroup([(1,2,3,4)])
sage: S4ms = SymmetricGroup(4).molien_series()
sage: G.molien_series() / S4ms
x^5 + 2*x^4 + x^3 + x^2 + 1

This works for not-transitive groups:

sage: G = PermutationGroup([[(1,2)],[[3,4]]])
sage: G.molien_series() / S4ms
x^4 + x^3 + 2*x^2 + x + 1

This works for groups with fixed points:

sage: G = PermutationGroup([[(2,)]])
sage: G.molien_series()
1/(x^2 - 2*x + 1)

ngens()

Return the number of generators of self.

EXAMPLES:

sage: A4 = PermutationGroup([[(1,2,3)],[[2,3,4]]]); A4
Permutation Group with generators [(2,3,4), (1,2,3)]
sage: A4.ngens()
2

non_fixed_points()

Return the list of points not fixed by self, i.e., the subset of self.domain() moved by some element of self.

EXAMPLES:

sage: G = PermutationGroup([[(3,4,5)],[[7,10]]])
sage: G.non_fixed_points()
[3, 4, 5, 7, 10]
sage: G = PermutationGroup([[(2,3,6)],[[9,]]]) # note: 9 is fixed
sage: G.non_fixed_points()
[2, 3, 6]

normal_subgroups()

Return the normal subgroups of this group as a (sorted in increasing order) list of permutation groups.

The normal subgroups of \( H = PSL(2,7) \times PSL(2,7) \) are 1, two copies of \( PSL(2,7) \) and \( H \) itself, as the following example shows.

EXAMPLES:

sage: G = PSL(2,7)
sage: D = G.direct_product(G)
sage: H = D[0]
sage: NH = H.normal_subgroups()
sage: len(NH)
4
sage: NH[1].is_isomorphic(G)
True
sage: NH[2].is_isomorphic(G)
True
normalizer\((g)\)

Returns the normalizer of \(g\) in self.

EXAMPLES:

```
sage: G = PermutationGroup([[1,2),(3,4)], [(1,2,3,4)])
sage: g = G([(1,3)])
sage: G.normalizer(g)
Subgroup generated by [(2,4), (1,3)] of (Permutation Group with generators
     -> [(1,2)(3,4), (1,2,3,4)])
sage: g = G([(1,2,3,4)])
sage: G.normalizer(g)
Subgroup generated by [(2,4), (1,2,3,4), (1,3)(2,4)] of (Permutation Group
     -> with generators [(1,2)(3,4), (1,2,3,4)])
sage: H = G.subgroup([G([(1,2,3,4)])])
sage: G.normalizer(H)
Subgroup generated by [(2,4), (1,2,3,4), (1,3)(2,4)] of (Permutation Group
     -> with generators [(1,2)(3,4), (1,2,3,4)])
```

normalizes\((\text{other})\)

Returns True if the group \(\text{other}\) is normalized by self. Wraps GAP’s IsNormal function.

A group \(G\) normalizes a group \(U\) if and only if for every \(g \in G\) and \(u \in U\) the element \(u^g\) is a member of \(U\). Note that \(U\) need not be a subgroup of \(G\).

EXAMPLES:

```
sage: G = PermutationGroup(['(1,2,3)(4,5)'])
sage: H = PermutationGroup(['(1,2,3)(4,5)', '(1,2,3,4,5)'])
sage: H.normalizes(G)
False
sage: G = SymmetricGroup(3)
```

```
sage: H = PermutationGroup( [ (4,5,6) ] )
sage: G.normalizes(H)
True
sage: H.normalizes(G)
True
```

In the last example, \(G\) and \(H\) are disjoint, so each normalizes the other.

orbit\((\text{point}, \text{action}=\text{\textquoteleft OnPoints\textquoteright})\)

Return the orbit of a point under a group action.

INPUT:

- point – can be a point or any of the list above, depending on the action to be considered.
- action – string. if point is an element from the domain, a tuple of elements of the domain, a tuple of tuples [...], this variable describes how the group is acting. The actions currently available through this method are "OnPoints", "OnTuples", "OnSets", "OnPairs", "OnSetsSets", "OnSetsDisjointSets", "OnSetsTuples", "OnTuplesSets", "OnTuplesTuples". They are taken from GAP’s list of group actions, see gap.help('Group Actions').

It is set to "OnPoints" by default. See below for examples.

OUTPUT:

The orbit of point as a tuple. Each entry is an image under the action of the permutation group, if necessary converted to the corresponding container. That is, if action='OnSets' then each entry will be a set even if point was given by a list/tuple/iterable.
EXAMPLES:

```python
sage: G = PermutationGroup([[(3,4)], [(1,3)]]
```
```
sage: G.orbit(3)
(3, 4, 1)
```
```
sage: G = PermutationGroup([[(1,2),(3,4), (3,4,10)]])
```
```
sage: G.orbit(3)
(3, 4, 10, 1, 2)
```
```
sage: G = PermutationGroup([ [(c,d)],[ (a,c)] ])
```
```
sage: G.orbit('a')
('a', 'c', 'd')
```

Action of $S_3$ on sets:

```python
sage: S3 = groups.permutation.Symmetric(3)
```
```
sage: S3.orbit((1,2), action = "OnSets")
((1, 2), (2, 3), (1, 3))
```

On tuples:

```python
sage: S3.orbit((1,2), action = "OnTuples")
((1, 2), (2, 3), (2, 1), (3, 1), (1, 3), (3, 2))
```

Action of $S_4$ on sets of disjoint sets:

```python
sage: S4 = groups.permutation.Symmetric(4)
```
```
sage: S4.orbit(((1,2),(3,4)), action = "OnSetsDisjointSets")
({{1, 2}, {3, 4}}, {{2, 3}, {1, 4}}, {{1, 3}, {2, 4}})
```

Action of $S_4$ (on a nonstandard domain) on tuples of sets:

```python
sage: S4 = PermutationGroup([ [(c,d)], [(a,c)], [(a,b)] ])
```
```
sage: S4.orbit(('a', 'c'),('b', 'd'),"OnTuplesSets")
(('a', 'c'), ('b', 'd'),
(('a', 'd'), ('c', 'b')),
(('c', 'b'), ('a', 'd')),
(('b', 'd'), ('a', 'c')),
(('c', 'd'), ('a', 'b')),
(('a', 'b'), ('c', 'd')))
```

Action of $S_4$ (on a very nonstandard domain) on tuples of sets:

```python
sage: S4 = PermutationGroup([ [(11, (12, 13)), 'd']],
.....
```
```
```
sage: S4.orbit((( (11,(12,13)), (12,(12,11))),('b','d')),"OnTuplesSets")
(( (11, (12, 13)), (12, (12, 11))), ('b', 'd')),
(( 'd', (12, (12, 11))), (11, (12, 13)), 'b')),
(( (11, (12, 13)), 'b'), ('d', (12, (12, 11)))),
(( (11, (12, 13)), 'd'), ('b', (12, (12, 11))))),
(( 'b', 'd'), (11, (12, 13)), (12, (12, 11)))
```
```
```
```
```
```
sage: S4.orbit((( 'b', (12, (12, 11))), (11, (12, 13)), 'd'))
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```python
sage: G = PermutationGroup([[3,4], [1,3]])
sage: G.orbits()
[[1, 3, 4], [2]]
sage: G = PermutationGroup(((1,2),(3,4)), [(1,2,3,4,10)])
sage: G.orbits()
[[1, 2, 3, 4, 10], [5], [6], [7], [8], [9]]
sage: G = PermutationGroup([('c','d'), ('a','c'), ('b',)])
sage: G.orbits()
[['a', 'c', 'd'], ['b']]
```

The answer is cached:

```python
sage: G.orbits() is G.orbits()
True
```

**AUTHORS:**

- Nathan Dunfield

**order()**

Return the number of elements of this group. See also: G.degree()

**EXAMPLES:**

```python
sage: G = PermutationGroup(((1,2,3),(4,5)), [(1,2)])
sage: G.order()
12
sage: G = PermutationGroup([()])
sage: G.order()
1
sage: G = PermutationGroup([()])
sage: G.order()
1
```

cardinality is just an alias:

```python
sage: PermutationGroup([(1,2,3)]).cardinality()
3
```

**poincare_series** (*p=2, n=10*)

Return the Poincaré series of \( G \) \mod \( p \) \( (p \geq 2 \) must be a prime), for \( n \) large.

In other words, if you input a finite group \( G \), a prime \( p \), and a positive integer \( n \), it returns a quotient of polynomials \( f(x) = P(x)/Q(x) \) whose coefficient of \( x^k \) equals the rank of the vector space \( H_k(G, \mathbb{Z}/p\mathbb{Z}) \), for all \( k \) in the range \( 1 \leq k \leq n \).

REQUIRES: GAP package HAP (in gap_packages-*\-spkg).

**EXAMPLES:**

```python
sage: G = SymmetricGroup(5)
sage: G.poincare_series(2,10)  # optional - gap_packages
(x^2 + 1)/(x^4 - x^3 - x + 1)
sage: G = SymmetricGroup(3)
sage: G.poincare_series(2,10)  # optional - gap_packages
-1/(x - 1)
```

24.2. Permutation groups
AUTHORS:

• David Joyner and Graham Ellis

**quotient** \((N)\)

Returns the quotient of this permutation group by the normal subgroup \(N\), as a permutation group.

Wraps the GAP operator “\(/\)”.  

**EXAMPLES:**

```python
sage: G = PermutationGroup([[1,2,3], (2,3)])
sage: N = PermutationGroup([[1,2,3]])
sage: G.quotient(N)
Permutation Group with generators [(1,2)]
sage: G.quotient(G)
Permutation Group with generators [()]
```

**random_element**()

Return a random element of this group.

**EXAMPLES:**

```python
sage: G = PermutationGroup([[1,2,3),(4,5)], [(1,2)])
sage: a = G.random_element()
sage: a in G
True
sage: a.parent() is G
True
sage: a^6
()
```

**representative_action** \((x, y)\)

Return an element of self that maps \(x\) to \(y\) if it exists.

This method wraps the gap function `RepresentativeAction`, which can also return elements that map a given set of points on another set of points.

**INPUT:**

• \(x, y\) – two elements of the domain.

**EXAMPLES:**

```python
sage: G = groups.permutation.Cyclic(14)
sage: g = G.representative_action(1,10)
sage: all(g(x) == 1+(x+9-1)%14 for x in G.domain())
True
```

**semidirect_product** \((N, mapping, check=True)\)

The semidirect product of self with \(N\).

**INPUT:**

• \(N\) - A group which is acted on by self and naturally embeds as a normal subgroup of the returned semidirect product.

• \(mapping\) - A pair of lists that together define a homomorphism, \(\phi : self \rightarrow \text{Aut}(N)\), by giving, in the second list, the images of the generators of self in the order given in the first list.

• \(check\) - A boolean that, if set to False, will skip the initial tests which are made on mapping. This may be beneficial for large \(N\), since in such cases the injectivity test can be expensive. Set to True by default.
The semidirect product of \texttt{self} and \(N\) defined by the action of \texttt{self} on \(N\) given in \texttt{mapping} (note that a homomorphism from \(A\) to the automorphism group of \(B\) is equivalent to an action of \(A\) on the \(B\)'s underlying set). The semidirect product of two groups, \(H\) and \(N\), is a construct similar to the direct product in so far as the elements are the Cartesian product of the elements of \(H\) and the elements of \(N\). The operation, however, is built upon an action of \(H\) on \(N\), and is defined as such:

\[(h_1, n_1)(h_2, n_2) = (h_1 h_2, n_1^{h_2} n_2)\]

This function is a wrapper for GAP's \texttt{SemidirectProduct} command. The permutation group returned is built upon a permutation representation of the semidirect product of \texttt{self} and \(N\) on a set of size \(|N|\). The generators of \(N\) are given as their right regular representations, while the generators of \texttt{self} are defined by the underlying action of \texttt{self} on \(N\). It should be noted that the defining action is not always faithful, and in this case the inputted representations of the generators of \texttt{self} are placed on additional letters and adjoined to the output's generators of \texttt{self}.

**EXAMPLES:**

Perhaps the most common example of a semidirect product comes from the family of dihedral groups. Each dihedral group is the semidirect product of \(C_2\) with \(C_n\), where, by convention, \(3 \leq n\). In this case, the nontrivial element of \(C_2\) acts on \(C_n\) so as to send each element to its inverse.

```python
sage: C2 = CyclicPermutationGroup(2)
sage: C8 = CyclicPermutationGroup(8)
sage: alpha = PermutationGroupMorphism_im_gens(C8,C8,[(1,8,7,6,5,4,3,2)])
sage: S = C2.semidirect_product(C8,[[1,2]],[alpha])
sage: S == DihedralGroup(8)
False
sage: S.is_isomorphic(DihedralGroup(8))
True
sage: S.gens()
[(3,4,5,6,7,8,9,10), (1,2) (4,10) (5,9) (6,8)]
```

A more complicated example can be drawn from [TW1980]. It is there given that a semidirect product of \(D_4\) and \(C_3\) is isomorphic to one of \(C_2\) and the dicyclic group of order 12. This nonabelian group of order 24 has very similar structure to the dicyclic and dihedral groups of order 24, the three being the only groups of order 24 with a two-element center and 9 conjugacy classes.

```python
sage: D4 = DihedralGroup(4)
sage: C3 = CyclicPermutationGroup(3)
sage: alpha1 = PermutationGroupMorphism_im_gens(C3,C3,[(1,3,2)])
sage: alpha2 = PermutationGroupMorphism_im_gens(C3,C3,[(1,2,3)])
sage: S1 = D4.semidirect_product(C3,[[1,2,3,4),(1,3)],[alpha1, alpha2])
sage: C2 = CyclicPermutationGroup(2)
sage: Q = DiCyclicGroup(3)
sage: a = Q.gens()[0]; b=Q.gens()[1].inverse()
sage: alpha = PermutationGroupMorphism_im_gens(Q,Q,[a,b])
sage: S2 = C2.semidirect_product(Q,[[1,2]],[alpha])
sage: S1.is_isomorphic(S2)
True
sage: S1.is_isomorphic(DihedralGroup(12))
False
sage: S1.is_isomorphic(DiCyclicGroup(6))
False
sage: S1.center()
Subgroup generated by [(1,3)(2,4)] of (Permutation Group with generators [(5,6,7), (1,2,3,4)(6,7), (1,3)])
```

(continues on next page)
If your normal subgroup is large, and you are confident that your inputs will successfully create a semidirect product, then it is beneficial, for the sake of time efficiency, to set the check parameter to False.

```python
sage: C2 = CyclicPermutationGroup(2)
sage: C2000 = CyclicPermutationGroup(500)
sage: alpha = PermutationGroupMorphism(C2000, C2000, [C2000.gen().inverse()])
sage: S = C2.semidirect_product(C2000, [(1,2)], [alpha], check=False)
```

AUTHOR:

• Kevin Halasz (2012-8-12)

**smallest_moved_point()**

Return the smallest point moved by a permutation in this group.

EXAMPLES:

```python
sage: G = PermutationGroup([[3,4], [2,3,4]])
sage: G.smallest_moved_point()
2
sage: G = PermutationGroup([[1,2], [3,4], [1,2,3,4,10]])
sage: G.smallest_moved_point()
1
```

Note that this function uses the ordering from the domain:

```python
sage: S = SymmetricGroup(['a','b','c'])
sage: S.smallest_moved_point()
'a'
```

**socle()**

Returns the socle of self. The socle of a group \(G\) is the subgroup generated by all minimal normal subgroups.

EXAMPLES:

```python
sage: G = SymmetricGroup(4)
sage: G.socle()
Subgroup generated by [(1,2)(3,4), (1,4)(2,3)] of (Symmetric group of order 4! as a permutation group)
sage: G.socle().socle()
Subgroup generated by [(1,2)(3,4), (1,4)(2,3)] of (Subgroup generated by [(1,2)(3,4), (1,4)(2,3)] of (Symmetric group of order 4! as a permutation group))
```

**solvable_radical()**

Returns the solvable radical of self. The solvable radical (or just radical) of a group \(G\) is the largest solvable normal subgroup of \(G\).

EXAMPLES:

```python
sage: G = SymmetricGroup(4)
sage: G.solvable_radical()
Subgroup generated by [(1,2), (1,2,3,4)] of (Symmetric group of order 4! as a permutation group)
```
sage: G=SymmetricGroup(5)
sage: G.solvable_radical()
Subgroup generated by [()] of (Symmetric group of order 5! as a permutation group)

stabilizer (point, action='OnPoints')
Return the subgroup of self which stabilize the given position. self and its stabilizers must have same degree.

INPUT:

- point – a point of the domain(), or a set of points depending on the value of action.
- action (string; default "OnPoints") – should the group be considered to act on points (action="OnPoints") or on sets of points (action="OnSets")? In the latter case, the first argument must be a subset of domain().

EXAMPLES:

sage: G = PermutationGroup([[(3,4)], [(1,3)]])
sage: G.stabilizer(1)
Subgroup generated by [(3,4)] of (Permutation Group with generators [(3,4), (1,3)])
sage: G.stabilizer(3)
Subgroup generated by [(1,4)] of (Permutation Group with generators [(3,4), (1,3)])

The stabilizer of a set of points:

sage: s10 = groups.permutation.Symmetric(10)
sage: s10.stabilizer([1..3],"OnSets").cardinality()
30240
sage: factorial(3)*factorial(7)
30240
sage: G = PermutationGroup([[(1,2),(3,4)], [(1,2,3,4,10)]])
sage: G.stabilizer(10)
Subgroup generated by [(2,3,4), (1,2)(3,4)] of (Permutation Group with generators [(1,2)(3,4), (1,2,3,4,10)])
sage: G.stabilizer(1)
Subgroup generated by [(2,3)(4,10), (2,10,4)] of (Permutation Group with generators [(1,2)(3,4), (1,2,3,4,10)])
sage: G = PermutationGroup([[(2,3,4)],[(6,7)]])
sage: G.stabilizer(1)
Subgroup generated by [(6,7), (2,3,4)] of (Permutation Group with generators [(6,7), (2,3,4)])
sage: G.stabilizer(2)
Subgroup generated by [(6,7)] of (Permutation Group with generators [(6,7), (2,3,4)])
sage: G.stabilizer(3)
Subgroup generated by [(6,7)] of (Permutation Group with generators [(6,7), (2,3,4)])
sage: G.stabilizer(4)
Subgroup generated by [(6,7)] of (Permutation Group with generators [(6,7), (2,3,4)])
sage: G.stabilizer(5)
Subgroup generated by [(6,7), (2,3,4)] of (Permutation Group with generators [(6,7), (2,3,4)])

(continues on next page)
\begin{verbatim}
sage: G.stabilizer(6)
Subgroup generated by [(2,3,4)] of (Permutation Group with generators [(6,7),
                               \(\rightarrow\)(2,3,4)])
sage: G.stabilizer(7)
Subgroup generated by [(2,3,4)] of (Permutation Group with generators [(6,7),
                               \(\rightarrow\)(2,3,4)])
sage: G.stabilizer(8)
Traceback (most recent call last):
  ... ValueError: 8 does not belong to the domain
\end{verbatim}

\begin{verbatim}
sage: G = PermutationGroup([ [('c','d')], [('a','c')] ], domain='abcd')
sage: G.stabilizer('a')
Subgroup generated by [('c','d')] of (Permutation Group with generators [('c','d'), ('a','c')])
sage: G.stabilizer('b')
Subgroup generated by [('c','d'), ('a','c')] of (Permutation Group with
generators [('c','d'), ('a','c')])
sage: G.stabilizer('c')
Subgroup generated by [('a','d')] of (Permutation Group with generators [('c','d'), ('a','c')])
sage: G.stabilizer('d')
Subgroup generated by [('a','c')] of (Permutation Group with generators [('c','d'),
                               ('a','c')])
\end{verbatim}

**strong_generating_system**(base_of_group=None, implementation='sage')

Return a Strong Generating System of self according the given base for the right action of self on itself.

base_of_group is a list of the positions on which self acts, in any order. The algorithm returns a list of transversals and each transversal is a list of permutations. By default, base_of_group is \([1, 2, 3, \ldots, d]\) where \(d\) is the degree of the group.

For base_of_group = \([pos_1, pos_2, \ldots, pos_d]\) let \(G_i\) be the subgroup of \(G = \text{self}\) which stabilizes \(pos_1, pos_2, \ldots, pos_i\), so

\[
G = G_0 \supset G_1 \supset G_2 \supset \cdots \supset G_n = \{e\}
\]

Then the algorithm returns \([G_i\text{.transversals}(pos_{i+1})]|_{1 \leq i \leq n}\)

INPUT:

- base_of_group (optional) – (default: \([1, 2, 3, \ldots, d]\)) a list containing the integers \(1, 2, \ldots, d\) in any order, where \(d\) is the degree of self
- implementation – (default: "sage") either
  - "sage" - use the direct implementation in Sage
  - "gap" - if used, the base_of_group must be None and the computation is directly performed in GAP

OUTPUT:

A list of lists of permutations from the group, which form a strong generating system.

**Warning:** The outputs for implementations "sage" and "gap" differ: First, the output is reversed, and second, it might be that "sage" does not contain the trivial subgroup while "gap" does.
Also, both algorithms might yield different results based on the order in which base_of_group is given in the first situation.

EXAMPLES:

```python
sage: G = PermutationGroup([(7,8), (3,4), (4,5)])
sage: G.strong_generating_system()
[(), (), (3,4,5), (3,5), (4,5), (1,3,2), (1,2)]
sage: G = PermutationGroup([(1,2,3,4),(1,2)])
sage: G.strong_generating_system()
[(1,2), (3,4), (1,3)(2,4), (1,4)(2,3), (1,2,4), (1,4,2), (1,3,2), (1,2,3)]
sage: G = PermutationGroup([(1,2,3)], [(4,5,7)], [(1,4,6)])
sage: G.strong_generating_system()
[(1,2,3), (1,3,2), (1,2,3), (1,2,3), (1,3,2), (1,2,3), (1,3,2), (1,2,3), (1,3,2), (1,2,3), (1,3,2), (1,2,3)]
```

`sage: G = PermutationGroup([(1,2,3)], [(2,3,4), (2,3)])
sage: G.strong_generating_system(
[(), (2,3,4), (2,3)], (1,3,4), (1,2)]
```

```python
sage: G = PermutationGroup([(1,2,3)], [(2,3,4)]
```sage: G.strong_generating_system()
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```
OUTPUT:

- string

**Warning:** From GAP’s documentation: The string returned by `StructureDescription` is **not** an isomorphism invariant: non-isomorphic groups can have the same string value, and two isomorphic groups in different representations can produce different strings.

**EXAMPLES:**

```sage
g = CyclicPermutationGroup(6)
g.structure_description()  # 'C6'
g.structure_description(latex=True)  # 'C_{6}'
G2 = G.direct_product(G, maps=False)
LatexExpr(G2.structure_description(latex=True))  # C_{6} \times C_{6}
```

This method is mainly intended for small groups or groups with few normal subgroups. Even then there are some surprises:

```sage
d3 = DihedralGroup(3)
d3.structure_description()  # 'S3'
```

We use the Sage notation for the degree of dihedral groups:

```sage
d4 = DihedralGroup(4)
d4.structure_description()  # 'D4'
```

Works for finitely presented groups (trac ticket #17573):

```sage
F.<x, y> = FreeGroup()
G = F / [x^2*y^-1, x^3*y^2, x*y*x^-1*y^-1]
G.structure_description()  # 'C7'
```

And matrix groups (trac ticket #17573):

```sage
groups.matrix.GL(4,2).structure_description()  # 'A8'
```

**subgroup** *(gens=None, gap_group=None, domain=None, category=None, canonicalize=True, check=True)*

Wraps the `PermutationGroup_subgroup` constructor. The argument `gens` is a list of elements of `self`.

**EXAMPLES:**

```sage
G = PermutationGroup([(1,2,3),(3,4,5)])
g = G((1,2,3))
G.subgroup([g])
Subgroup generated by [(1,2,3)] of (Permutation Group with generators [(3,4,5), (1,2,3)])
```
**subgroups()**

Returns a list of all the subgroups of self.

**OUTPUT:**

Each possible subgroup of self is contained once in the returned list. The list is in order, according to the size of the subgroups, from the trivial subgroup with one element on through up to the whole group. Conjugacy classes of subgroups are contiguous in the list.

**Warning:** For even relatively small groups this method can take a very long time to execute, or create vast amounts of output. Likely both. Its purpose is instructional, as it can be useful for studying small groups. The 156 subgroups of the full symmetric group on 5 symbols of order 120, $S_5$, can be computed in about a minute on commodity hardware in 2011. The 64 subgroups of the cyclic group of order $30030 = 2 \cdot 3 \cdot 5 \cdot 7 \cdot 11 \cdot 13$ takes about twice as long.

For faster results, which still exhibit the structure of the possible subgroups, use `conjugacy_classes_subgroups()`.

**EXAMPLES:**

```python
sage: G = SymmetricGroup(3)
sage: G.subgroups()

[Subgroup generated by [()] of (Symmetric group of order 3! as a permutation group),
 Subgroup generated by [(2,3)] of (Symmetric group of order 3! as a permutation group),
 Subgroup generated by [(1,2)] of (Symmetric group of order 3! as a permutation group),
 Subgroup generated by [(1,3)] of (Symmetric group of order 3! as a permutation group),
 Subgroup generated by [(1,2,3)] of (Symmetric group of order 3! as a permutation group),
 Subgroup generated by [(2,3), (1,2,3)] of (Symmetric group of order 3! as a permutation group)]

sage: G = CyclicPermutationGroup(14)
sage: G.subgroups()

[Subgroup generated by [()] of (Cyclic group of order 14 as a permutation group),
 Subgroup generated by [(1,8)(2,9)(3,10)(4,11)(5,12)(6,13)(7,14)] of (Cyclic group of order 14 as a permutation group),
 Subgroup generated by [(1,3,5,7,9,11,13)(2,4,6,8,10,12,14)] of (Cyclic group of order 14 as a permutation group),
 Subgroup generated by [(1,2,3,4,5,6,7,8,9,10,11,12,13,14), (1,3,5,7,9,11,13)(2,4,6,8,10,12,14)] of (Cyclic group of order 14 as a permutation group)]
```

**AUTHOR:**

- Rob Beezer (2011-01-24)

**sylow_subgroup(p)**

Returns a Sylow $p$-subgroup of the finite group $G$, where $p$ is a prime. This is a $p$-subgroup of $G$ whose index in $G$ is coprime to $p$.

Wraps the GAP function `SylowSubgroup`.

**EXAMPLES:**
transversals (point)
If $G$ is a permutation group acting on the set $X = \{1, 2, \ldots, n\}$ and $H$ is the stabilizer subgroup of <integer>, a right (respectively left) transversal is a set containing exactly one element from each right (respectively left) coset of $H$. This method returns a right transversal of $self$ by the stabilizer of $self$ on <integer> position.

EXAMPLES:

```
sage: G = PermutationGroup([[(3,4)], [(1,3)]]
sage: G.transversals(1)
[(()], (1,3,4), (1,4,3)]
sage: G = PermutationGroup([[(1,2),(3,4)]], [(1,2,3,4,10)])
sage: G.transversals(1)
[(()], (1,2)(3,4), (1,3,2,10,4), (1,4,2,10,3), (1,10,4,3,2)]
sage: G = PermutationGroup([['c','d'], ['a','c']])
sage: G.transversals('a')
[(()], ('a','c','d'), ('a','d','c')]
```

trivial_character()
Returns the trivial character of $self$.

EXAMPLES:

```
sage: SymmetricGroup(3).trivial_character()
Character of Symmetric group of order 3! as a permutation group
```

upper_central_series()
Return the upper central series of this group as a list of permutation groups.

EXAMPLES:

These computations use pseudo-random numbers, so we set the seed for reproducible testing:

```
sage: G = PermutationGroup([[(1,2,3),(4,5)],[(3,4)]])
sage: G.upper_central_series()
[Subgroup generated by [()] of (Permutation Group with generators [(3,4), (1, -→2,3)(4,5)])]
```

```
class sage.groups.perm_gps.permgroup.PermutationGroup_subgroup

Bases: sage.groups.perm_gps.permgroup.PermutationGroup_generic

Subgroup subclass of PermutationGroup_generic, so instance methods are inherited.
```
EXAMPLES:

```python
sage: G = CyclicPermutationGroup(4)
sage: gens = G.gens()
sage: H = DihedralGroup(4)
sage: H.subgroup(gens)
Subgroup generated by [(1,2,3,4)] of (Dihedral group of order 8 as a permutation group)
sage: K = H.subgroup(gens)
sage: K.ambient_group()
Dihedral group of order 8 as a permutation group
sage: K.gens()
[(1,2,3,4)]
```

**ambient_group()**

Return the ambient group related to self.

**EXAMPLES:**

An example involving the dihedral group on four elements, $D_8$:

```python
sage: G = DihedralGroup(4)
sage: H = CyclicPermutationGroup(4)
sage: gens = H.gens()
sage: S = PermutationGroup_subgroup(G, list(gens))
sage: S.ambient_group()
Dihedral group of order 8 as a permutation group
sage: S.ambient_group() == G
True
```

**is_normal (other=None)**

Return True if this group is a normal subgroup of other. If other is not specified, then it is assumed to be the ambient group.

**EXAMPLES:**

```python
sage: S = SymmetricGroup(['a','b','c'])
sage: H = S.subgroup([['a','b','c']]); H
Subgroup generated by [['a','b','c']] of (Symmetric group of order 3! as a permutation group)
sage: H.is_normal()
True
```

`sage.groups.perm_gps.permgroup.direct_product_permgroups(P)`

Takes the direct product of the permutation groups listed in P.

**EXAMPLES:**

```python
sage: G1 = AlternatingGroup([1,2,4,5])
sage: G2 = AlternatingGroup([3,4,6,7])
sage: D = direct_product_permgroups([G1,G2,G1])
sage: D.order()
1728
sage: D = direct_product_permgroups([G1])
sage: D==G1
True
```
sage: direct_product_permgroups([])
Symmetric group of order 0! as a permutation group

sage.groups.perm_gps.permgroup.from_gap_list(G, src)
Convert a string giving a list of GAP permutations into a list of elements of G.

EXAMPLES:

sage: from sage.groups.perm_gps.permgroup import from_gap_list
sage: G = PermutationGroup([(1,2,3),(4,5)], [(3,4)])

sage: L = from_gap_list(G, "[(1,2,3)(4,5), (3,4)]"); L
[(1,2,3)(4,5), (3,4)]

sage: L[0].parent() is G
True

sage: L[1].parent() is G
True

sage.groups.perm_gps.permgroup.hap_decorator(f)
A decorator for permutation group methods that require HAP. It checks to see that HAP is installed as well as checks that the argument \( p \) is either 0 or prime.

EXAMPLES:

sage: from sage.groups.perm_gps.permgroup import hap_decorator
sage: def foo(self, n, p=0):
    print(\"Done\")

sage: foo = hap_decorator(foo)

sage: foo(None, 3)
#optional - gap_packages
Done

sage: foo(None, 3, 0) # optional - gap_packages
Done

sage: foo(None, 3, 5) # optional - gap_packages
Done

sage: foo(None, 3, 4) #optional - gap_packages
Traceback (most recent call last):
... 
ValueError: p must be 0 or prime

sage.groups.perm_gps.permgroup.load_hap()
Load the GAP hap package into the default GAP interpreter interface.

EXAMPLES:

sage: sage.groups.perm_gps.permgroup.load_hap() # optional - gap_packages

24.3 “Named” Permutation groups (such as the symmetric group, \( S_n \))

You can construct the following permutation groups:

– SymmetricGroup, \( S_n \) of order \( n! \) (n can also be a list \( X \) of distinct positive integers, in which case it returns \( S_X \))

– AlternatingGroup, \( A_n \) of order \( n!/2 \) (n can also be a list \( X \) of distinct positive integers, in which case it returns \( A_X \))
– DihedralGroup, $D_n$ of order $2n$
– GeneralDihedralGroup, $Dih(G)$, where $G$ is an abelian group
– CyclicPermutationGroup, $C_n$ of order $n$
– DiCyclicGroup, nonabelian groups of order $4m$ with a unique element of order 2

**TransitiveGroup**, $n^{th}$ transitive group of degree $d$ from the GAP tables of transitive groups

**PrimitiveGroup**, $n^{th}$ primitive group of degree $d$ from the GAP tables of primitive groups

– MathieuGroup(degree), Mathieu group of degree 9, 10, 11, 12, 21, 22, 23, or 24.
– KleinFourGroup, subgroup of $S_4$ of order 4 which is not $C_2 \times C_2$
– QuaternionGroup, non-abelian group of order 8, \{±1, ±I, ±J, ±K\}
– SplitMetacyclicGroup, nonabelian groups of order $p^m$ with cyclic subgroups of index $p$
– SemidihedralGroup, nonabelian 2-groups with cyclic subgroups of index 2

– PGL(n,q), projective general linear group of $n \times n$ matrices over the finite field GF(q)
– PSL(n,q), projective special linear group of $n \times n$ matrices over the finite field GF(q)
– PSp(2n,q), projective symplectic linear group of $2n \times 2n$ matrices over the finite field GF(q)
– PSU(n,q), projective special unitary group of $n \times n$ matrices having coefficients in the finite field GF(q^2)$ that respect a fixed nondegenerate sesquilinear form, of determinant 1.
– PGU(n,q), projective general unitary group of $n \times n$ matrices having coefficients in the finite field GF(q^2)$ that respect a fixed nondegenerate sesquilinear form, modulo the centre.
– SuzukiGroup(q), Suzuki group over GF(q), $2B_2(2^{2k+1}) = S_z(2^{2k+1})$.

**ComplexReflectionGroup**, the complex reflection group $G(m, p, n)$ or the exceptional complex reflection group $G_m$

AUTHOR:

• David Joyner (2007-06): split from permgp.py (suggested by Nick Alexander)

REFERENCES:


Note: Though Suzuki groups are okay, Ree groups should not be wrapped as permutation groups - the construction is too slow - unless (for small values or the parameter) they are made using explicit generators.

```python
class sage.groups.perm_gps.permgroup_named.AlternatingGroup(domain=None)
    Bases: sage.groups.perm_gps.permgroup_named.PermutationGroup_symalt

    The alternating group of order $n!/2$, as a permutation group.

    INPUT:

    • n – a positive integer, or list or tuple thereof
```
Note: This group is also available via `groups.permutation.Alternating()`.

EXAMPLES:

```python
sage: G = AlternatingGroup(6)
sage: G.order()
360
sage: G
Alternating group of order 6!/2 as a permutation group
sage: G.category()
Category of finite enumerated permutation groups
sage: TestSuite(G).run()  # long time

sage: G = AlternatingGroup([1, 2, 4, 5])
sage: G
Alternating group of order 4!/2 as a permutation group
sage: G.domain()
{1, 2, 4, 5}
sage: G.category()
Category of finite enumerated permutation groups
sage: TestSuite(G).run()
```

class `sage.groups.perm_gps.permgroup_named.ComplexReflectionGroup` ($m, p=None, n=None$)

Bases: `sage.groups.perm_gps.permgroup_named.PermutationGroup_unique`

A finite complex reflection group as a permutation group.

We can realize $G(m, 1, n)$ as $m$ copies of the symmetric group $S_n$ with $s_i$ for $1 \leq i < n$ acting as the usual adjacent transposition on each copy of $S_n$. We construct the cycle $s_n = (n, 2n, \ldots, mn)$.

We construct $G(m, p, n)$ as a subgroup of $G(m, 1, n)$ by $s_i \mapsto s_i$ for all $1 \leq i < n$,

$$
s_n \mapsto s_n^{-1}s_{n-1}s_n, \quad s_{n+1} \mapsto s_n^p.
$$

Note that if $p = m$, then $s_{n+1} = 1$, in which case we do not consider it as a generator.

The exceptional complex reflection groups $G_m$ (in the Shephard-Todd classification) are not yet implemented.

INPUT:

One of the following:

- $m, p, n$ – positive integers to construct $G(m, p, n)$
- $m$ – integer such that $4 \leq m \leq 37$ to construct an exceptional complex reflection $G_m$

Note: This group is also available via `groups.permutation.ComplexReflection()`.

Note: The convention for the index set is for $G(m, 1, n)$ to have the complex reflection of order $m$ correspond to $s_n$: i.e., $s_n^m = 1$ and $s_i^2 = 1$ for all $i < m$.

EXAMPLES:
sage: G = groups.permutation.ComplexReflection(3, 1, 5)
sage: G.order()
29160
sage: G
Complex reflection group G(3, 1, 5) as a permutation group
sage: G.category()
Join of Category of finite enumerated permutation groups
     and Category of finite complex reflection groups
sage: G = groups.permutation.ComplexReflection(3, 3, 4)
sage: G.cardinality()
648
sage: s1, s2, s3, s4 = G.simple_reflections()
sage: s4*s2*s4 == s2*s4*s2
True
sage: (s4*s3*s2)^2 == (s2*s4*s3)^2
True
sage: G = groups.permutation.ComplexReflection(6, 2, 3)
sage: G.cardinality()
648
sage: s1, s2, s3, s4 = G.simple_reflections()
sage: s3^2 == G.one()
True
sage: s4^3 == G.one()
True
sage: s4 * s3 * s2 == s3 * s2 * s4
True
sage: (s3*s2*s1)^2 == (s1*s3*s2)^2
True
sage: s3 * s1 * s3 == s1 * s3 * s1
True
sage: s4 * s3 * (s2*s3)^(2-1) == s2 * s4
True
sage: G = groups.permutation.ComplexReflection(4, 2, 5)
sage: G.cardinality()
61440
sage: G = groups.permutation.ComplexReflection(4)
Traceback (most recent call last):
  ... NotImplementedError: exceptional complex reflection groups are not yet implemented

REFERENCES:

- Wikipedia article Complex_reflection_group
codegrees ()

Return the codegrees of self.

Let $G$ be a complex reflection group. The codegrees $d_1^* \leq d_2^* \leq \cdots \leq d_\ell^*$ of $G$ can be defined by:

$$
\prod_{i=1}^\ell (q - d_i^* - 1) = \sum_{g \in G} \det(g)q^\dim(V^g),
$$

where $V$ is the natural complex vector space that $G$ acts on and $\ell$ is the rank().

If $m = 1$, then we are in the special case of the symmetric group and the codegrees are $(n - 2, n - 24.3. “Named” Permutation groups (such as the symmetric group, S_n) 245
3, \ldots 1, 0). Otherwise the codegrees are \(((n - 1)m, (n - 2)m, \ldots, m, 0)\).

EXAMPLES:

```
sage: C = groups.permutation.ComplexReflection(4, 1, 3)
sage: C.codegrees()
(8, 4, 0)
sage: G = groups.permutation.ComplexReflection(3, 3, 4)
sage: G.codegrees()
(6, 5, 3, 0)
sage: S = groups.permutation.ComplexReflection(1, 1, 3)
sage: S.codegrees()
(1, 0)
```

degrees()  
Return the degrees of self.

The degrees of a complex reflection group are the degrees of the fundamental invariants of the ring of polynomial invariants.

If \( m = 1 \), then we are in the special case of the symmetric group and the degrees are \((2, 3, \ldots, n, n + 1)\). Otherwise the degrees are \((m, 2m, \ldots, (n - 1)m, nm/p)\).

EXAMPLES:

```
sage: C = groups.permutation.ComplexReflection(4, 1, 3)
sage: C.degrees()
(4, 8, 12)
sage: G = groups.permutation.ComplexReflection(4, 2, 3)
sage: G.degrees()
(4, 6, 8)
sage: Gp = groups.permutation.ComplexReflection(4, 4, 3)
sage: Gp.degrees()
(3, 4, 8)
sage: S = groups.permutation.ComplexReflection(1, 1, 3)
sage: S.degrees()
(2, 3)
```

Check that the product of the degrees is equal to the cardinality:

```
sage: prod(C.degrees()) == C.cardinality()
True
sage: prod(G.degrees()) == G.cardinality()
True
sage: prod(Gp.degrees()) == Gp.cardinality()
True
sage: prod(S.degrees()) == S.cardinality()
True
```

index_set()  
Return the index set of self.

EXAMPLES:

```
sage: G = groups.permutation.ComplexReflection(4, 1, 3)
sage: G.index_set()
(1, 2, 3)
sage: G = groups.permutation.ComplexReflection(1, 1, 3)
(continues on next page)
```
simple_reflection(i)
Return the i-th simple reflection of self.

EXAMPLES:

```plaintext
sage: G = groups.permutation.ComplexReflection(3, 1, 4)
sage: G.simple_reflection(2)
(2,3)(6,7)(10,11)
sage: G.simple_reflection(4)
(4,8,12)
sage: G = groups.permutation.ComplexReflection(1, 1, 4)
sage: G.simple_reflections()
Finite family {1: (1,2), 2: (2,3), 3: (3,4)}
```

class sage.groups.perm_gps.permgroup_named.CyclicPermutationGroup(n)
Bases: sage.groups.perm_gps.permgroup_named.PermutationGroup_unique
A cyclic group of order n, as a permutation group.

INPUT:

n – a positive integer

Note: This group is also available via groups.permutation.Cyclic().

EXAMPLES:

```plaintext
sage: G = CyclicPermutationGroup(8)
sage: G.order()
8
sage: G
Cyclic group of order 8 as a permutation group
sage: G.category()
Category of finite enumerated permutation groups
sage: TestSuite(G).run()
sage: C = CyclicPermutationGroup(10)
sage: C.is_abelian()
True
sage: C = CyclicPermutationGroup(10)
sage: C.as_AbelianGroup()
Multiplicative Abelian group isomorphic to C2 x C5
```
EXAMPLES:

```python
sage: C = CyclicPermutationGroup(8)
sage: C.as_AbelianGroup()
Multiplicative Abelian group isomorphic to C8
```

**is_abelian()**

Return True if this group is abelian.

EXAMPLES:

```python
sage: C = CyclicPermutationGroup(8)
sage: C.is_abelian()
True
```

**is_commutative()**

Return True if this group is commutative.

EXAMPLES:

```python
sage: C = CyclicPermutationGroup(8)
sage: C.is_commutative()
True
```

class sage.groups.perm_gps.permgroup_named.DiCyclicGroup(n)

Bases: sage.groups.perm_gps.permgroup_named.PermutationGroup_unique

The dicyclic group of order $4n$, for $n \geq 2$.

INPUT:

- $n$ – a positive integer, two or greater

OUTPUT:

This is a nonabelian group similar in some respects to the dihedral group of the same order, but with far fewer elements of order 2 (it has just one). The permutation representation constructed here is based on the presentation

$$\langle a, x \mid a^{2n} = 1, x^2 = a^n, x^{-1}ax = a^{-1} \rangle$$

For $n = 2$ this is the group of quaternions ($\pm 1, \pm i, \pm j, \pm k$), which is the nonabelian group of order 8 that is not the dihedral group $D_4$, the symmetries of a square. For $n = 3$ this is the nonabelian group of order 12 that is not the dihedral group $D_6$ nor the alternating group $A_4$. This group of order 12 is also the semi-direct product of $C_2$ by $C_4$, $C_3 \rtimes C_4$. [Con]

When the order of the group is a power of 2 it is known as a “generalized quaternion group.”

IMPLEMENTATION:

The presentation above means every element can be written as $a^i x^j$ with $0 \leq i < 2n$, $j = 0, 1$. We code $a^i$ as the symbol $i + 1$ and code $a^i x$ as the symbol $2n + i + 1$. The two generators are then represented using a left regular representation.

**Note:** This group is also available via `groups.permutation.DiCyclic()`.

EXAMPLES:

A dicyclic group of order 384, with a large power of 2 as a divisor:
A large generalized quaternion group (order is a power of 2):

```sage	n = 2^10
sage: G=DiCyclicGroup(n)
sage: G.order()
4096
sage: a = G.gen(0)
sage: x = G.gen(1)
sage: a^(2*n)
()
sage: a^n==x^2
True
sage: x^-1*a*x==a^-1
True
```

Just like the dihedral group, the dicyclic group has an element whose order is half the order of the group. Unlike
the dihedral group, the dicyclic group has only one element of order 2. Like the dihedral groups of even order,
the center of the dicyclic group is a subgroup of order 2 (thus has the unique element of order 2 as its non-identity
element).

```sage:
G=DiCyclicGroup(3*5*4)
sage: G.order()
240
sage: two = [g for g in G if g.order()==2]; two
[(1,5)(2,6)(3,7)(4,8)(9,13)(10,14)(11,15)(12,16)]
sage: G.center().order()
2
```

For small orders, we check this is really a group we do not have in Sage otherwise.

```sage:
G = DiCyclicGroup(2)
sage: H = DihedralGroup(4)
sage: G.is_isomorphic(H)
False
sage: G = DiCyclicGroup(3)
sage: H = DihedralGroup(6)
sage: K = AlternatingGroup(6)
sage: G.is_isomorphic(H) or G.is_isomorphic(K)
False
```

AUTHOR:

- Rob Beezer (2009-10-18)
Return True if this group is abelian.

EXAMPLES:

```
sage: D = DiCyclicGroup(12)
sage: D.is_abelian()
False
```

.. _is_commutative:

.. _is_commutative:

\textbf{is\_commutative()}  
Return True if this group is commutative.

EXAMPLES:

```
sage: D = DiCyclicGroup(12)
sage: D.is_commutative()
False
```

\textbf{class} \ sage\_groups\_perm\_gps\_permgroup\_named.DihedralGroup(n)

Bases: \ sage\_groups\_perm\_gps\_permgroup\_named.PermutationGroup\_unique

The Dihedral group of order 2n for any integer $n \geq 1$.

\textbf{INPUT:}

- $n$ – a positive integer

\textbf{OUTPUT:}

The dihedral group of order 2n, as a permutation group

\textbf{Note:} This group is also available via \texttt{groups.permutation.Dihedral()}.

\textbf{EXAMPLES:}

```
sage: DihedralGroup(1)
Dihedral group of order 2 as a permutation group

sage: DihedralGroup(2)
Dihedral group of order 4 as a permutation group
sage: DihedralGroup(2).gens()
\[(3,4), (1,2)\]

sage: DihedralGroup(5).gens()
\[(1,2,3,4,5), (1,5)(2,4)\]

sage: sorted(DihedralGroup(5))
\[(), (2,5)(3,4), (1,2)(3,5), (1,2,3,4,5), (1,3)(4,5), (1,3,5,2,4), (1,4)(2,3), (1,5,4,3,2), (1,5)(2,4)\]

sage: G = DihedralGroup(6)
sage: G.order()
12

sage: G = DihedralGroup(5)
sage: G.order()
10

dihedral group of order 10 as a permutation group
sage: G.gens()
\[(1,2,3,4,5), (1,5)(2,4)\]
```

(continues on next page)
```sage
sage: DihedralGroup(0)
Traceback (most recent call last):
...
ValueError: n must be positive
```

```python
class sage.groups.perm_gps.permgroup_named.GeneralDihedralGroup(factors):
   _bases: sage.groups.perm_gps.permgroup.PermutationGroup_generic

The Generalized Dihedral Group generated by the abelian group with direct factors in the input list.

**INPUT:**

- `factors` - a list of the sizes of the cyclic factors of the abelian group being dihedralized (this will be sorted once entered)

**OUTPUT:**

For a given abelian group (noting that each finite abelian group can be represented as the direct product of cyclic groups), the General Dihedral Group it generates is simply the semi-direct product of the given group with \( C_2 \), where the nonidentity element of \( C_2 \) acts on the abelian group by turning each element into its inverse. In this implementation, each input abelian group will be standardized so as to act on a minimal amount of letters. This will be done by breaking the direct factors into products of \( p \)-groups, before this new set of factors is ordered from smallest to largest for complete standardization. Note that the generalized dihedral group corresponding to a cyclic group, \( C_n \), is simply the dihedral group \( D_n \).

**EXAMPLES:**

As is noted in [TW1980], \( Dih(C_3 \times C_3) \) has the presentation

\[
\langle a, b, c \mid a^3, b^3, c^2, ab = ba, ac = ca^{-1}, bc = cb^{-1} \rangle
\]

Note also the fact, verified by [TW1980], that the dihedralization of \( C_3 \times C_3 \) is the only nonabelian group of order 18 with no element of order 6.

```sage
sage: G = GeneralDihedralGroup([3,3])
sage: G
Generalized dihedral group generated by C3 x C3
sage: G.order()
18
sage: G gens()
[(4,5,6), (2,3)(5,6), (1,2,3)]
sage: a = G gens()[2]; b = G gens()[0]; c = G gens()[1]
sage: a.order() == 3, b.order() == 3, c.order() == 2
(True, True, True)
sage: a*b == b*a, a*c == c*a.inverse(), b*c == c*b.inverse()
(True, True, True)
sage: G subgroup([a,b,c]) == G
True
sage: G.is_abelian()
False
sage: all([x.order() != 6 for x in G])
True
```

If all of the direct factors are \( C_2 \), then the action turning each element into its inverse is trivial, and the semi-direct product becomes a direct product.

```sage
sage: G = GeneralDihedralGroup([2,2,2])
sage: G.order()
```

(continues on next page)
If two nonidentical input lists generate isomorphic abelian groups, then they will generate identical groups (with each direct factor broken up into its prime factors), but they will still have distinct descriptions. Note that if \( \gcd(n, m) = 1 \), then \( C_n \times C_m \cong C_{nm} \), while the general dihedral groups generated by isomorphic abelian groups should be themselves isomorphic.

A cyclic input yields a Classical Dihedral Group.

A Generalized Dihedral Group will always have size twice the underlying group, be solvable (as it has an abelian subgroup with index 2), and, unless the underlying group is of the form \( C_2^n \), be nonabelian (by the structure theorem of finite abelian groups and the fact that a semi-direct product is a direct product only when the underlying action is trivial).

AUTHOR:

- Kevin Halasz (2012-7-12)

```python
sage: G = GeneralDihedralGroup([6,18,33,60])
sage: (6*18*33*60)*2
427680
sage: G.order()
427680
sage: G.is_solvable()
True
sage: G.is_abelian()
False
```

class sage.groups.perm_gps.permgroup_named.JankoGroup(n)

Bases: sage.groups.perm_gps.permgroup_named.PermutationGroup_unique

Janko Groups \( J1, J2, \) and \( J3 \). (Note that \( J4 \) is too big to be treated here.)

INPUT:
• \( n \) – an integer among \( \{1, 2, 3\} \).

EXAMPLES:

```python
sage: G = groups.permutation.Janko(1); G
Janko group J1 of order 175560 as a permutation group
```

```python
class sage.groups.perm_gps.permgroup_named.KleinFourGroup
    Bases: sage.groups.perm_gps.permgroup_named.PermutationGroup_unique

The Klein 4 Group, which has order 4 and exponent 2, viewed as a subgroup of \( S_4 \).

OUTPUT:
the Klein 4 group of order 4, as a permutation group of degree 4.

Note: This group is also available via `groups.permutation.KleinFour()`.
```

```python
sage: G = KleinFourGroup(); G
The Klein 4 group of order 4, as a permutation group
sage: sorted(G)
[((), (3,4), (1,2), (1,2)(3,4))]
```

AUTHOR: – Bobby Moretti (2006-10)

```python
class sage.groups.perm_gps.permgroup_named.MathieuGroup(n)
    Bases: sage.groups.perm_gps.permgroup_named.PermutationGroup_unique

The Mathieu group of degree \( n \).

INPUT:
\( n \) – a positive integer in \( \{9, 10, 11, 12, 21, 22, 23, 24\} \).

OUTPUT:
the Mathieu group of degree \( n \), as a permutation group

Note: This group is also available via `groups.permutation.Mathieu()`.
```

```python
sage: G = MathieuGroup(12)
sage: G
Mathieu group of degree 12 and order 95040 as a permutation group
```

```python
class sage.groups.perm_gps.permgroup_named.PGL(n, q, name='a')
    Bases: sage.groups.perm_gps.permgroup_named.PermutationGroup_plg

The projective general linear groups over GF(q).

INPUT:
• \( n \) – positive integer; the degree
• \( q \) – prime power; the size of the ground field
• name – (default: ‘a’) variable name of indeterminate of finite field GF(q)
```
OUTPUT:
PGL(n,q)

**Note:** This group is also available via `groups.permutation.PGL()`.

**EXAMPLES:**

```python
sage: G = PGL(2,3); G
Permutation Group with generators [(3,4), (1,2,4)]
sage: print(G)
The projective general linear group of degree 2 over Finite Field of size 3
sage: G.base_ring()
Finite Field of size 3
sage: G.order()
24

sage: G = PGL(2, 9, 'b'); G
Permutation Group with generators [(3,10,9,8,4,7,6,5), (1,2,4)(5,6,8)(7,9,10)]
sage: G.base_ring()
Finite Field in b of size 3^2
sage: G.category()
Category of finite enumerated permutation groups
sage: TestSuite(G).run() # long time
```

```python
class sage.groups.perm_gps.permgroup_named.PGU(n, q, name='a')
Bases: sage.groups.perm_gps.permgroup_named.PermutationGroup_pug
The projective general unitary groups over GF(q).
INPUT:

- n – positive integer; the degree
- q – prime power; the size of the ground field
- name – (default: 'a') variable name of indeterminate of finite field GF(q)

OUTPUT:
PGU(n,q)

**Note:** This group is also available via `groups.permutation.PGU()`.

**EXAMPLES:**

```python
sage: PGU(2,3)
The projective general unitary group of degree 2 over Finite Field of size 3
sage: G = PGU(2, 8, 'alpha'); G
The projective general unitary group of degree 2 over Finite Field in alpha of size 2^3
sage: G.base_ring()
Finite Field in alpha of size 2^3
```

```python
class sage.groups.perm_gps.permgroup_named.PSL(n, q, name='a')
Bases: sage.groups.perm_gps.permgroup_named.PermutationGroup_plg
```
The projective special linear groups over GF(q).

**INPUT:**
- n – positive integer; the degree
- q – either a prime power (the size of the ground field) or a finite field
- name – (default: 'a') variable name of indeterminate of finite field GF(q)

**OUTPUT:**
the group PSL(n,q)

**Note:** This group is also available via groups.permutation.PSL().

**EXAMPLES:**

```python
sage: G = PSL(2,3); G
Permutation Group with generators [(2,3,4), (1,2)(3,4)]
sage: G.order()
12
sage: G.base_ring()
Finite Field of size 3
sage: G.category()
Category of finite enumerated permutation groups
sage: TestSuite(G).run() # long time
```

We create two groups over nontrivial finite fields:

```python
sage: G = PSL(2, 4, 'b'); G
Permutation Group with generators [(3,4,5), (1,2,3)]
sage: G.base_ring()
Finite Field in b of size 2^2
sage: G = PSL(2, 8); G
Permutation Group with generators [(3,8,6,4,9,7,5), (1,2,3)(4,7,5)(6,9,8)]
sage: G.base_ring()
Finite Field in a of size 2^3
sage: G.category()
Category of finite enumerated permutation groups
sage: TestSuite(G).run() # long time
```

`ramification_module_decomposition_hurwitz_curve()`

Helps compute the decomposition of the ramification module for the Hurwitz curves $X$ (over CC say) with automorphism group $G = \text{PSL}(2,q)$, $q$ a “Hurwitz prime” (ie, $p$ is $\pm 1 \pmod{7}$). Using this computation and Borne’s formula helps determine the $G$-module structure of the RR spaces of equivariant divisors can be determined explicitly.

The output is a list of integer multiplicities: $[m_1,\ldots,m_n]$, where $n$ is the number of conj classes of $G=\text{PSL}(2,p)$ and $m_i$ is the multiplicity of $\pi_i$ in the ramification module of a Hurwitz curve with automorphism group $G$. Here $\text{IrrRepns}(G) = [\pi_1,\ldots,\pi_n]$ (in the order listed in the output of self.character_table()).


**EXAMPLES:**
This means, for example, that the trivial representation does not occur in the ramification module of a Hurwitz curve with automorphism group PSL(2,13), since the trivial representation is listed first and that entry has multiplicity 0. The “randomness” is due to the fact that GAP randomly orders the conjugacy classes of the same order in the list of all conjugacy classes. Similarly, there is some randomness to the ordering of the characters.

If you try to use this function on a group PSL(2,q) where q is not a (smallish) “Hurwitz prime”, an error message will be printed.

**ramification_module_decomposition_modular_curve()**

Helps compute the decomposition of the ramification module for the modular curve X(p) (over CC say) with automorphism group G = PSL(2,q), q a prime > 5. Using this computation and Borne’s formula helps determine the G-module structure of the RR spaces of equivariant divisors can be determined explicitly.

The output is a list of integer multiplicities: [m1, ..., mn], where n is the number of conj classes of G=PSL(2,p) and mi is the multiplicity of pi_i in the ramification module of a modular curve with automorphism group G. Here IrrRepns(G) = [pi_1, ..., pi_n] (in the order listed in the output of self.character_table()).


**EXAMPLES:**

```
sage: G = PSL(2,7)
sage: G.ramification_module_decomposition_modular_curve() # random, optional - gap_packages
[0, 4, 3, 6, 7, 8]
```

This means, for example, that the trivial representation does not occur in the ramification module of X(7), since the trivial representation is listed first and that entry has multiplicity 0. The “randomness” is due to the fact that GAP randomly orders the conjugacy classes of the same order in the list of all conjugacy classes. Similarly, there is some randomness to the ordering of the characters.

sage.groups.perm_gps.permgroup_named.PSP

alias of sage.groups.perm_gps.permgroup_named.PSp

class sage.groups.perm_gps.permgroup_named.PSU(n, q, name='a')

Bases: sage.groups.perm_gps.permgroup_named.PermutationGroup_pug

The projective special unitary groups over GF(q).

**INPUT:**

- n – positive integer; the degree
- q – prime power; the size of the ground field
- name – (default: ‘a’) variable name of indeterminate of finite field GF(q)

**OUTPUT:**

PSU(n,q)
Note: This group is also available via `groups.permutation.PSU()`.

EXAMPLES:

```sage
sage: PSU(2, 3)
The projective special unitary group of degree 2 over Finite Field of size 3
sage: G = PSU(2, 8, name='alpha'); G
The projective special unitary group of degree 2 over Finite Field in alpha of size 2^3
sage: G.base_ring()
Finite Field in alpha of size 2^3
```

class `sage.groups.perm_gps.permgroup_named.PSp(n, q, name='a')`
Bases: `sage.groups.perm_gps.permgroup_named.PermutationGroup_plg`

The projective symplectic linear groups over GF(q).

INPUT:
- n – positive integer; the degree
- q – prime power; the size of the ground field
- name – (default: 'a') variable name of indeterminate of finite field GF(q)

OUTPUT:
PSp(n,q)

Note: This group is also available via `groups.permutation.PSp()`.

EXAMPLES:

```sage
sage: G = PSp(2, 3); G
Permutation Group with generators [(2,3,4), (1,2)(3,4)]
sage: G.order()
12
sage: G = PSp(4, 3); G
sage: G.order()
25920
sage: print(G)
The projective symplectic linear group of degree 4 over Finite Field of size 3
sage: G.base_ring()
Finite Field of size 3
sage: G = PSp(2, 8, name='alpha'); G
Permutation Group with generators [(3,8,6,4,9,7,5), (1,2,3)(4,7,5)(6,9,8)]
sage: G.base_ring()
Finite Field in alpha of size 2^3
```

24.3. “Named” Permutation groups (such as the symmetric group, S_n) 257
class sage.groups.perm_gps.permgroup_named.PermutationGroup_plg(gens=None,
gap_group=None,
canonicalize=True,
domain=None,
category=None)

Bases: sage.groups.perm_gps.permgroup_named.PermutationGroup_unique

base_ring()

EXAMPLES:

```sage
g = PGL(2,3)
sage: G = PGL(2,3)
sage: G.base_ring()
Finite Field of size 3
```

```sage
g = PSL(2,3)
sage: G = PSL(2,3)
sage: G.base_ring()
Finite Field of size 3
```

matrix_degree()

EXAMPLES:

```sage
g = PSL(2,3)
sage: G = PSL(2,3)
sage: G.matrix_degree()
2
```

class sage.groups.perm_gps.permgroup_named.PermutationGroup_pug(gens=None,
gap_group=None,
canonicalize=True,
domain=None,
category=None)

Bases: sage.groups.perm_gps.permgroup_named.PermutationGroup_plg

field_of_definition()

EXAMPLES:

```sage
PSU(2,3).field_of_definition()
Finite Field in a of size 3^2
```

class sage.groups.perm_gps.permgroup_named.PermutationGroup_symalt(gens=None,
gap_group=None,
canonicalize=True,
domain=None,
category=None)

Bases: sage.groups.perm_gps.permgroup_named.PermutationGroup_unique

This is a class used to factor out some of the commonality in the SymmetricGroup and AlternatingGroup classes.
class sage.groups.perm_gps.permgroup_named.PermutationGroup_unique(gens=None, gap_group=None, canonicalize=True, domain=None, category=None)

Bases: sage.structure.unique_representation.CachedRepresentation, sage.groups.perm_gps.permgroup.PermutationGroup_generic

Todo: Fix the broken hash.

```sage
g = SymmetricGroup(6)
g3 = G.subgroup([G((1,2,3,4,5,6)), G((1,2))])
hash(g) == hash(g3)  # todo: Should be True!
False
```

class sage.groups.perm_gps.permgroup_named.PrimitiveGroup(d, n)

Bases: sage.groups.perm_gps.permgroup_named.PermutationGroup_unique

The primitive group from the GAP tables of primitive groups.

INPUT:

- `d` – non-negative integer. the degree of the group.
- `n` – positive integer. the index of the group in the GAP database, starting at 1

OUTPUT:

The `n`-th primitive group of degree `d`.

EXAMPLES:

```sage
G = PrimitiveGroup(0, 1)
Trivial group
sage: G = PrimitiveGroup(1, 1)
Trivial group
sage: G = PrimitiveGroup(5, 2); G
D(2*5)
sage: G.gens()
[(2,4)(3,5), (1,2,3,5,4)]
sage: G.category()
Category of finite enumerated permutation groups
```

Warning: this follows GAP's naming convention of indexing the primitive groups starting from 1:

```sage
G = PrimitiveGroup(5, 0)
Traceback (most recent call last):
...
ValueError: Index n must be in {1,..,5}
```

Only primitive groups of “small” degree are available in GAP’s database:

24.3. "Named" Permutation groups (such as the symmetric group, S_n)
sage: PrimitiveGroup(2500,1)
Traceback (most recent call last):
...
NotImplementedError: Only the primitive groups of degree less than 2500 are available in GAP's database

`group_primitive_id()`

Return the index of this group in the GAP database of primitive groups.

**OUTPUT:**

A positive integer, following GAP’s conventions.

**EXAMPLES:**

```python
sage: G = PrimitiveGroup(5,2); G.group_primitive_id() 2
```

`sage.groups.perm_gps.permgroup_named.PrimitiveGroups(d=None)`

Return the set of all primitive groups of a given degree \(d\)

**INPUT:**

- \(d\) – an integer (optional)

**OUTPUT:**

The set of all primitive groups of a given degree \(d\) up to isomorphisms using GAP. If \(d\) is not specified, it returns the set of all primitive groups up to isomorphisms stored in GAP.

**EXAMPLES:**

```python
sage: PrimitiveGroups(3)
Primitive Groups of degree 3
sage: PrimitiveGroups(7)
Primitive Groups of degree 7
sage: PrimitiveGroups(8)
Primitive Groups of degree 8
sage: PrimitiveGroups()
Primitive Groups
```

The database currently only contains primitive groups up to degree 2499:

```python
sage: PrimitiveGroups(2500).cardinality() Traceback (most recent call last): ...
NotImplementedError: Only the primitive groups of degree less than 2500 are available in GAP's database
```

**Todo:** This enumeration helper could be extended based on `PrimitiveGroupsIterator` in GAP. This method allows to enumerate groups with specified properties such as transitivity, solvability, …, without creating all groups.

```python
class sage.groups.perm_gps.permgroup_named.PrimitiveGroupsAll
    Bases: sage.sets.disjoint_union_enumerated_sets.DisjointUnionEnumeratedSets

    The infinite set of all primitive groups up to isomorphisms.

    **EXAMPLES:**
```
sage: L = PrimitiveGroups(); L
Primitive Groups
sage: L.category()
Category of facade infinite enumerated sets
sage: L.cardinality()
+Infinity
sage: p = L.__iter__()
sage: (next(p), next(p), next(p), next(p),
....: next(p), next(p), next(p), next(p))
(Trivial group, Trivial group, S(2), A(3), S(3), A(4), S(4), C(5))

class sage.groups.perm_gps.permgroup_named.PrimitiveGroupsOfDegree(n)
structure.parent.Parent

The set of all primitive groups of a given degree up to isomorphisms.

EXAMPLES:

sage: S = PrimitiveGroups(5); S
Primitive Groups of degree 5
sage: S.list()
[C(5), D(2*5), AGL(1, 5), A(5), S(5)]
sage: S.an_element()
C(5)

We write the cardinality of all primitive groups of degree 5:

    sage: for G in PrimitiveGroups(5):
    ....:     print(G.cardinality())
5
10
20
60
120

cardinality()

Return the cardinality of self.

OUTPUT:

An integer. The number of primitive groups of a given degree up to isomorphism.

EXAMPLES:

sage: PrimitiveGroups(0).cardinality()
1
sage: PrimitiveGroups(2).cardinality()
1
sage: PrimitiveGroups(7).cardinality()
7
sage: PrimitiveGroups(12).cardinality()
6
sage: [PrimitiveGroups(i).cardinality() for i in range(11)]
[1, 1, 1, 2, 2, 5, 4, 7, 7, 11, 9]

GAP contains all primitive groups up to degree 2499:

24.3. “Named” Permutation groups (such as the symmetric group, S_n)
sage: PrimitiveGroups(2500).cardinality()
Traceback (most recent call last):
...
NotImplementedError: Only the primitive groups of degree less than 2500 are available in GAP's database

class sage.groups.perm_gps.permgroup_named.QuaternionGroup
Bases: sage.groups.perm_gps.permgroup_named.DiCyclicGroup

The quaternion group of order 8.

OUTPUT:

The quaternion group of order 8, as a permutation group. See the DiCyclicGroup class for a generalization of this construction.

Note: This group is also available via groups.permutation.Quaternion().

EXAMPLES:
The quaternion group is one of two non-abelian groups of order 8, the other being the dihedral group $D_4$. One way to describe this group is with three generators, $I, J, K$, so the whole group is then given as the set $\{ \pm 1, \pm I, \pm J, \pm K \}$ with relations such as $I^2 = J^2 = K^2 = -1, IJ = K$ and $JI = -K$.

The examples below illustrate how to use this group in a similar manner, by testing some of these relations. The representation used here is the left-regular representation.

sage: Q = QuaternionGroup()
sage: I = Q.gen(0)
sage: J = Q.gen(1)
sage: K = I*J
sage: [I,J,K]
[(1,2,3,4)(5,6,7,8), (1,5,3,7)(2,8,4,6), (1,8,3,6)(2,7,4,5)]
sage: neg_one = I^2; neg_one
(1,3)(2,4)(5,7)(6,8)
sage: J^2 == neg_one and K^2 == neg_one
True
sage: J*I == neg_one*K
True
sage: Q.center().order() == 2
True
sage: neg_one in Q.center()
True

AUTHOR:

• Rob Beezer (2009-10-09)

class sage.groups.perm_gps.permgroup_named.SemidihedralGroup($m$)
Bases: sage.groups.perm_gps.permgroup_named.PermutationGroup_unique

The semidihedral group of order $2^m$.

INPUT:

• $m$ - a positive integer; the power of 2 that is the group’s order

OUTPUT:
The semidihedral group of order $2^m$. These groups can be thought of as a semidirect product of $C_{2^{m-1}}$ with $C_2$, where the nontrivial element of $C_2$ is sent to the element of the automorphism group of $C_{2^{m-1}}$ that sends elements to their $-1 + 2^{m-2}$ th power. Thus, the group has the presentation:

$$\langle x, y \mid x^{2^{m-1}}, y^2, y^{-1}xy = x^{-1+2^{m-2}} \rangle$$

This family is notable because it is made up of non-abelian 2-groups that all contain cyclic subgroups of index 2. It is one of only four such families.

**EXAMPLES:**

In [Gor1980] it is shown that the semidihedral groups have center of order 2. It is also shown that they have a Frattini subgroup equal to their commutator, which is a cyclic subgroup of order $2^{m-2}$.

```python
sage: G = SemidihedralGroup(12)
sage: G.order() == 2^12
True
sage: G.commutator() == G.frattini_subgroup()
True
sage: G.commutator().order() == 2^10
True
sage: G.commutator().is_cyclic()
True
sage: G.center().order()
2
sage: G = SemidihedralGroup(4)
sage: len([H for H in G.subgroups() if H.is_cyclic() and H.order() == 8])
1
sage: G.gens()
[(2,4)(3,7)(6,8), (1,2,3,4,5,6,7,8)]
sage: x = G.gens()[1]; y = G.gens()[0]
sage: x.order() == 2^3; y.order() == 2
True
True
sage: y*x*y == x^(-1+2^2)
True
```

**AUTHOR:**

• Kevin Halasz (2012-8-7)

### sage.groups.perm_gps.permgroup_named.SplitMetacyclicGroup(p, m)

Bases: `sage.groups.perm_gps.permgroup_named.PermutationGroup_unique`

The split metacyclic group of order $p^m$.

**INPUT:**

- $p$ – a prime number that is the prime underlying this p-group
- $m$ – a positive integer such that the order of this group is $p^m$. Be aware that, for even $p$, $m$ must be greater than 3, while for odd $p$, $m$ must be greater than 2.

**OUTPUT:**

The split metacyclic group of order $p^m$. This family of groups has presentation

$$\langle x, y \mid x^{p^{m-1}}, y^p, y^{-1}xy = x^{1+p^{m-2}} \rangle$$

This family is notable because, for odd $p$, these are the only $p$-groups with a cyclic subgroup of index $p$, a result proven in [Gor1980]. It is also shown in [Gor1980] that this is one of four families containing nonabelian
EXAMPLES:

Using the last relation in the group’s presentation, one can see that the elements of the form $y^i x$, $0 \leq i \leq p - 1$ all have order $p^{m-1}$, as it can be shown that their $p$th powers are all $x^{p^{m-2}+p}$, an element with order $p^{m-2}$. Manipulation of the same relation shows that none of these elements are powers of any other. Thus, there are $p$ cyclic maximal subgroups in each split metacyclic group. It is also proven in [Gor1980] that this family has commutator subgroup of order $p$, and the Frattini subgroup is equal to the center, with this group being cyclic of order $p^{m-2}$. These characteristics are necessary to identify these groups in the case that $p = 2$, although the possession of a cyclic maximal subgroup in a non-abelian $p$-group is enough for odd $p$ given the group’s order.

```python
sage: G = SplitMetacyclicGroup(2,8)
sage: G.order() == 2**8
True
sage: G.is_abelian()
False
sage: len([H for H in G.subgroups() if H.order() == 2^7 and H.is_cyclic()])
2
sage: G.commutator().order()
2
sage: G.frattini_subgroup() == G.center()
True
sage: G.center().order() == 2^6
True
sage: G.center().is_cyclic()
True

sage: G = SplitMetacyclicGroup(3,3)
sage: len([H for H in G.subgroups() if H.order() == 3^2 and H.is_cyclic()])
3
sage: G.commutator().order()
3
sage: G.frattini_subgroup() == G.center()
True
sage: G.center().order()
3
```

AUTHOR:

- Kevin Halasz (2012-8-7)
Note: This group is also available via `groups.permutation.Suzuki()`.

EXAMPLES:

```python
sage: SuzukiGroup(8)
Permutation Group with generators [(1,2) (3,10) (4,42) (5,18) (6,50) (7,26) (8,58) (9, -> 34) (12,28) (13,45) (14,44) (15,23) (16,31) (17,21) (19,39) (20,38) (22,25) (24,61) (27, 
- 60) (29,65) (30,55) (32,33) (35,52) (36,49) (37,59) (40,54) (41,62) (43,53) (46,48) (47, 
- 56) (51,63) (57,64),
(1,28,10,44) (3,50,11,42) (4,43,53,64) (5,9,39,52) (6,36,63,13) (7,51,60,57) (8,33,37, 
- 16) (12,24,55,29) (14,30,48,47) (15,19,61,54) (17,59,22,62) (18,23,34,31) (20,38,49, 
- 25) (21,26,45,58) (27,32,41,65) (35,46,40,56)]
sage: print(SuzukiGroup(8))
The Suzuki group over Finite Field in a of size 2^3
sage: G = SuzukiGroup(32, name='alpha')
sage: G.order()
32537600
sage: G.order().factor()
2^10 * 5^2 * 31 * 41
sage: G.base_ring()
Finite Field in alpha of size 2^5
```

REFERENCES:

- Wikipedia article Group_of_Lie_type#Suzuki-Ree_groups

```python
sage: base_ring()
```

EXAMPLES:

```python
sage: G = SuzukiGroup(32, name='alpha')
sage: G.base_ring()
Finite Field in alpha of size 2^5
```

### class `sage.groups.perm_gps.permgroup_named.SuzukiSporadicGroup`

Bases: `sage.groups.perm_gps.permgroup_named.PermutationGroup_unique`

Suzuki Sporadic Group

INPUT:

* `n` – a positive integer, or list or tuple thereof

The full symmetric group of order \( n! \), as a permutation group.

If \( n \) is a list or tuple of positive integers then it returns the symmetric group of the associated set.

INPUT:

* `n` – a positive integer, or list or tuple thereof

Note: This group is also available via `groups.permutation.Symmetric()`.

24.3. “Named” Permutation groups (such as the symmetric group, \( S_n \))
EXAMPLES:

```python
sage: G = SymmetricGroup(8)
sage: G.order()
40320
sage: G
Symmetric group of order 8! as a permutation group
sage: G.degree()
8
sage: S8 = SymmetricGroup(8)
sage: G = SymmetricGroup([1,2,4,5])
sage: G
Symmetric group of order 4! as a permutation group
sage: G.domain()
{1, 2, 4, 5}
sage: G = SymmetricGroup(4)
sage: G
Symmetric group of order 4! as a permutation group
sage: G.domain()
{1, 2, 3, 4}
sage: G.category()
Join of Category of finite enumerated permutation groups and
Category of finite weyl groups and
Category of well generated finite irreducible complex reflection groups
```

**Element**

alias of `sage.groups.perm_gps.permgroup_element.SymmetricGroupElement`

**algebra** *(base_ring, category=None)*

Return the symmetric group algebra associated to `self`.

**INPUT:**

- `base_ring` - a ring
- `category` - a category (default: the category of `self`)

If `self` is the symmetric group on 1,..., `n`, then this is special cased to take advantage of the features in `SymmetricGroupAlgebra`. Otherwise the usual group algebra is returned.

**EXAMPLES:**

```python
sage: S4 = SymmetricGroup(4)
sage: A = S4.algebra(QQ); A
Symmetric group algebra of order 4 over Rational Field
sage: A
Symmetric group algebra of order 3 over Rational Field
sage: a = S3.an_element(); a
(2,3)
sage: A(a)
(2,3)
```

We illustrate the choice of the category:

```python
sage: A.category()
Join of Category of coxeter group algebras over Rational Field
and Category of finite group algebras over Rational Field
and Category of finite dimensional cellular algebras with basis
```

(continues on next page)
In the following case, a usual group algebra is returned:

    sage: S = SymmetricGroup([2,3,5])
    sage: S.algebra(QQ)
    Algebra of Symmetric group of order 3! as a permutation group over Rational Field
    sage: a = S.an_element(); a
    (3,5)
    sage: S.algebra(QQ)(a)
    (3,5)

\textbf{cartan_type()}

Return the Cartan type of \texttt{self}

The symmetric group $S_n$ is a Coxeter group of type $A_{n-1}$.

**EXAMPLES:**

    sage: A = SymmetricGroup([2,3,7]); A.cartan_type()
    ['A', 2]
    sage: A = SymmetricGroup([]); A.cartan_type()
    ['A', 0]

\textbf{conjugacy_class(g)}

Return the conjugacy class of \texttt{g} inside the symmetric group \texttt{self}.

**INPUT:**

- \texttt{g} – a partition or an element of the symmetric group \texttt{self}

**OUTPUT:**

A conjugacy class of a symmetric group.

**EXAMPLES:**

    sage: G = SymmetricGroup(5)
    sage: g = G((1,2,3,4))
    sage: G.conjugacy_class(g)
    Conjugacy class of cycle type [4, 1] in
    Symmetric group of order 5! as a permutation group

\textbf{conjugacy_classes()}

Return a list of the conjugacy classes of \texttt{self}.

**EXAMPLES:**

    sage: G = SymmetricGroup(5)
    sage: G.conjugacy_classes()

(continues on next page)
Symmetric group of order 5! as a permutation group,
Conjugacy class of cycle type [4, 1] in
Symmetric group of order 5! as a permutation group,
Conjugacy class of cycle type [5] in
Symmetric group of order 5! as a permutation group]

**conjugacy_classes_iterator()**

Iterate over the conjugacy classes of self.

**EXAMPLES:**

```python
sage: G = SymmetricGroup(5)
sage: list(G.conjugacy_classes_iterator()) == G.conjugacy_classes()
True
```

**conjugacy_classes_representatives()**

Return a complete list of representatives of conjugacy classes in a permutation group $G$.

Let $S_n$ be the symmetric group on $n$ letters. The conjugacy classes are indexed by partitions $\lambda$ of $n$. The ordering of the conjugacy classes is reverse lexicographic order of the partitions.

**EXAMPLES:**

```python
sage: G = SymmetricGroup(5)
sage: G.conjugacy_classes_representatives()
[(), (1,2), (1,2)(3,4), (1,2,3), (1,2,3)(4,5),
 (1,2,3,4), (1,2,3,4,5)]
sage: S = SymmetricGroup(['a','b','c'])
sage: S.conjugacy_classes_representatives()
[(), ('a','b'), ('a','b','c')]
```

**coxeter_matrix()**

Return the Coxeter matrix of self.

**EXAMPLES:**

```python
sage: A = SymmetricGroup([2,3,7,'a']); A.coxeter_matrix()
[1 3 2]
[3 1 3]
[2 3 1]
```

**index_set()**

Return the index set for the descents of the symmetric group self.

**EXAMPLES:**

```python
sage: S8 = SymmetricGroup(8)
sage: S8.index_set()
(1, 2, 3, 4, 5, 6, 7)
sage: S = SymmetricGroup([3,1,4,5])
sage: S.index_set()
(3, 1, 4)
```

**major_index**(parameter=None)

Return the major index generating polynomial of self, which is a gadget counting the elements of self by major index.
INPUT:

- parameter – an element of a ring; the result is more explicit with a formal variable (default: element \( q \) of Univariate Polynomial Ring in \( q \) over Integer Ring)

\[
P(q) = \sum_{g \in S_n} q^{\text{major index}(g)}
\]

EXAMPLES:

```python
sage: S4 = SymmetricGroup(4)
sage: S4.major_index()
qu^6 + 3*q^5 + 5*q^4 + 6*q^3 + 5*q^2 + 3*q + 1
sage: K.<t> = QQ[]
sage: S4.major_index(t)
t^6 + 3*t^5 + 5*t^4 + 6*t^3 + 5*t^2 + 3*t + 1
```

**reflections()**

Return the list of all reflections in self.

EXAMPLES:

```python
sage: A = SymmetricGroup(3)
sage: A.reflections()
[(1,2), (1,3), (2,3)]
```

**simple_reflection**(i)

For \( i \) in the index set of self, this returns the elementary transposition \( s_i = (i, i+1) \).

EXAMPLES:

```python
sage: A = SymmetricGroup(5)
sage: A.simple_reflection(3)
(3,4)
sage: A = SymmetricGroup([2,3,7])
sage: A.simple_reflections()
Finite family {2: (2,3), 3: (3,7)}
```

**young_subgroup**(comp)

Return the Young subgroup associated with the composition comp.

EXAMPLES:

```python
sage: S = SymmetricGroup(8)
sage: c = Composition([2,2,2,2])
sage: S.young_subgroup(c)
Subgroup generated by [(7,8), (5,6), (3,4), (1,2)] of (Symmetric group of order 8! as a permutation group)
sage: S = SymmetricGroup(['a','b','c'])
sage: S.young_subgroup([2,1])
Subgroup generated by [('a','b')] of (Symmetric group of order 3! as a permutation group)
sage: Y = S.young_subgroup([2,2,2,2])
Traceback (most recent call last):
  ...
ValueError: The composition is not of expected size
```
class sage.groups.perm_gps.permgroup_named.TransitiveGroup(d, n)

The transitive group from the GAP tables of transitive groups.

INPUT:

• d – non-negative integer; the degree

• n – positive integer; the index of the group in the GAP database, starting at 1

OUTPUT:

the n-th transitive group of degree d

Note: This group is also available via groups.permutation.Transitive().

EXAMPLES:

sage: TransitiveGroup(0,1)
Transitive group number 1 of degree 0
sage: TransitiveGroup(1,1)
Transitive group number 1 of degree 1
sage: G = TransitiveGroup(5, 2); G
Transitive group number 2 of degree 5
sage: G.gens()
[(1,2,3,4,5), (1,4)(2,3)]
sage: G.category()
Category of finite enumerated permutation groups

Warning: this follows GAP’s naming convention of indexing the transitive groups starting from 1:

sage: TransitiveGroup(5,0)
Traceback (most recent call last):
...
ValueError: Index n must be in {1,..,5}

Warning: only transitive groups of “small” degree are available in GAP’s database:

sage: TransitiveGroup(32,1)
Traceback (most recent call last):
...
NotImplementedError: Only the transitive groups of degree at most 31 are available in GAP’s database

sage.groups.perm_gps.permgroup_named.TransitiveGroups(d=None)

INPUT:

• d – an integer (optional)

Returns the set of all transitive groups of a given degree d up to isomorphisms. If d is not specified, it returns the set of all transitive groups up to isomorphisms.

EXAMPLES:
sage: TransitiveGroups(3)
Transitive Groups of degree 3
sage: TransitiveGroups(7)
Transitive Groups of degree 7
sage: TransitiveGroups(8)
Transitive Groups of degree 8
sage: TransitiveGroups()
Transitive Groups

**Warning:** in practice, the database currently only contains transitive groups up to degree 31:

```python
sage: TransitiveGroups(32).cardinality()
Traceback (most recent call last):
...  
NotImplementedError: Only the transitive groups of degree at most 31 are available in GAP's database
```

```python
class sage.groups.perm_gps.permgroup_named.TransitiveGroupsAll
    Bases: sage.sets.disjoint_unionEnumeratedSets

The infinite set of all transitive groups up to isomorphisms.

EXAMPLES:
```
sage: L = TransitiveGroups(); L
Transitive Groups
sage: L.category()
Category of facade infinite enumerated sets
sage: L.cardinality()
+Infinity
sage: p = L.__iter__()
sage: (next(p), next(p), next(p), next(p), next(p), next(p), next(p))
(Transitive group number 1 of degree 0, Transitive group number 1 of degree 1, ...
Transitive group number 2 of degree 4, Transitive group number 3 of degree 4)
```

```python
class sage.groups.perm_gps.permgroup_named.TransitiveGroupsOfDegree(n)
structure.parent.Parent

The set of all transitive groups of a given (small) degree up to isomorphisms.

EXAMPLES:
```
sage: S = TransitiveGroups(4); S
Transitive Groups of degree 4
sage: list(S)
[Transitive group number 1 of degree 4, Transitive group number 2 of degree 4,...
Transitive group number 5 of degree 4]
```
We write the cardinality of all transitive groups of degree 5:

```
sage: for G in TransitiveGroups(5):
....:   print(G.cardinality())
5
10
20
60
120
```

cardinality()

Returns the cardinality of self, that is the number of transitive groups of a given degree.

EXAMPLES:

```
sage: TransitiveGroups(0).cardinality()
1
sage: TransitiveGroups(2).cardinality()
1
sage: TransitiveGroups(7).cardinality()
7
sage: TransitiveGroups(12).cardinality()
301
sage: [TransitiveGroups(i).cardinality() for i in range(11)]
[1, 1, 1, 2, 5, 5, 16, 7, 50, 34, 45]
```

Warning: GAP comes with a database containing all transitive groups up to degree 31:

```
sage: TransitiveGroups(32).cardinality()
Traceback (most recent call last):
  ...:
NotImplementedError: Only the transitive groups of degree at most 31 are available in GAP's database
```

## 24.4 Permutation group elements

AUTHORS:

- David Joyner (2006-02)
- David Joyner (2006-03): word problem method and reorganization
- Sebastian Oehms (2018-11): Added gap() as synonym to _gap_() (compatibility to libgap framework, see trac ticket #26750)
- Sebastian Oehms (2019-02): Implemented gap() properly (trac ticket #27234)

There are several ways to define a permutation group element:

- Define a permutation group \( G \), then use \( G.gens() \) and multiplication \( \ast \) to construct elements.
- Define a permutation group \( G \), then use, e.g., \( G([[1, 2, (3, 4, 5)]) \) to construct an element of the group. You could also use \( G('1, 2, (3, 4, 5)' ) \)
- Use, e.g., \( \text{PermutationGroupElement}([[1, 2], (3, 4, 5)]) \) or \( \text{PermutationGroupElement}('1, 2, (3, 4, 5)' ) \) to make a permutation group element with parent \( S_5 \).
EXAMPLES:

We illustrate construction of permutation using several different methods.

First we construct elements by multiplying together generators for a group:

```python
sage: G = PermutationGroup(['(1,2)(3,4)', '(3,4,5,6)'], canonicalize=False)
sage: s = G.gens()
sage: s[0]
(1,2)(3,4)
sage: s[1]
(3,4,5,6)
sage: s[0]*s[1]
(1,2)(3,5,6)
sage: (s[0]*s[1]).parent()
Permutation Group with generators [(1,2)(3,4), (3,4,5,6)]
```

Next we illustrate creation of a permutation using coercion into an already-created group:

```python
sage: g = G([(1,2),(3,5,6)])
sage: g
(1,2)(3,5,6)
sage: g.parent()
Permutation Group with generators [(1,2)(3,4), (3,4,5,6)]
sage: g == s[0]*s[1]
True
```

We can also use a string or one-line notation to specify the permutation:

```python
sage: h = G('(1,2)(3,5,6)')
sage: i = G([2,1,5,4,6,3])
sage: g == h == i
True
```

The Rubik’s cube group:

```python
sage: f = [(17,19,24,22),(18,21,23,20),( 6,25,43,16),( 7,28,42,13),( 8,30,41,11)]
sage: b = [(33,35,40,38),(34,37,39,36),( 3, 9,46,32),( 2,12,47,29),( 1,14,48,27)]
sage: l = [( 9,11,16,14),(10,13,15,12),( 1,17,41,40),( 4,20,44,37),( 5,22,46,35)]
sage: r = [(25,27,32,30),(26,29,31,28),( 3,38,43,19),( 5,36,45,21),( 8,33,48,24)]
sage: u = [( 1, 3, 8, 6),( 2, 5, 7, 4),( 9,33,25,17),(10,34,26,18),(11,35,27,19)]
sage: d = [(41,43,48,46),(42,45,47,44),(14,22,30,38),(15,23,31,39),(16,24,32,40)]
sage: cube = PermutationGroup([f, b, l, r, u, d])
sage: F, B, L, R, U, D = cube.gens()
sage: cube.order()
43252003274489856000
sage: F.order()
4
```

We create element of a permutation group of large degree:

```python
sage: G = SymmetricGroup(30)
sage: s = G(srange(30,0,-1)); s
```

The class `sage.groups.perm_gps.permgroup_element.PermutationGroupElement` is defined as follows:

```python
class sage.groups.perm_gps.permgroup_element.PermutationGroupElement
    Bases: sage.structure.element.MultiplicativeGroupElement

    An element of a permutation group.
```

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EXAMPLES:

```
sage: G = PermutationGroup(['(1,2,3)(4,5)'])
sage: G
Permutation Group with generators [(1,2,3)(4,5)]
sage: g = G.random_element()
sage: g in G
True
sage: g = G.gen(0); g
(1,2,3)(4,5)
sage: print(g)
(1,2,3)(4,5)
sage: g*g
(1,3,2)
sage: g**(-1)
(1,3,2)(4,5)
sage: g**2
(1,3,2)
sage: G = PermutationGroup([(1,2,3)])
sage: g = G.gen(0); g
(1,2,3)
sage: g.order()
3
```

This example illustrates how permutations act on multivariate polynomials.

```
sage: R = PolynomialRing(RationalField(), 5, ["x", "y", "z", "u", "v"])
sage: x, y, z, u, v = R.gens()
sage: f = x**2 - y**2 + 3*z**2
sage: G = PermutationGroup(['(1,2,3)(4,5)', '(1,2,3,4,5)'])
sage: sigma = G.gen(0)
sage: f * sigma
3*x^2 + y^2 - z^2
```

`cycle_string(singletons=False)`

Return string representation of this permutation.

EXAMPLES:

```
sage: g = PermutationGroupElement([(1,2,3),(4,5)])
sage: g.cycle_string()
'(1,2,3)(4,5)'
sage: g = PermutationGroupElement([3,2,1])
sage: g.cycle_string(singletons=True)
'(1,3)(2)'
```

`cycle_tuples(singletons=False)`

Return self as a list of disjoint cycles, represented as tuples rather than permutation group elements.

INPUT:

- `singletons` - boolean (default: False) whether or not consider the cycle that correspond to fixed point

EXAMPLES:

```
sage: p = PermutationGroupElement('(2,6)(4,5,1)')
sage: p.cycle_tuples()
```
EXAMPLES:

sage: S = SymmetricGroup(4)
sage: S.gen(0).cycle_tuples()
[(1, 2, 3, 4)]

sage: S = SymmetricGroup(['a','b','c','d'])
sage: S.gen(0).cycle_tuples()
[('a', 'b', 'c', 'd')]

sage: S([('a', 'b'), ('c', 'd')]).cycle_tuples()
[('a', 'b'), ('c', 'd')]

\textbf{cycle_type \texttt{(singletons=True, as_list=False)}}

Return the partition that gives the cycle type of \textit{g} as an element of self.

INPUT:

\begin{itemize}
  \item \textit{g} – an element of the permutation group self.parent()
  \item \textit{singletons} – True or False depending on whether on or not trivial cycles should be counted (default: True)
  \item \textit{as_list} – True or False depending on whether the cycle type should be returned as a list or as a Partition (default: False)
\end{itemize}

OUTPUT:

A Partition, or list if \texttt{is_list} is True, giving the cycle type of \textit{g}

If speed is a concern then \texttt{as_list=True} should be used.

EXAMPLES:

sage: G = DihedralGroup(3)
sage: [g.cycle_type() for g in G]
[[1, 1, 1], [3], [3], [2, 1], [2, 1], [2, 1]]

sage: G = SymmetricGroup(3); G('(1,2,3)(4,5)'.cycle_type()
[3, 3, 2]

sage: G = SymmetricGroup(4); G('(1,2)').cycle_type()
[2, 1]

sage: G = SymmetricGroup(4); G('(1,2)').cycle_type(singletons=False)
[2]

sage: G = SymmetricGroup(4); G('(1,2)').cycle_type(as_list=False)
[2, 1, 1]

\textbf{cycles()}

Return self as a list of disjoint cycles.

EXAMPLES:

sage: G = PermutationGroup(['(1,2,3)(4,5,6,7)'])
sage: g = G.0
sage: g.cycles()
[(1,2,3), (4,5,6,7)]
sage: a, b = g.cycles()
sage: a(1), b(1)
(2, 1)

dict()

Returns a dictionary associating each element of the domain with its image.

EXAMPLES:

sage: G = SymmetricGroup(4)
sage: g = G((1,2,3,4)); g
(1,2,3,4)
sage: v = g.dict(); v
{1: 2, 2: 3, 3: 4, 4: 1}
sage: type(v[1])
<... 'int'>
sage: x = G([2,1]); x
(1,2)
sage: x.dict()
{1: 2, 2: 1, 3: 3, 4: 4}

domain()

Returns the domain of self.

EXAMPLES:

sage: G = SymmetricGroup(4)
sage: x = G([2,1,4,3]); x
(1,2)(3,4)
sage: v = x.domain(); v
[2, 1, 4, 3]
sage: type(v[0])
<... 'int'>
sage: x = G([2,1]); x
(1,2)
sage: x.domain()
[2, 1, 3, 4]

gap()

Returns self as a libgap element

EXAMPLES:

sage: P = PGU(8,2)
sage: p, q = P.gens()
sage: p_libgap = p.gap()
sage: p_pexpect = gap(p)
sage: p_libgap == p_pexpect
True
sage: type(p_libgap) == type(p_pexpect)
False

has_descent (i, side='right', positive=False)

INPUT:

- i: an element of the index set
- side: “left” or “right” (default: “right”)
**positive**: a boolean (default: False)

Returns whether `self` has a left (resp. right) descent at position `i`. If `positive` is True, then test for a non descent instead.

Beware that, since permutations are acting on the right, the meaning of descents is the reverse of the usual convention. Hence, `self` has a left descent at position `i` if `self(i) > self(i+1)`.

**EXAMPLES:**

```python
sage: S = SymmetricGroup([1,2,3])
sage: S.one().has_descent(1)
False
sage: S.one().has_descent(2)
False
sage: s = S.simple_reflections()
sage: x = s[1]*s[2]
sage: x.has_descent(1, side = "right")
False
sage: x.has_descent(2, side = "right")
True
sage: x.has_descent(1, side = "left")
True
sage: x.has_descent(2, side = "left")
False
sage: S._test_has_descent()
```

The symmetric group acting on a set not of the form \((1, \ldots, n)\) is also supported:

```python
sage: S = SymmetricGroup([2,4,1])
sage: s = S.simple_reflections()
sage: x = s[2]*s[4]
sage: x.has_descent(4)
True
sage: S._test_has_descent()
```

**inverse()**

Returns the inverse permutation.

**OUTPUT:**

For an element of a permutation group, this method returns the inverse element, which is both the inverse function and the inverse as an element of a group.

**EXAMPLES:**

```python
sage: s = PermutationGroupElement("(1,2,3)(4,5)")
sage: s.inverse()
(1,3,2)(4,5)

sage: A = AlternatingGroup(4)
sage: t = A("(1,2,3)")
sage: t.inverse()
(1,3,2)
```

There are several ways (syntactically) to get an inverse of a permutation group element.

```python
sage: s = PermutationGroupElement("(1,2,3,4)(6,7,8)")
sage: s.inverse() == s^\-1
True
```

(continues on next page)
sage: s.inverse() == ~s
True

matrix()

Returns deg x deg permutation matrix associated to the permutation self

EXAMPLES:

sage: G = PermutationGroup(['(1,2,3)(4,5)'])
sage: g = G.gen(0)
sage: g.matrix()
[0 1 0 0 0]
[0 0 1 0 0]
[1 0 0 0 0]
[0 0 0 1 0]
[0 0 1 0]

multiplicative_order()

Return the order of this group element, which is the smallest positive integer $n$ for which $g^n = 1$.

EXAMPLES:

sage: s = PermutationGroupElement('(1,2)(3,5,6)')
sage: s.multiplicative_order()
6

order is just an alias for multiplicative_order:

sage: s.order()
6

orbit (n, sorted=True)

Returns the orbit of the integer $n$ under this group element, as a sorted list.

EXAMPLES:

sage: G = PermutationGroup(['(1,2,3)(4,5)'])
sage: g = G.gen(0)
sage: g.orbit(4)
[4, 5]
sage: g.orbit(3)
[1, 2, 3]
sage: g.orbit(10)
[10]

sage: s = SymmetricGroup(['a', 'b']).gen(0); s
('a','b')
sage: s.orbit('a')
['a', 'b']

sign()

Returns the sign of self, which is $(-1)^s$, where $s$ is the number of swaps.

EXAMPLES:

sage: s = PermutationGroupElement('(1,2)(3,5,6)')
sage: s.sign()
-1
ALGORITHM: Only even cycles contribute to the sign, thus

\[ \text{sign}(\sigma) = (-1)^{\sum \text{len}(c) - 1} \]

where the sum is over cycles in self.

tuple()
Return tuple of images of the domain under self.

EXAMPLES:

```python
sage: G = SymmetricGroup(5)
sage: s = G([2,1,5,3,4])
sage: s.tuple()
(2, 1, 5, 3, 4)
sage: S = SymmetricGroup(['a', 'b'])
sage: S.gen().tuple()
('b', 'a')
```

word_problem(words, display=True)
G and H are permutation groups, \( g \) in G, H is a subgroup of G generated by a list (words) of elements of G. If \( g \) is in H, return the expression for \( g \) as a word in the elements of (words).

This function does not solve the word problem in Sage. Rather it pushes it over to GAP, which has optimized algorithms for the word problem. Essentially, this function is a wrapper for the GAP functions “EpimorphismFromFreeGroup” and “PreImagesRepresentative”.

EXAMPLES:

```python
sage: G = PermutationGroup([[1,2,3),(4,5)],[[3,4]]), canonicalize=False)
sage: g1, g2 = G.gens()
sage: h = g1^2*g2*g1
sage: h.word_problem([g1,g2], False)
('x1^2*x2^-1*x1', '(1,2,3)(4,5)^2*(3,4)^-1*(1,2,3)(4,5)')
sage: h.word_problem([g1,g2])
('x1^2*x2^-1*x1', '(1,2,3)(4,5)^2*(3,4)^-1*(1,2,3)(4,5)')
```

class \( \text{sage.groups.perm_gps.permgroup_element.SymmetricGroupElement} \)
Bases: \( \text{sage.groups.perm_gps.permgroup_element.PermutationGroupElement} \)

An element of the symmetric group.

absolute_length()
Return the absolute length of self.

The absolute length is the size minus the number of its disjoint cycles. Alternatively, it is the length of the shortest expression of the element as a product of reflections.

See also:

absolute_le()

EXAMPLES:

```python
sage: S = SymmetricGroup(3)
sage: [x.absolute_length() for x in S]
[0, 2, 2, 1, 1, 1]
```
**has_left_descent**(*i*)

Return whether *i* is a left descent of self.

**EXAMPLES:**

```python
sage: W = SymmetricGroup(4)
sage: w = W.from_reduced_word([1,3,2,1])
sage: [i for i in W.index_set() if w.has_left_descent(i)]
[1, 3]
```

**sage.groups.perm_gps.permgroup_element.is_PermutationGroupElement**(*x*)

Returns True if *x* is a PermutationGroupElement.

**EXAMPLES:**

```python
sage: p = PermutationGroupElement([(1,2),(3,4,5)])
sage: from sage.groups.perm_gps.permgroup_element import is_PermutationGroupElement
sage: is_PermutationGroupElement(p)
True
```

**sage.groups.perm_gps.permgroup_element.make_permgroup_element**(*G, x*)

Returns a PermutationGroupElement given the permutation group *G* and the permutation *x* in list notation.

This is function is used when unpickling old (pre-domain) versions of permutation groups and their elements. This now does a bit of processing and calls `make_permgroup_element_v2()` which is used in unpickling the current PermutationGroupElements.

**EXAMPLES:**

```python
sage: from sage.groups.perm_gps.permgroup_element import make_permgroup_element
sage: S = SymmetricGroup(3)
sage: make_permgroup_element(S, [1,3,2])
(2,3)
```

**sage.groups.perm_gps.permgroup_element.make_permgroup_element_v2**(*G, x, domain*)

Returns a PermutationGroupElement given the permutation group *G*, the permutation *x* in list notation, and the domain of the permutation group.

This is function is used when unpickling permutation groups and their elements.

**EXAMPLES:**

```python
sage: from sage.groups.perm_gps.permgroup_element import make_permgroup_element_v2
sage: S = SymmetricGroup(3)
sage: make_permgroup_element_v2(S, [1,3,2], S.domain())
(2,3)
```

**sage.groups.perm_gps.permgroup_element.standardize_generator**(*g, convert_dict=None*)

Standardizes the input for permutation group elements to a list of tuples. This was factored out of the PermutationGroupElement.__init__ since PermutationGroup_generic.__init__ needs to do the same computation in order to compute the domain of a group when it's not explicitly specified.

**INPUT:**

- *g* - a list, tuple, string, GapElement, PermutationGroupElement, Permutation
- *convert_dict* - (optional) a dictionary used to convert the points to a number compatible with GAP.
OUTPUT:

The permutation in as a list of cycles.

EXAMPLES:

```python
sage: from sage.groups.perm_gps.permgroup_element import standardize_generator
sage: standardize_generator('(1,2)')
[(1, 2)]
sage: p = PermutationGroupElement([(1,2)])
sage: standardize_generator(p)
[(1, 2)]
sage: standardize_generator(p._gap_())
[(1, 2)]
sage: standardize_generator((1,2))
[(1, 2)]
sage: standardize_generator([('a','b')])
[(1, 2)]
sage: standardize_generator(Permutation([2,1,3]))
[(1, 2), (3,)]
```

```python
d = {'a': 1, 'b': 2}
sage: p = SymmetricGroup(['a', 'b']).gen(0); p
('a','b')
sage: standardize_generator(p, convert_dict=d)
[(1, 2)]
sage: standardize_generator(p._gap_(), convert_dict=d)
[(1, 2)]
sage: standardize_generator(('a','b'), convert_dict=d)
[(1, 2)]
sage: standardize_generator([('a','b')], convert_dict=d)
[(1, 2)]
```

```python
sage: from sage.groups.perm_gps.permgroup_element import string_to_tuples
sage: string_to_tuples('(1,2,3)')
[(1, 2, 3)]
sage: string_to_tuples('(1,2,3)(4,5)')
[(1, 2, 3), (4, 5)]
sage: string_to_tuples('(1,2,3) (4,5)')
[(1, 2, 3), (4, 5)]
sage: string_to_tuples('(1,2)(3)')
[(1, 2), (3,)]
```

### 24.5 Permutation group homomorphisms

**AUTHORS:**

- David Joyner (2006-03-21): first version
- David Joyner (2008-06): fixed kernel and image to return a group, instead of a string.

**EXAMPLES:**
sage: G = CyclicPermutationGroup(4)
sage: H = DihedralGroup(4)
sage: g = G([(1,2,3,4)])
sage: phi = PermutationGroupMorphism_im_gens(G, H, map(H, G.gens()))
sage: phi.image(G)
Subgroup generated by [(1,2,3,4)] of (Dihedral group of order 8 as a permutation group)
sage: phi.image(g)
(1,2,3,4)
sage: phi.kernel()
Subgroup generated by [()] of (Cyclic group of order 4 as a permutation group)
sage: phi.domain()
Cyclic group of order 4 as a permutation group

class sage.groups.perm_gps.permgroup_morphism.PermutationGroupMorphism

Bases: sage.categories.morphism.Morphism

A set-theoretic map between PermutationGroups.

image(J)

J must be a subgroup of G. Computes the subgroup of H which is the image of J.

EXAMPLES:

sage: G = CyclicPermutationGroup(4)
sage: H = DihedralGroup(4)
sage: g = G([(1,2,3,4)])
sage: phi = PermutationGroupMorphism_im_gens(G, H, map(H, G.gens()))
sage: phi.image(G)
Subgroup generated by [(1,2,3,4)] of (Dihedral group of order 8 as a permutation group)
sage: phi.image(g)
(1,2,3,4)

sage: G = PSL(2,7)
sage: D = G.direct_product(G)
sage: H = D[0]
sage: pr1 = D[3]
sage: pr1.image(G)
Subgroup generated by [(3,7,5)(4,8,6), (1,2,6)(3,4,8)] of (The projective special linear group of degree 2 over Finite Field of size 7)
sage: G.is_isomorphic(pr1.image(G))
True

kernel()

Returns the kernel of this homomorphism as a permutation group.

EXAMPLES:

sage: G = CyclicPermutationGroup(4)
sage: H = DihedralGroup(4)
sage: g = G([(1,2,3,4)])
sage: phi = PermutationGroupMorphism_im_gens(G, H, [1])
sage: phi.kernel()
Subgroup generated by [(1,2,3,4)] of (Cyclic group of order 4 as a permutation group)

sage: G = PSL(2,7)
sage: D = G.direct_product(G)
sage: H = D[0]
sage: pr1 = D[3]
sage: G.is_isomorphic(pr1.kernel())
True

class sage.groups.perm_gps.permgroup_morphism.PermutationGroupMorphism_from_gap(G, H, gap_hom)

Bases: sage.groups.perm_gps.permgroup_morphism.PermutationGroupMorphism

This is a Python trick to allow Sage programmers to create a group homomorphism using GAP using very general constructions. An example of its usage is in the direct_product instance method of the PermutationGroup_generic class in permgroup.py.

Basic syntax:
PermutationGroupMorphism_from_gap(domain_group, range_group,'phi:=gap_hom_command;','phi') And don’t forget the line: from sage.groups.perm_gps.permgroup_morphism import PermutationGroupMorphism_from_gap in your program.

EXAMPLES:

sage: from sage.groups.perm_gps.permgroup_morphism import PermutationGroupMorphism_from_gap
sage: G = PermutationGroup([[[(1,2),(3,4)], [(1,2,3,4)]]])
sage: H = G.subgroup([G([[(1,2,3,4)]]]])
sage: PermutationGroupMorphism_from_gap(H, G, gap.Identity)
Permutation group morphism:
From: Subgroup generated by [(1,2,3,4)] of (Permutation Group with generators [(1,2)(3,4), (1,2,3,4)])
To: Permutation Group with generators [(1,2)(3,4), (1,2,3,4)]
Defn: Identity

class sage.groups.perm_gps.permgroup_morphism.PermutationGroupMorphism_id

Bases: sage.groups.perm_gps.permgroup_morphism.PermutationGroupMorphism

class sage.groups.perm_gps.permgroup_morphism.PermutationGroupMorphism_im_gens(G, H, gens=None)

Bases: sage.groups.perm_gps.permgroup_morphism.PermutationGroupMorphism

Some python code for wrapping GAP’s GroupHomomorphismByImages function but only for permutation groups. Can be expensive if G is large. Returns “fail” if gens does not generate self or if the map does not extend to a group homomorphism, self - other.

EXAMPLES:

sage: G = CyclicPermutationGroup(4)
sage: H = DihedralGroup(4)
sage: phi = PermutationGroupMorphism_im_gens(G, H, map(H, G.gens())); phi
Permutation group morphism:
From: Cyclic group of order 4 as a permutation group
To: Dihedral group of order 8 as a permutation group
Defn: \([(1,2,3,4)] \rightarrow [(1,2,3,4)]

```
sage: g = G([(1,3),(2,4)]); g
(1,3)(2,4)
sage: phi(g)
(1,3)(2,4)
sage: images = ((4,3,2,1),)
sage: phi = PermutationGroupMorphism_im_gens(G, G, images)
sage: g = G([(1,2,3,4)]); g
(1,2,3,4)
sage: phi(g)
(1,4,3,2)
```

AUTHORS:
- David Joyner (2006-02)

`sage.groups.perm_gps.permgroup_morphism.is_PermutationGroupMorphism(f)`

Returns True if the argument `f` is a PermutationGroupMorphism.

EXAMPLES:

```
sage: from sage.groups.perm_gps.permgroup_morphism import is_
       PermutationGroupMorphism
sage: G = CyclicPermutationGroup(4)
sage: H = DihedralGroup(4)
sage: phi = PermutationGroupMorphism_im_gens(G, H, G.gens())
sage: G = CyclicPermutationGroup(4)
sage: H = DihedralGroup(4)
sage: phi = PermutationGroupMorphism_im_gens(G, H, G.gens())
sage: is_PermutationGroupMorphism(phi)
True
```

### 24.6 Rubik’s cube group functions

**Note:** “Rubik’s cube” is trademarked. We shall omit the trademark symbol below for simplicity.

**NOTATION:**

- `B` denotes a clockwise quarter turn of the back face,
- `D` denotes a clockwise quarter turn of the down face, and similarly for `F` (front), `L` (left), `R` (right), and `U` (up).

Products of moves are read right to left, so for example, `R · U` means move `U` first and then `R`.

See `CubeGroup.parse()` for all possible input notations.

The “Singmaster notation”:

- **moves:** `U, D, R, L, F, B` as in the diagram below,
- **corners:** `xyz` means the facet is on face `x` (in `R, F, L, U, D, B`) and the clockwise rotation of the corner sends `x − y − z`
- **edges:** `xy` means the facet is on face `x` and a flip of the edge sends `x − y`.

```
sage: rubik = CubeGroup()
sage: rubik.display2d(""")
+--------------------------+
```

(continues on next page)
AUTHORS:

- David Joyner (2006-10-21): first version
- David Joyner (2007-05): changed faces, added legal and solve
- David Joyner (2007-06): added plotting functions
- Robert Miller (2007, 2008): editing, cleaned up display2d
- David Joyner (2007-09): rewrote docstring for CubeGroup’s “solve”.

REFERENCES:


class sage.groups.perm_gps.cubegroup.CubeGroup

Bases: sage.groups.perm_gps.permgroup.PermutationGroup_generic

A python class to help compute Rubik’s cube group actions.

Note: This group is also available via groups.permutation.RubiksCube().

EXAMPLES:

If G denotes the cube group then it may be regarded as a subgroup of SymmetricGroup(48), where the 48 facets are labeled as follows.

```sage
rubik = CubeGroup()
rubik.display2d("")
```

(continues on next page)
sage: rubik

B()
Return the generator $B$ in Singmaster notation.

EXAMPLES:

```python
sage: rubik = CubeGroup()
sage: rubik.B()
(1,14,48,27)(2,12,47,29)(3,9,46,32)(33,35,40,38)(34,37,39,36)
```

D()
Return the generator $D$ in Singmaster notation.

EXAMPLES:

```python
sage: rubik = CubeGroup()
sage: rubik.D()
(14,22,30,38)(15,23,31,39)(16,24,32,40)(41,43,48,46)(42,45,47,44)
```

F()
Return the generator $F$ in Singmaster notation.

EXAMPLES:

```python
sage: rubik = CubeGroup()
sage: rubik.F()
(6,25,43,16)(7,28,42,13)(8,30,41,11)(17,19,24,22)(18,21,23,20)
```

L()
Return the generator $L$ in Singmaster notation.

EXAMPLES:

```python
sage: rubik = CubeGroup()
sage: rubik.L()
(1,17,41,40)(4,20,44,37)(6,22,46,35)(9,11,16,14)(10,13,15,12)
```

R()
Return the generator $R$ in Singmaster notation.

EXAMPLES:

```python
sage: rubik = CubeGroup()
sage: rubik.R()
(3,38,43,19)(5,36,45,21)(8,33,48,24)(25,27,32,30)(26,29,31,28)
```
Return the generator $U$ in Singmaster notation.

EXAMPLES:

```
sage: rubik = CubeGroup()
sage: rubik.U()
(1,3,8,6)(2,5,7,4)(9,33,25,17)(10,34,26,18)(11,35,27,19)
```

Print the 2d representation of self.

EXAMPLES:

```
sage: rubik = CubeGroup()
sage: rubik.display2d("R")
+--------------+
| 1 2 38 |
| 4 top 36 |
| 6 7 33 |
+------------+
| 9 10 11 | 17 18 3 | 27 29 32 | 48 34 35 |
| 12 left 13 | 20 front 5 | 26 right 31 | 45 rear 37 |
| 14 15 16 | 22 23 8 | 25 28 30 | 43 39 40 |
+------------+
| 41 42 19 |
| 44 bottom 21 |
| 46 47 24 |
+------------+
```

Return the dictionary of faces created by the effect of the move mv, which is a string of the form $X^a Y^b \ldots$, where $X, Y, \ldots$ are in \{R, L, F, B, U, D\} and $a, b, \ldots$ are integers. We call this ordering of the faces the "BDFLRU, L2R, T2B ordering".

EXAMPLES:

```
sage: rubik = CubeGroup()
Here is the dictionary of the solved state:
```
```
sage: sorted(rubik.faces("").items())
[('back', [[33, 34, 35], [36, 0, 37], [38, 39, 40]]),
 ('down', [[41, 42, 43], [44, 0, 45], [46, 47, 48]]),
 ('front', [[17, 18, 19], [20, 0, 21], [22, 23, 24]]),
 ('left', [[9, 10, 11], [12, 0, 13], [14, 15, 16]]),
 ('right', [[25, 26, 27], [28, 0, 29], [30, 31, 32]]),
 ('up', [[1, 2, 3], [4, 0, 5], [6, 7, 8]])
```
```
Now the dictionary of the state obtained after making the move R followed by L:
```
```
sage: sorted(rubik.faces("R*U").items())
[('back', [[48, 26, 27], [45, 0, 37], [43, 39, 40]]),
 ('down', [[41, 42, 11], [44, 0, 21], [46, 47, 24]]),
 ('front', [[9, 10, 8], [20, 0, 7], [22, 23, 6]]),
 ('left', [[33, 34, 35], [12, 0, 13], [14, 15, 16]]),
 ('right', [[19, 29, 32], [18, 0, 31], [17, 28, 30]]),
 ('up', [[3, 5, 38], [2, 0, 36], [1, 4, 25]])
```
```

facets(g=None)
Return the set of facets on which the group acts. This function is a “constant”.
EXAMPLES:
sage: rubik = CubeGroup()
sage: rubik.facets() == list(range(1,49))
True

gen_names()
Return the names of the generators.
EXAMPLES:
sage: rubik = CubeGroup()
sage: rubik.gen_names()
['B', 'D', 'F', 'L', 'R', 'U']

legal(state, mode=’quiet’)
Return 1 (true) if the dictionary state (in the same format as returned by the faces method) represents a
legal position (or state) of the Rubik’s cube or 0 (false) otherwise.
EXAMPLES:
sage: rubik = CubeGroup()
sage: r0 = rubik.faces("")
sage: r1 = {'back': [[33, 34, 35], [36, 0, 37], [38, 39, 40]], 'down': [[41,
˓→42, 43], [44, 0, 45], [46, 47, 48]],'front': [[17, 18, 19], [20, 0, 21],
˓→[22, 23, 24]],'left': [[9, 10, 11], [12, 0, 13], [14, 15, 16]],'right':
˓→[[25, 26, 27], [28, 0, 29], [30, 31, 32]],'up': [[1, 2, 3], [4, 0, 5], [6,
˓→8, 7]]}
sage: rubik.legal(r0)
1
sage: rubik.legal(r0,"verbose")
(1, ())
sage: rubik.legal(r1)
0

move(mv)
Return the group element and the reordered list of facets, as moved by the list mv (read left-to-right)
INPUT:
• mv – A string of the form Xa*Yb*..., where X, Y, . . . are in R, L, F, B, U, D and a, b, . . . are
integers.
EXAMPLES:
sage: rubik = CubeGroup()
sage: rubik.move("")[0]
()
sage: rubik.move("R")[0]
(3,38,43,19)(5,36,45,21)(8,33,48,24)(25,27,32,30)(26,29,31,28)
sage: rubik.R()
(3,38,43,19)(5,36,45,21)(8,33,48,24)(25,27,32,30)(26,29,31,28)

parse(mv, check=True)
This function allows one to create the permutation group element from a variety of formats.
INPUT:

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• mv – Can one of the following:
  – list - list of facets (as returned by self.facets())
  – dict - list of faces (as returned by self.faces())
  – str - either cycle notation (passed to GAP) or a product of generators or Singmaster notation
  – perm_group element - returned as an element of self
• check – check if the input is valid

EXAMPLES:

```
sage: C = CubeGroup()
sage: C.parse(list(range(1,49)))
()
sage: g = C.parse("L"); g
(1,17,41,40)(4,20,44,37)(6,22,46,35)(9,11,16,14)(10,13,15,12)
sage: C.parse(str(g)) == g
True
sage: facets = C.facets(g); facets
[17, 2, 3, 20, 5, 22, 7, 8, 11, 13, 16, 10, 15, 9, 12, 14, 41, 18, 19, 44, 20, 23,
  24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 6, 36, 4, 38, 39, 1, 46, 43, 37, 45, 35,
  47, 48]
sage: C.parse(facets) == C.parse("L")
True
sage: faces = C.faces("L"); faces
{'back': [[33, 34, 6], [36, 0, 4], [38, 39, 1]],
 'down': [[40, 42, 43], [37, 0, 45], [35, 47, 48]],
 'front': [[41, 18, 19], [44, 0, 21], [46, 23, 24]],
 'left': [[11, 13, 16], [10, 0, 15], [9, 12, 14]],
 'right': [[25, 26, 27], [28, 0, 29], [30, 31, 32]],
 'up': [[17, 2, 3], [20, 0, 5], [22, 7, 8]]}
sage: C.parse(faces) == C.parse("L")
True
sage: C.parse("L'R") == C.parse("L^(-1)*R^2")
True
sage: C.parse("L'R")
(1,40,41,17)(3,43)(4,37,44,20)(5,45)(6,35,46,22)(8,48)(9,14,16,11)(10,12,15,13)
sage: C.parse("L^4")
()
```

plot3d_cube (mv, title=True)

Displays $F, U, R$ faces of the cube after the given move $mv$. Mostly included for the purpose of drawing pictures and checking moves.

INPUT:

• mv – A string in the Singmaster notation
• title – (Default: True) Display the title information

The first one below is “superflip+4 spot” (in 26q* moves) and the second one is the superflip (in 20f* moves). Type show(P) to view them.
EXAMPLES:

```python
sage: rubik = CubeGroup()
```

`plot_cube(mv, title=True, colors=((1, 0.63, 1), (1, 1, 0), (1, 0, 0), (0, 1, 0), (1, 0.6, 0.3), (0, 0, 1)))`

Input the move `mv`, as a string in the Singmaster notation, and output the 2D plot of the cube in that state.

Type `P.show()` to display any of the plots below.

EXAMPLES:

```python
sage: rubik = CubeGroup()
sage: # (R^2U^2)^3 permutes 2 pairs of edges (uf,ub)(fr,br)
sage: # the superflip (in 20f* moves)
sage: # "superflip+4 spot" (in 26q* moves)
```

`repr2d(mv)`

Displays a 2D map of the Rubik’s cube after the move `mv` has been made. Nothing is returned.

EXAMPLES:

```python
sage: rubik = CubeGroup()
sage: print(rubik.repr2d"
```

(continues on next page)
You can see the right face has been rotated but not the left face.

solve(state, algorithm='default')

Solves the cube in the state, given as a dictionary as in legal. See the solve method of the RubiksCube class for more details.

This may use GAP’s EpimorphismFromFreeGroup and PreImagesRepresentative as explained below, if ‘gap’ is passed in as the algorithm.

This algorithm

1. constructs the free group on 6 generators then computes a reasonable set of relations which they satisfy
2. computes a homomorphism from the cube group to this free group quotient
3. takes the cube position, regarded as a group element, and maps it over to the free group quotient
4. using those relations and tricks from combinatorial group theory (stabilizer chains), solves the “word problem” for that element.
5. uses python string parsing to rewrite that in cube notation.

The Rubik’s cube group has about $4.3 \times 10^{19}$ elements, so this process is time-consuming. See http://www.gap-system.org/Doc/Examples/rubik.html for an interesting discussion of some GAP code analyzing the Rubik’s cube.

EXAMPLES:

```
sage: rubik = CubeGroup()
sage: state = rubik.faces("R")
sage: rubik.solve(state)
'R'
sage: state = rubik.faces("R*U")
sage: rubik.solve(state, algorithm='gap')
# long time
'R*U'
```

You can also check this another (but similar) way using the word_problem method (eg. G = rubik.group(); g = G("(3,38,43,19)(5,36,45,21)(8,33,48,24)(25,27,32,30)(26,29,31,28)")); g.word_problem([b,d,f,l,r,u]), though the output will be less intuitive).

```
class sage.groups.perm_gps.cubegroup.RubiksCube

Bases: sage.structure.sage_object.SageObject

The Rubik’s cube (in a given state).

EXAMPLES:

```
sage: C = RubiksCube().move("R U R")
sage: C.show3d()
```

| 46 47 24 |
+-----------+

| 17  2  38 |
| 20  top  36 |
| 22   7  33 |
cubie (size, gap, x, y, z, colors, stickers=True)
  Return the cubie at (x, y, z).

  INPUT:
  • size – The size of the cubie
  • gap – The gap between cubies
  • x, y, z – The position of the cubie
  • colors – The list of colors
  • stickers – (Default True) Boolean to display stickers

  EXAMPLES:

  sage: C = RubiksCube("R*U")
  sage: C.cubie(0.15, 0.025, 0,0,0, C.colors*3)
  Graphics3d Object

facets ()
  Return the facets of self.

  EXAMPLES:

  sage: C = RubiksCube("R*U")
  sage: C.facets()
  [3, 5, 38, 2, 36, 1, 4, 25, 33, 34, 35, 12, 13, 14, 15, 16, 9, 10, 8, 20, 7, 22, 23, 6, 19, 29, 32, 18, 31, 17, 28, 30, 48, 26, 27, 45, 37, 43, 39, 40, 41, 42, 11, 44, 21, 46, 47, 24]

move (g)
  Move the Rubik’s cube by g.

  EXAMPLES:

  sage: RubiksCube().move("R*U") == RubiksCube("R*U")
  True

plot ()
  Return a plot of self.

  EXAMPLES:
\begin{verbatim}
    sage: C = RubiksCube("R*U")
    sage: C.plot()
    Graphics object consisting of 55 graphics primitives

    plot3d(stickers=True)
    Return a 3D plot of self.

    EXAMPLES:
    sage: C = RubiksCube("R*U")
    sage: C.plot3d()
    Graphics3d Object

    scramble(moves=30)
    Scramble the Rubik's cube.

    EXAMPLES:
    sage: C = RubiksCube()
    sage: C.scramble()  # random
    +--------------+
    | 38 29 35     |
    | 20 top 42    |
    | 11 44 30     |
    +--------------+
    | 48 13 17     |
    | 4 left 18    |
    | 33 31 40     |
    +--------------+
    | 46 21 19     |
    | 45 bottom 39 |
    | 27 34 41     |
    +--------------+

    show()
    Show a plot of self.

    EXAMPLES:
    sage: C = RubiksCube("R*U")
    sage: C.show()

    show3d()
    Show a 3D plot of self.

    EXAMPLES:
    sage: C = RubiksCube("R*U")
    sage: C.show3d()

    solve(algorithm='hybrid', timeout=15)
    Solve the Rubik's cube.

    INPUT:
    - algorithm - must be one of the following:
      - hybrid - try kociemba for timeout seconds, then dietz
      - kociemba - Use Dik T. Winter's program (reasonable speed, few moves)
\end{verbatim}
dietz - Use Eric Dietz's cube program (fast but lots of moves)
optimal - Use Michael Reid's optimal program (may take a long time)
gap - Use GAP word solution (can be slow)

EXAMPLES:

```python
sage: C = RubiksCube("R U F L B D")
sage: C.solve()
' R U F L B D'
```

Dietz's program is much faster, but may give highly non-optimal solutions:

```python
sage: s = C.solve('dietz'); s
```

undo() Undo the last move of the Rubik's cube.

EXAMPLES:

```python
sage: C = RubiksCube()
sage: D = C.move("R*U")
sage: D.undo() == C
True
```

sage.groups.perm_gps.cubegroup.color_of_square(facet, colors=['lpurple', 'yellow', 'red', 'green', 'orange', 'blue'])
Return the color the facet has in the solved state.

EXAMPLES:

```python
sage: from sage.groups.perm_gps.cubegroup import color_of_square
sage: color_of_square(41)
'blue'
```

sage.groups.perm_gps.cubegroup.create_poly(face, color)
Create the polygon given by face with color color.

EXAMPLES:

```python
sage: from sage.groups.perm_gps.cubegroup import create_poly, red
sage: create_poly('ur', red)
Graphics object consisting of 1 graphics primitive
```

sage.groups.perm_gps.cubegroup.cubie_centers(label)
Return the cubie center list element given by label.

EXAMPLES:

```python
sage: from sage.groups.perm_gps.cubegroup import cubie_centers
sage: cubie_centers(3)
[0, 2, 2]
```
sage.groups.perm_gps.cubegroup.cubie_colors(label, state0)
Return the color of the cubie given by label at state0.

EXAMPLES:

```python
sage: from sage.groups.perm_gps.cubegroup import cubie_colors
sage: G = CubeGroup()
sage: g = G.parse("R*U")
sage: cubie_colors(3, G.facets(g))
[(1, 1, 1), (1, 0.63, 1), (1, 0.6, 0.3)]
```

sage.groups.perm_gps.cubegroup.cubie_faces()
This provides a map from the 6 faces of the 27 cubies to the 48 facets of the larger cube.

-1,-1,-1 is left, top, front

EXAMPLES:

```python
sage: from sage.groups.perm_gps.cubegroup import cubie_faces
sage: sorted(cubie_faces().items())
[((-1, -1, -1), [6, 17, 11, 0, 0, 0]),
((-1, -1, 0), [4, 0, 10, 0, 0, 0]),
((-1, -1, 1), [1, 0, 9, 0, 35, 0]),
((-1, 0, -1), [0, 20, 13, 0, 0, 0]),
((-1, 0, 0), [0, 0, -5, 0, 37, 0]),
((-1, 0, 1), [0, 0, 12, 0, 37, 0]),
((-1, 1, -1), [0, 22, 16, 41, 0, 0]),
((-1, 1, 0), [0, 0, 15, 44, 0, 0]),
((-1, 1, 1), [0, 0, 14, 46, 40, 0]),
((0, -1, -1), [7, 18, 0, 0, 0, 0]),
((0, -1, 0), [-6, 0, 0, 0, 0, 0]),
((0, -1, 1), [2, 0, 0, 0, 34, 0]),
((0, 0, -1), [0, -4, 0, 0, 0, 0]),
((0, 0, 0), [0, 0, 0, 0, 0, 0]),
((0, 0, 1), [0, 0, 0, 0, -2, 0]),
((0, 1, -1), [0, 23, 0, 42, 0, 0]),
((0, 1, 0), [0, 0, 0, -1, 0, 0]),
((0, 1, 1), [0, 0, 0, 47, 39, 0]),
((1, -1, -1), [8, 19, 0, 0, 0, 25]),
((1, -1, 0), [5, 0, 0, 0, 26, 0]),
((1, -1, 1), [3, 0, 0, 0, 33, 27]),
((1, 0, -1), [0, 21, 0, 0, 0, 28]),
((1, 0, 0), [0, 0, 0, 0, 29, 0]),
((1, 0, 1), [0, 0, 0, 0, 36, 29]),
((1, 1, -1), [0, 24, 0, 43, 0, 30]),
((1, 1, 0), [0, 0, 0, 45, 0, 31]),
((1, 1, 1), [0, 0, 0, 48, 38, 32])]
```

sage.groups.perm_gps.cubegroup.index2singmaster(facet)
Translate index used (eg, 43) to Singmaster facet notation (eg, fdr).

EXAMPLES:

```python
sage: from sage.groups.perm_gps.cubegroup import index2singmaster
sage: index2singmaster(41)
'dlf'
```

sage.groups.perm_gps.cubegroup.inv_list(lst)
Input a list of ints 1,...,m (in any order), outputs inverse perm.
EXAMPLES:

```
sage: from sage.groups.perm_gps.cubegroup import inv_list
sage: L = [2,3,1]
sage: inv_list(L)
[3, 1, 2]
```

```
sage.groups.perm_gps.cubegroup.plot3d_cubie(cnt, clrs)
Plot the front, up and right face of a cubie centered at cnt and rgbcolors given by clrs (in the order FUR).
Type P.show() to view.

EXAMPLES:

```
sage: from sage.groups.perm_gps.cubegroup import plot3d_cubie, blue, red, green
sage: clrF = blue; clrU = red; clrR = green
sage: P = plot3d_cubie([1/2,1/2,1/2],[clrF,clrU,clrR])
```

```
sage.groups.perm_gps.cubegroup.polygon_plot3d(points, tilt=30, turn=30, **kwargs)
Plot a polygon viewed from an angle determined by tilt, turn, and vertices points.

Warning: The ordering of the points is important to get “correct” and if you add several of these plots together, the one added first is also drawn first (ie, addition of Graphics objects is not commutative).

The following example produced a green-colored square with vertices at the points indicated.

EXAMPLES:

```
sage: from sage.groups.perm_gps.cubegroup import polygon_plot3d,green
sage: P = polygon_plot3d([[1,3,1],[2,3,1],[2,3,2],[1,3,2],[1,3,1]],rgbcolor=green)
```

```
sage.groups.perm_gps.cubegroup.rotation_list(tilt, turn)
Return a list $[\sin(\theta), \sin(\phi), \cos(\theta), \cos(\phi)]$ of rotations where $\theta$ is tilt and $\phi$ is turn.

EXAMPLES:

```
sage: from sage.groups.perm_gps.cubegroup import rotation_list
sage: rotation_list(30, 45)
[0.49999999999999994, 0.7071067811865475, 0.8660254037844387, 0.7071067811865476]
```

```
sage.groups.perm_gps.cubegroup.xproj(x, y, z, r)
Return the $x$-projection of $(x, y, z)$ rotated by $r$.

EXAMPLES:

```
sage: from sage.groups.perm_gps.cubegroup import rotation_list, xproj
sage: rot = rotation_list(30, 45)
sage: xproj(1, 2, 3, rot)
0.6123724356957945
```

```
sage.groups.perm_gps.cubegroup.yproj(x, y, z, r)
Return the $y$-projection of $(x, y, z)$ rotated by $r$.

EXAMPLES:

```
sage: from sage.groups.perm_gps.cubegroup import rotation_list, yproj
sage: rot = rotation_list(30, 45)
```
(continues on next page)
24.7 Conjugacy Classes Of The Symmetric Group

AUTHORS:

- Vincent Delecroix, Travis Scrimshaw (2014-11-23)

```python
class sage.groups.perm_gps.symgp_conjugacy_class.PermutationsConjugacyClass(P, part):
    Bases: sage.groups.perm_gps.symgp_conjugacy_class.SymmetricGroupConjugacyClassMixin,
           sage.groups.conjugacy_classes.ConjugacyClass
    A conjugacy class of the permutations of n.
    INPUT:
    • P – the permutations of n
    • part – a partition or an element of P
    set()
    The set of all elements in the conjugacy class self.
    EXAMPLES:
    sage: G = Permutations(3)
    sage: g = G([2, 1, 3])
    sage: C = G.conjugacy_class(g)
    sage: S = [[1, 3, 2], [2, 1, 3], [3, 2, 1]]
    sage: C.set() == Set(G(x) for x in S)
    True
```

```python
class sage.groups.perm_gps.symgp_conjugacy_class.SymmetricGroupConjugacyClass(group, part):
    Bases: sage.groups.perm_gps.symgp_conjugacy_class.SymmetricGroupConjugacyClassMixin,
           sage.groups.conjugacy_classes.ConjugacyClassGAP
    A conjugacy class of the symmetric group.
    INPUT:
    • group – the symmetric group
    • part – a partition or an element of group
    set()
    The set of all elements in the conjugacy class self.
    EXAMPLES:
    sage: G = SymmetricGroup(3)
    sage: g = G((1,2))
    sage: C = G.conjugacy_class(g)
    sage: S = [(2,3), (1,2), (1,3)]
    sage: C.set() == Set(G(x) for x in S)
    True
```
class sage.groups.perm_gps.symgp_conjugacy_class.SymmetricGroupConjugacyClassMixin(domain, part):

    Mixin class which contains methods for conjugacy classes of the symmetric group.

    partition()
    Return the partition of self.

    EXAMPLES:

    sage: G = SymmetricGroup(5)
sage: g = G([(1,2), (3,4,5)])
sage: C = G.conjugacy_class(g)

sage.groups.perm_gps.symgp_conjugacy_class.conjugacy_class_iterator(part, S=None)

    Return an iterator over the conjugacy class associated to the partition part.
    The elements are given as a list of tuples, each tuple being a cycle.

    INPUT:
    • part – partition
    • S – (optional, default: \{1, 2, \ldots, n\}, where n is the size of part) a set

    OUTPUT:
    An iterator over the conjugacy class consisting of all permutations of the set S whose cycle type is part.

    EXAMPLES:

    sage: from sage.groups.perm_gps.symgp_conjugacy_class import conjugacy_class_iterator
    sage: for p in conjugacy_class_iterator([2,2]): print(p)
    [(1, 2), (3, 4)]
    [(1, 4), (2, 3)]
    [(1, 3), (2, 4)]

    In order to get permutations, one just has to wrap:

    sage: S = SymmetricGroup(5)
sage: for p in conjugacy_class_iterator([3,2]): print(S(p))
    (1,3) (2,4,5)
    (1,3) (2,5,4)
    (1,2) (3,4,5)
    (1,2) (3,5,4)
    ...
    (1,4) (2,3,5)
    (1,4) (2,5,3)

    Check that the number of elements is the number of elements in the conjugacy class:

    sage: s = lambda p: sum(1 for _ in conjugacy_class_iterator(p))
sage: all(s(p) == p.conjugacy_class_size() for p in Partitions(5))
    True

    It is also possible to specify any underlying set:
sage: it = conjugacy_class_iterator([2,2,2], 'abcdef')
sage: next(it)
[('a', 'c'), ('b', 'e'), ('d', 'f')]
sage: next(it)
[('a', 'f'), ('c', 'b'), ('e', 'd')]

sage.groups.perm_gps.symgp_conjugacy_class.default_representative(part, G)

Construct the default representative for the conjugacy class of cycle type part of a symmetric group G.

Let $\lambda$ be a partition of $n$. We pick a representative by

$$(1,2,\ldots,\lambda_1)(\lambda_1 + 1,\ldots,\lambda_1 + \lambda_2)(\lambda_1 + \lambda_2 + \cdots + \lambda_{\ell-1},\ldots,n),$$

where $\ell$ is the length (or number of parts) of $\lambda$.

INPUT:

• part – partition
• G – a symmetric group

EXAMPLES:

sage: from sage.groups.perm_gps.symgp_conjugacy_class import default_representative
sage: S = SymmetricGroup(4)
sage: for p in Partitions(4):
...:     print(default_representative(p, S))
(1,2,3,4)
(1,2,3)
(1,2) (3,4)
(1,2)
()
25.1 Library of Interesting Groups

Type `groups.matrix.<tab>` to access examples of groups implemented as permutation groups.

25.2 Base classes for Matrix Groups

Loading, saving, ... works:

```sage
sage: G = GL(2,5); G
General Linear Group of degree 2 over Finite Field of size 5
sage: TestSuite(G).run()

sage: g = G.1; g
[4 1]
[4 0]
sage: TestSuite(g).run()
```

We test that trac ticket #9437 is fixed:

```sage
sage: len(list(SL(2, Zmod(4))))
48
```

AUTHORS:

- William Stein: initial version
- David Joyner (2006-03-15): degree, base_ring, _contains_, list, random, order methods; examples
- William Stein (2006-12): rewrite
- David Joyner (2007-12): Added invariant_generators (with Martin Albrecht and Simon King)
- David Joyner (2008-08): Added module_composition_factors (interface to GAP’s MeatAxe implementation) and as_permutation_group (returns isomorphic PermutationGroup).
- Sebastian Oehms (2018-07): Add subgroup() and ambient() see trac ticket #25894

```python
class sage.groups.matrix_gps.matrix_group.MatrixGroup_base
    Bases: sage.groups.group.Group

    Base class for all matrix groups.
```
This base class just holds the base ring, but not the degree. So it can be a base for affine groups where the
natural matrix is larger than the degree of the affine group. Makes no assumption about the group except that its
elements have a matrix() method.

ambient()
Return the ambient group of a subgroup.

OUTPUT:
A group containing self. If self has not been defined as a subgroup, we just return self.

EXAMPLES:

```
sage: G = GL(2,QQ)
sage: m = matrix(QQ, 2,2, [[3, 0],[5,1]])
sage: S = G.subgroup([m])
sage: S.ambient() is G
True
```

as_matrix_group()
Return a new matrix group from the generators.

This will throw away any extra structure (encoded in a derived class) that a group of special matrices has.

EXAMPLES:

```
sage: G = SU(4,GF(5))
sage: G.as_matrix_group()
Matrix group over Finite Field in a of size 5^2 with 2 generators ( [ a 0 0 0] 1 0 4*a + 3 0 [ 0 2*a + 3 0 0] 1 0 0 0 [ 0 0 4*a + 1 0] 0 2*a + 4 0 1 [ 0 0 0 3*a], 0 3*a + 1 0 0 )
sage: G = GO(3,GF(5))
sage: G.as_matrix_group()
Matrix group over Finite Field of size 5 with 2 generators ( [2 0 0] [0 1 0] [0 3 0] [1 4 4] [0 0 1], [0 2 1] )
```

subgroup(generators, check=True)
Return the subgroup generated by the given generators.

INPUT:

- generators – a list/tuple/iterable of group elements of self
- check – boolean (optional, default: True). Whether to check that each matrix is invertible.

OUTPUT: The subgroup generated by generators as an instance of FinitelyGeneratedMatrixGroup_gap

EXAMPLES:

```
sage: UCF = UniversalCyclotomicField()
sage: G = GL(3, UCF)
sage: e3 = UCF.gen(3); e5 =UCF.gen(5)
sage: m = matrix(UCF, 3,3, [[e3, 1, 0], [0, e5, 7],[4, 3, 2]])
```
```python
sage: S = G.subgroup([m]); S
Subgroup with 1 generators (  
[ E(3)  1  0]  
[  0 E(5)  7]  
[  4   3  2]  ) of General Linear Group of degree 3 over Universal Cyclotomic Field

sage: CF3 = CyclotomicField(3)
sage: G = GL(3, CF3)
sage: e3 = CF3.gen()
sage: m = matrix(CF3, 3, 3, [[e3, 1, 0], [0, -e3, 7], [4, 3, 2]])
sage: S = G.subgroup([m]); S
Subgroup with 1 generators (  
[ zeta3  1  0]  
[  0 -zeta3 -1  7]  
[  4   3   2]  ) of General Linear Group of degree 3 over Cyclotomic Field of order 3 and _degree 2
```

**class** `sage.groups.matrix_gps.matrix_group.MatrixGroup_gap`

```
Bases: `sage.groups.libgap_mixin.GroupMixinLibGAP`, `sage.groups.matrix_gps.matrix_group.MatrixGroup_generic`, `sage.groups.libgap_wrapper.ParentLibGAP`

Base class for matrix groups that implements GAP interface.

**INPUT:**

- `degree` – integer. The degree (matrix size) of the matrix group.
- `base_ring` – ring. The base ring of the matrices.
- `libgap_group` – the defining libgap group.
- `ambient` – A derived class of `ParentLibGAP` or None (default). The ambient class if `libgap_group` has been defined as a subgroup.

```
```

```python
sage: from sage.groups.matrix_gps.matrix_group import MatrixGroup_gap
sage: MatrixGroup_gap(2, ZZ, libgap.eval('GL(2, Integers)'))
Matrix group over Integer Ring with 3 generators (  
[0 1]  
[1 0]  
[1 1]  
)

Check that the slowness of GAP iterators and enumerators for matrix groups (cf. [issue/369](http://tracker.gap-system.org/issues/369)) has been fixed:

```python
sage: i = iter(GL(6,5))
sage: [ next(i) for j in range(8) ]
```
```
```
And the same for listing the group elements, as well as few other issues:

```
sage: F = GF(3)
sage: gens = [matrix(F,2, [1,0, -1,1]), matrix(F, 2, [1,1,0,1])]
sage: G = MatrixGroup(gens)
sage: G.cardinality()
24
sage: v = G.list()
sage: len(v)
24
sage: v[:5]
([0 1] [0 1] [0 1] [0 2] [0 2]
[2 0], [2 1], [2 2], [1 0], [1 1])
sage: all(g in G for g in G.list())
True
```

An example over a ring (see trac ticket #5241):

```
sage: M1 = matrix(ZZ,2,[[[-1,0],[0,1]])
sage: M2 = matrix(ZZ,2,[[[1,0],[0,-1]])
sage: M3 = matrix(ZZ,2,[[[-1,0],[0,-1]])
sage: MG = MatrixGroup([M1, M2, M3])
sage: MG.list()
([[-1 0] [-1 0] [ 1 0] [1 0]
[ 0 1], [ 0 -1], [0 1])
sage: MG.list()[1]
[-1 0]
[ 0 1]
sage: MG.list()[1].parent()
Matrix group over Integer Ring with 3 generators {
[[-1 0] [ 1 0] [-1 0]
[ 0 1], [ 0 -1], [ 0 -1]}
```

An example over a field (see trac ticket #10515):

```
sage: gens = [matrix(QQ,2, [1,0, 0,1])]
sage: MatrixGroup(gens).list()()
([1 0]
[0 1])
```

Another example over a ring (see trac ticket #9437):
An error is raised if the group is not finite:

```python
sage: GL(2,ZZ).list()
Traceback (most recent call last):
  ...  
NotImplementedError: group must be finite
```

**Element**

alias of `sage.groups.matrix_gps.group_element.MatrixGroupElement_gap`

**structure_description** *(G, latex=False)*

Return a string that tries to describe the structure of \( G \).

This method wraps GAP’s `StructureDescription` method.

For full details, including the form of the returned string and the algorithm to build it, see GAP’s documentation.

**INPUT:**

- `latex` – a boolean (default: \( \text{False} \)). If \( \text{True} \) return a LaTeX formatted string.

**OUTPUT:**

- string

**Warning:** From GAP’s documentation: The string returned by `StructureDescription` is not an isomorphism invariant: non-isomorphic groups can have the same string value, and two isomorphic groups in different representations can produce different strings.

**EXAMPLES:**

```python
sage: G = CyclicPermutationGroup(6)
sage: G.structure_description()
'C6'
sage: G.structure_description(latex=True)
'C_{6}'
sage: G2 = G.direct_product(G, maps=False)
sage: LatexExpr(G2.structure_description(latex=True))
C_{6} \times C_{6}
```

This method is mainly intended for small groups or groups with few normal subgroups. Even then there are some surprises:

```python
sage: D3 = DihedralGroup(3)
sage: D3.structure_description()
'S3'
```

We use the Sage notation for the degree of dihedral groups:

```python
sage: D4 = DihedralGroup(4)
sage: D4.structure_description()
'D4'
```

Works for finitely presented groups (trac ticket #17573):
sage: F.<x, y> = FreeGroup()
sage: G = F / [x^2*y^-1, x^3*y^2, x*y*x^-1*y^-1]
sage: G.structure_description()
"C7"

And matrix groups (trac ticket #17573):

sage: groups.matrix.GL(4,2).structure_description()
"A8"

class sage.groups.matrix_gps.matrix_group.MatrixGroup_generic(degree, base_ring, category=None)

Bases: sage.groups.matrix_gps.matrix_group.MatrixGroup_base

Base class for matrix groups over generic base rings

You should not use this class directly. Instead, use one of the more specialized derived classes.

INPUT:

- degree – integer. The degree (matrix size) of the matrix group.
- base_ring – ring. The base ring of the matrices.

Element

alias of sage.groups.matrix_gps.group_element.MatrixGroupElement_generic

degree()

Return the degree of this matrix group.

OUTPUT:

Integer. The size (number of rows equals number of columns) of the matrices.

EXAMPLES:

sage: SU(5,5).degree()
5

matrix_space()

Return the matrix space corresponding to this matrix group.

This is a matrix space over the field of definition of this matrix group.

EXAMPLES:

sage: F = GF(5); MS = MatrixSpace(F,2,2)
sage: G = MatrixGroup([MS(1), MS([1,2,3,4])])
sage: G.matrix_space()
Full MatrixSpace of 2 by 2 dense matrices over Finite Field of size 5
sage: G.matrix_space() is MS
True

sage.groups.matrix_gps.matrix_group.is_MatrixGroup(x)

Test whether x is a matrix group.

EXAMPLES:

sage: from sage.groups.matrix_gps.matrix_group import is_MatrixGroup
sage: is_MatrixGroup(MatrixSpace(QQ,3))
False
sage: is_MatrixGroup(Mat(QQ,3))
False
sage: is_MatrixGroup(GL(2,ZZ))
True
sage: is_MatrixGroup(MatrixGroup([matrix(2,[1,1,0,1])]))
True

25.3 Matrix Group Elements

EXAMPLES:

sage: F = GF(3); MS = MatrixSpace(F,2,2)
sage: gens = [MS([[1,0],[0,1]]),MS([[1,1],[0,1]])]
sage: G = MatrixGroup(gens); G
Matrix group over Finite Field of size 3 with 2 generators (
[1 0] [1 1]
[0 1], [0 1]
)
sage: g = G([[1,1],[0,1]])
sage: h = G([[1,2],[0,1]])
sage: g*h
[1 0]
[0 1]

You cannot add two matrices, since this is not a group operation. You can coerce matrices back to the matrix space and add them there:

sage: g + h
Traceback (most recent call last):
...  
TypeError: unsupported operand parent(s) for +:
'Matrix group over Finite Field of size 3 with 2 generators (
[1 0] [1 1]
[0 1], [0 1]
)' and
'Matrix group over Finite Field of size 3 with 2 generators (
[1 0] [1 1]
[0 1], [0 1]
)'

sage: g.matrix() + h.matrix()
[2 0]
[0 2]

Similarly, you cannot multiply group elements by scalars but you can do it with the underlying matrices:

sage: 2*g
Traceback (most recent call last):
...
TypeError: unsupported operand parent(s) for *: 'Integer Ring' and 'Matrix group over
---Finite Field of size 3 with 2 generators {
[1 0] [1 1]
AUTHORS:

- David Joyner (2006-05): initial version
- David Joyner (2006-05): various modifications to address William Stein’s TODO’s.
- Volker Braun (2013-1) port to new Parent, libGAP.
- Travis Scrimshaw (2016-01): reworks class hierarchy in order to cythonize

```python
class sage.groups.matrix_gps.group_element.MatrixGroupElement_gap
    Bases: sage.groups.libgap_wrapper.ElementLibGAP

Element of a matrix group over a generic ring.

The group elements are implemented as wrappers around libGAP matrices.

INPUT:

- M – a matrix
- parent – the parent
- check – bool (default: True); if True does some type checking
- convert – bool (default: True); if True convert M to the right matrix space

list()

Return list representation of this matrix.

EXAMPLES:

```sage
F = GF(3); MS = MatrixSpace(F,2,2)
sage: gens = [MS([[1,0],[0,1]]),MS([[1,1],[0,1]])]
sage: G = MatrixGroup(gens)
sage: g = G.0
sage: g.list()
[[1, 0], [0, 1]]
```

matrix()

Obtain the usual matrix (as an element of a matrix space) associated to this matrix group element.

EXAMPLES:

```sage
F = GF(3); MS = MatrixSpace(F,2,2)
sage: gens = [MS([[1,0],[0,1]]),MS([[1,1],[0,1]])]
sage: G = MatrixGroup(gens)
sage: m = G.gen(0).matrix(); m
[1 0]
[0 1]
sage: m.parent()
Full MatrixSpace of 2 by 2 dense matrices over Finite Field of size 3
```

(continues on next page)
Matrices have extra functionality that matrix group elements do not have:

```python
sage: g.matrix().charpoly('t')
t^2 + 5*t + 1
```

**multiplicative_order()**

Return the order of this group element, which is the smallest positive integer \( n \) such that \( g^n = 1 \), or \(+\infty\) if no such integer exists.

**EXAMPLES:**

```python
sage: k = GF(7)
sage: G = MatrixGroup([matrix(k,2,[1,1,0,1]), matrix(k,2,[1,0,0,2])]); G
Matrix group over Finite Field of size 7 with 2 generators (\n[1 1] \[1 0]
[0 1], \[0 2]
)
sage: G.order()
21
sage: G.gen(0).multiplicative_order(), G.gen(1).multiplicative_order()
(7, 3)
```

```python
sage: k = QQ
sage: G = MatrixGroup([matrix(k,2,[1,1,0,1]), matrix(k,2,[1,0,0,2])]); G
Matrix group over Rational Field with 2 generators (\n[1 1] \[1 0]
[0 1], \[0 2]
)
sage: G.order()
+Infinity
sage: G.gen(0).multiplicative_order(), G.gen(1).multiplicative_order()
(+Infinity, +Infinity)
```

```python
sage: gl = GL(2, ZZ); gl
General Linear Group of degree 2 over Integer Ring
sage: g = gl.gen(2); g
[1 1]
[0 1]
sage: g.order()
+Infinity
```

**word_problem** *(gens=None)*

Solve the word problem.

This method writes the group element as a product of the elements of the list \( \text{gens} \), or the standard generators of the parent of self if \( \text{gens} \) is None.
INPUT:

- `gens` – a list/tuple/iterable of elements (or objects that can be converted to group elements), or `None` (default). By default, the generators of the parent group are used.

OUTPUT:

A factorization object that contains information about the order of factors and the exponents. A `ValueError` is raised if the group element cannot be written as a word in `gens`.

ALGORITHM:

Use GAP, which has optimized algorithms for solving the word problem (the GAP functions `EpimorphismFromFreeGroup` and `PreImagesRepresentative`).

EXAMPLES:

```python
sage: G = GL(2,5); G
General Linear Group of degree 2 over Finite Field of size 5
sage: G gens()
( [2 0] [4 1] [0 1], [4 0] )
sage: G(1).word_problem([G.gen(0)])
1
sage: type(_)
<class 'sage.structure.factorization.Factorization'>
```

Next we construct a more complicated element of the group from the generators:

```python
sage: s,t = G(0), G(1)
sage: a = (s * t * s); b = a.word_problem(); b
([2 0] [0 1]) * ([4 1] [4 0]) * ([2 0] [0 1])
sage: flatten(b)
[ [2 0] [4 1] [2 0] [0 1], 1, [4 0], 1, [0 1], 1 ]
sage: b.prod() == a
True
```

We solve the word problem using some different generators:

```python
sage: s = G([2,0,0,1]); t = G([1,1,0,1]); u = G([0,-1,1,0])
sage: a = word_problem([s,t,u])
([2 0] [0 1])^-1 * ([1 1] [4 0])^-1 * ([0 1])^-1
```

(continues on next page)
We try some elements that don’t actually generate the group:

```
sage: a.word_problem([t,u])
Traceback (most recent call last):
...
ValueError: word problem has no solution
```

AUTHORS:

- David Joyner and William Stein
- David Loeffler (2010): fixed some bugs
- Volker Braun (2013): LibGAP

class sage.groups.matrix_gps.group_element.MatrixGroupElement_generic

Bases: sage.structure.element.MultiplicativeGroupElement

Element of a matrix group over a generic ring.

The group elements are implemented as Sage matrices.

INPUT:

- M – a matrix
- parent – the parent
- check – bool (default: True); if True, then does some type checking
- convert – bool (default: True); if True, then convert M to the right matrix space

EXAMPLES:

```
sage: W = CoxeterGroup(['A',3], base_ring=ZZ)
sage: g = W.an_element()
sage: g
[ 0 0 -1]
[ 1 0 -1]
[ 0 1 -1]
```

inverse()  
Return the inverse group element

OUTPUT:

A matrix group element.

EXAMPLES:

```
sage: W = CoxeterGroup(['A',3], base_ring=ZZ)
sage: g = W.an_element()
sage: ~g
[-1 1 0]
[-1 0 1]
[-1 0 0]
sage: g * ~g == W.one()
```

Return list representation of this matrix.

One reason to compute the associated matrix is that matrices support a huge range of functionality.

is_one()

Return whether self is the identity of the group.

EXAMPLES:

is_one()

Return whether self is the identity of the group.

is_one()

Return whether self is the identity of the group.

EXAMPLES:

is_one()
Matrices have extra functionality that matrix group elements do not have:

```
sage: g.matrix().charpoly('t')
t^3 - t^2 - t + 1
```

`sage.groups.matrix_gps.group_element.is_MatrixGroupElement(x)`
Test whether \( x \) is a matrix group element

**INPUT:**

- \( x \) – anything.

**OUTPUT:**

Boolean.

**EXAMPLES:**

```
sage: from sage.groups.matrix_gps.group_element import is_MatrixGroupElement
sage: is_MatrixGroupElement('helloooo')
False
sage: G = GL(2,3)
sage: is_MatrixGroupElement(G.an_element())
True
```

## 25.4 Finitely Generated Matrix Groups

This class is designed for computing with matrix groups defined by a finite set of generating matrices.

**EXAMPLES:**

```
sage: F = GF(3)
sage: gens = [matrix(F,2, [1,0, -1,1]), matrix(F,2, [1,1,0,1])]
sage: G = MatrixGroup(gens)
sage: G.conjugacy_classes_representatives()
([1 0]
 [0 2]
[0 1], [1 1], [2 1], [0 2], [1 2], [2 2], [1 0])
```

The finitely generated matrix groups can also be constructed as subgroups of matrix groups:

```
sage: SL2Z = SL(2,ZZ)
sage: S, T = SL2Z.gens()
sage: SL2Z.subgroup([T^2])
Subgroup with 1 generators (
[1 2]
[0 1]) of Special Linear Group of degree 2 over Integer Ring
```

**AUTHORS:**

- William Stein: initial version
- David Joyner (2006-03-15): degree, base_ring, _contains_, list, random, order methods; examples
- William Stein (2006-12): rewrite
- David Joyner (2007-12): Added invariant_generators (with Martin Albrecht and Simon King)
• David Joyner (2008-08): Added module_composition_factors (interface to GAP’s MeatAxe implementation) and as_permutation_group (returns isomorphic PermutationGroup).
• Simon King (2010-05): Improve invariant_generators by using GAP for the construction of the Reynolds operator in Singular.
• Volker Braun (2013-1) port to new Parent, libGAP.
• Sebastian Oehms (2018-07): Added _permutation_group_element_ (Trac #25706)
• Sebastian Oehms (2019-01): Revision of trac ticket #25706 (trac ticket #26903 and :trac:27143).

```python
class sage.groups.matrix_gps.finitely_generated.FinitelyGeneratedMatrixGroup_gap(degree, base_ring, libgap_group, ambient=None, category=None)

Bases: sage.groups.matrix_gps.matrix_group.MatrixGroup_gap

Matrix group generated by a finite number of matrices.

EXAMPLES:

```sage
m1 = matrix(GF(11), [[1,2],[3,4]])
m2 = matrix(GF(11), [[1,3],[10,0]])
G = MatrixGroup(m1, m2); G
```

```
Matrix group over Finite Field of size 11 with 2 generators ( [1 2] [1 3] [3 4], [10 0] )
```

```sage
type(G)
<class 'sage.groups.matrix_gps.finitely_generated.FinitelyGeneratedMatrixGroup_gap_with_category'>
sage: TestSuite(G).run()
```

```python
as_permutation_group(algorithm=None, seed=None)

Return a permutation group representation for the group.

In most cases occurring in practice, this is a permutation group of minimal degree (the degree being determined from orbits under the group action). When these orbits are hard to compute, the procedure can be time-consuming and the degree may not be minimal.

INPUT:

• algorithm=None or 'smaller'. In the latter case, try harder to find a permutation representation of small degree.

• seed=None or an integer specifying the seed to fix results depending on pseudo-random-numbers. Here it makes sense to be used with respect to the 'smaller' option, since gap produces random output in that context.

OUTPUT:

A permutation group isomorphic to self. The algorithm='smaller' option tries to return an isomorphic group of low degree, but is not guaranteed to find the smallest one and must not even differ from the one obtained without the option. In that case repeating the invocation may help (see the example below).

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EXAMPLES:

```python
sage: MS = MatrixSpace(GF(2), 5, 5)
sage: A = MS([[0,0,0,0,1], [0,0,0,1,0], [0,0,1,0,0], [0,1,0,0,0], [1,0,0,0,0]])
sage: G = MatrixGroup([A])
sage: G.as_permutation_group()
Permutation Group with generators [(1,2)]
```

A finite subgroup of GL(12, Z) as a permutation group:

```python
sage: imf=libgap.function_factory('ImfMatrixGroup')
sage: GG = imf(12, 3)
sage: G = MatrixGroup(GG.GeneratorsOfGroup())
sage: G.cardinality()
21499084800
sage: P = G.as_permutation_group()
sage: Psmaller = G.as_permutation_group(algorithm="smaller", seed=6)
sage: P == Psmaller  # see the note below
True
sage: Psmaller = G.as_permutation_group(algorithm="smaller")
sage: P == Psmaller
False
sage: P.cardinality()
21499084800
sage: P.degree()
144
sage: Psmaller.cardinality()
21499084800
sage: Psmaller.degree()
80
```

**Note:** In this case, the “smaller” option returned an isomorphic group of lower degree. The above example used GAP’s library of irreducible maximal finite (“imf”) integer matrix groups to construct the MatrixGroup G over GF(7). The section “Irreducible Maximal Finite Integral Matrix Groups” in the GAP reference manual has more details.

**Note:** Concerning the option `algorithm='smaller'` you should note the following from GAP documentation: “The methods used might involve the use of random elements and the permutation representation (or even the degree of the representation) is not guaranteed to be the same for different calls of SmallerDegreePermutationRepresentation.”

To obtain a reproducible result the optional argument `seed` may be used as in the example above.

`invariant_generators()`

Return invariant ring generators.

Computes generators for the polynomial ring $\mathbb{F}[x_1, \ldots, x_n]^G$, where $G$ in $GL(n, \mathbb{F})$ is a finite matrix group.

In the “good characteristic” case the polynomials returned form a minimal generating set for the algebra of $G$-invariant polynomials. In the “bad” case, the polynomials returned are primary and secondary invariants, forming a not necessarily minimal generating set for the algebra of $G$-invariant polynomials.

**ALGORITHM:**

Wraps Singular’s `invariant_algebra_reynolds` and `invariant_ring` in `finvar.lib`.

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EXAMPLES:

```python
sage: F = GF(7); MS = MatrixSpace(F,2,2)
sage: gens = [MS([[0,1],[-1,0]]), MS([[1,1],[2,3]])]
sage: G = MatrixGroup(gens)
sage: G.invariant_generators()
[x1^7*x2 - x1*x2^7,
 x1^12 - 2*x1^9*x2^3 - x1^6*x2^6 + 2*x1^3*x2^9 + x2^12,
 x1^18 + 2*x1^15*x2^3 + 3*x1^12*x2^6 + 3*x1^6*x2^12 - 2*x1^3*x2^15 + x2^18]
sage: q = 4; a = 2
sage: MS = MatrixSpace(QQ, 2, 2)
sage: gen1 = [[1/a,(q-1)/a],[1/a, -1/a]]; gen2 = [[1,0],[0,-1]]; gen3 = [[-1, 0],[0,1]]
sage: G = MatrixGroup([MS(gen1), MS(gen2), MS(gen3)])
sage: G.cardinality()
12
sage: G.invariant_generators()
[x1^2 + 3*x2^2, x1^6 + 15*x1^4*x2^2 + 15*x1^2*x2^4 + 33*x2^6]
sage: F = CyclotomicField(8)
sage: z = F.gen()
sage: a = z+1/z
sage: b = z^2
sage: MS = MatrixSpace(F,2,2)
sage: g1 = MS([[1/a, 1/a], [1/a, -1/a]])
sage: g2 = MS([[-b, 0], [0, b]])
sage: G=MatrixGroup([g1,g2])
sage: G.invariant_generators()
[x1^4 + 2*x1^2*x2^2 + x2^4,
 x1^5*x2 - x1*x2^5,
 x1^8 + 28/9*x1^6*x2^2 + 70/9*x1^4*x2^4 + 28/9*x1^2*x2^6 + x2^8]
```

AUTHORS:

- David Joyner, Simon King and Martin Albrecht.

REFERENCES:

- Singular reference manual
- [Stu1993]

invariants_of_degree (deg, chi=None, R=None)

Return the (relative) invariants of given degree for this group.

For this group, compute the invariants of degree deg with respect to the group character chi. The method is to project each possible monomial of degree deg via the Reynolds operator. Note that if the polynomial ring R is specified it’s base ring may be extended if the resulting invariant is defined over a bigger field.

INPUT:

- degree – a positive integer
- chi – (default: trivial character) a linear group character of this group
- R – (optional) a polynomial ring

OUTPUT: list of polynomials
EXAMPLES:

```python
sage: Gr = MatrixGroup(SymmetricGroup(2))
sage: sorted(Gr.invariants_of_degree(3))
[x0^2*x1 + x0*x1^2, x0^3 + x1^3]
sage: R.<x,y> = QQ[]
sage: sorted(Gr.invariants_of_degree(4, R=R))
[x^2*y^2, x^3*y + x*y^3, x^4 + y^4]

sage: R.<x,y,z> = QQ[

sage: G = MatrixGroup(SymmetricGroup(5))
sage: R = QQ['x,y']
sage: G.invariants_of_degree(3, R=R)
Traceback (most recent call last):
  ...TypeError: number of variables in polynomial ring must match size of matrices

sage: R.<x,y,z> = K[

sage: S3 = MatrixGroup(SymmetricGroup(3))
sage: chi = S3.character(S3.character_table()[0])
sage: sorted(S3.invariants_of_degree(5, chi=chi))
[x0^3*x1^2 - x0^2*x1^3 - x0^3*x2^2 + x1^3*x2^2 + x0^2*x2^3 - x1^2*x2^3, x0^4*x1 - x0*x1^4 - x0^4*x2 + x1^4*x2 + x0*x2^4 + x0*x2^4 - x1*x2^4]
```

**module_composition_factors** (*algorithm=None*)

Return a list of triples consisting of [base field, dimension, irreducibility], for each of the Meataxe composition factors modules. The *algorithm="verbose"* option returns more information, but in Meataxe notation.

**EXAMPLES:**

```python
sage: F=GF(3);MS=MatrixSpace(F,4,4)
sage: M=MS(0)
sage: M[0,1]=1;M[1,2]=1;M[2,3]=1;M[3,0]=1
sage: G = MatrixGroup([M])
```
 sage: G.module_composition_factors()
[(Finite Field of size 3, 1, True),
 (Finite Field of size 3, 1, True),
 (Finite Field of size 3, 2, True)]

 sage: F = GF(7); MS = MatrixSpace(F,2,2)
 sage: gens = [MS([[0,1],[1,0]]), MS([[1,1],[2,3]])]
 sage: G = MatrixGroup(gens)
 sage: G.module_composition_factors()
[(Finite Field of size 7, 2, True)]

 Type \texttt{G.module\_composition\_factors(algorithm='verbose')} to get a more verbose version.

 For more on MeatAxe notation, see \url{http://www.gap-system.org/Manuals/doc/ref/chap69.html}

 **molien\_series** (chi=None, return\_series=True, prec=20, variable='t')

 Compute the Molien series of this finite group with respect to the character \emph{chi}. It can be returned either as a rational function in one variable or a power series in one variable. The base field must be a finite field, the rationals, or a cyclotomic field.

 Note that the base field characteristic cannot divide the group order (i.e., the non-modular case).

 **ALGORITHM:**

 For a finite group \( G \) in characteristic zero we construct the Molien series as

 \[
 \frac{1}{|G|} \sum_{g \in G} \frac{\chi(g)}{\det(I - tg)} ,
 \]

 where \( I \) is the identity matrix and \( t \) an indeterminate.

 For characteristic \( p \) not dividing the order of \( G \), let \( k \) be the base field and \( N \) the order of \( G \). Define \( \lambda \) as a primitive \( N \)-th root of unity over \( k \) and \( \omega \) as a primitive \( N \)-th root of unity over \( \mathbb{Q} \). For each \( g \in G \) define \( k_i(g) \) to be the positive integer such that \( e_i = \lambda^{k_i(g)} \) for each eigenvalue \( e_i \) of \( g \). Then the Molien series is computed as

 \[
 \frac{1}{|G|} \sum_{g \in G} \frac{\chi(g)}{\prod_{i=1}^n (1 - t \omega^{k_i(g)})} ,
 \]

 where \( t \) is an indeterminate. [Dec1998]

 **INPUT:**

 - \emph{chi} – (default: trivial character) a linear group character of this group
 - \emph{return\_series} – boolean (default: True) if True, then returns the Molien series as a power series, False as a rational function
 - \emph{prec} – integer (default: 20); power series default precision
 - \emph{variable} – string (default: ‘t’); Variable name for the Molien series

 **OUTPUT:** single variable rational function or power series with integer coefficients

 **EXAMPLES:**

 sage: MatrixGroup(matrix(QQ,2,2,[1,1,0,1])).molien_series()
 Traceback (most recent call last):
   ...
 NotImplementedError: only implemented for finite groups
Tetrahedral Group:

```python
sage: K.<i> = CyclotomicField(4)
sage: Tetra = MatrixGroup([(−1+i)/2, (−1+i)/2, (1+i)/2, (−1−i)/2], [0,i, −i,0])
sage: Tetra.molien_series(prec=30)
1 + t^8 + 2*t^12 + t^16 + 2*t^20 + 3*t^24 + 2*t^28 + O(t^30)
sage: mol = Tetra.molien_series(return_series=False); mol
(t^8 - t^4 + 1)/(t^16 - t^12 - t^4 + 1)
sage: mol.parent()
Fraction Field of Univariate Polynomial Ring in t over Integer Ring
```
```
sage: chi = Tetra.character(Tetra.character_table()[1])
sage: Tetra.molien_series(chi, prec=30, variable='u')
u^6 + u^14 + 2*u^18 + u^22 + 2*u^26 + 3*u^29 + 2*u^34 + O(u^36)
sage: chi = Tetra.character(Tetra.character_table()[2])
sage: Tetra.molien_series(chi)
t^10 + t^14 + t^18 + 2*t^22 + 2*t^26 + O(t^30)
```
```
sage: S3 = MatrixGroup(SymmetricGroup(3))
sage: mol = S3.molien_series(prec=10); mol
1 + t + 2*t^2 + 3*t^3 + 4*t^4 + 5*t^5 + 7*t^6 + 8*t^7 + 10*t^8 + 12*t^9 + O(t^10)
sage: mol.parent()
Power Series Ring in t over Integer Ring
```
```
Octahedral Group:

```python
sage: K.<v> = CyclotomicField(8)
sage: a = v-v^3 # sqrt(2)
sage: i = v^2
sage: Octa = MatrixGroup([(−1+i)/2, (−1+i)/2, (1+i)/2, (−1−i)/2], [(1+i)/a,0, 0, −(1−i)/a])
sage: Octa.molien_series(prec=30)
1 + t^8 + t^12 + t^16 + t^18 + t^20 + 2*t^24 + t^26 + t^28 + O(t^30)
```
```
Icosahedral Group:

```python
sage: K.<v> = CyclotomicField(10)
sage: z5 = v^2
sage: a = 2*z5^3 + 2*z5^2 + 1 # sqrt(5)
sage: Ico = MatrixGroup([(z5^3,0, 0,z5^2), [0,1, −1,0], [(z5^4−z5)/a, (z5^2−z5^3)/a, -(z5^4−z5)/a]])
sage: Ico.molien_series(prec=40)
1 + t^12 + t^20 + t^24 + t^30 + t^32 + t^36 + O(t^40)
```
```
Icosahedral Group:

```python
sage: G = MatrixGroup(CyclicPermutationGroup(3))
sage: chi = G.character(G.character_table()[1])
sage: G.molien_series(chi, prec=10)
t + 2*t^2 + 3*t^3 + 5*t^4 + 7*t^5 + 9*t^6 + 12*t^7 + 15*t^8 + 18*t^9 + 22*t^10 + O(t^11)
```
```
25.4. Finitely Generated Matrix Groups
sage: K = GF(5)
sage: S = MatrixGroup(SymmetricGroup(4))
sage: G = MatrixGroup([matrix(K,4,4,[K(y) for u in m.list() for y in u]) for m in S.gens()])
sage: G.molien_series(return_series=False)
1/(t^10 - t^9 - t^8 + 2*t^5 - t^2 - t + 1)

sage: i = GF(7)(3)
sage: G = MatrixGroup([[i^3,0,0,-i^3],[i^2,0,0,-i^2]])
sage: chi = G.character(G.character_table()[4])
sage: G.molien_series(chi)
3*t^5 + 6*t^11 + 9*t^17 + 12*t^23 + O(t^25)

**reynolds_operator** *(poly, chi=None)*

Compute the Reynolds operator of this finite group G.

This is the projection from a polynomial ring to the ring of relative invariants [Stu1993]. If possible, the invariant is returned defined over the base field of the given polynomial `poly`, otherwise, it is returned over the compositum of the fields involved in the computation. Only implemented for absolute fields.

**ALGORITHM:**

Let $K[x]$ be a polynomial ring and $\chi$ a linear character for $G$. Let

be the ring of invariants of $G$ relative to $\chi$. Then the Reynolds’s operator is a map $R$ from $K[x]$ into $K[x]^G$ defined by

**INPUT:**

- `poly` – a polynomial
- `chi` – (default: trivial character) a linear group character of this group

**OUTPUT:** an invariant polynomial relative to $\chi$

**AUTHORS:**

Rebecca Lauren Miller and Ben Hutz

**EXAMPLES:**

```sage
sage: S3 = MatrixGroup(SymmetricGroup(3))
sage: R.<x,y,z> = QQ[]
sage: f = x*y*z^3
sage: S3.reynolds_operator(f)
1/3*x^3*y*z + 1/3*x*y^3*z + 1/3*x*y*z^3
sage: G = MatrixGroup(CyclicPermutationGroup(4))
sage: chi = G.character(G.character_table()[3])
sage: K.<v> = CyclotomicField(4)
sage: R.<x,y,z,w> = K[]
sage: G.reynolds_operator(x, chi)
1/4*x + (-1/4*v)*y - 1/4*z + (1/4*v)*w
sage: chi = G.character(G.character_table()[2])
sage: R.<x,y,z,w> = QQ[]
sage: G.reynolds_operator(x*y, chi)
1/4*x*y + (1/4*zeta4)*y*z + (-1/4*zeta4)*x*w - 1/4*z*w
sage: K.<i> = CyclotomicField(4)
sage: G = MatrixGroup(CyclicPermutationGroup(3))
```

(continues on next page)
sage: chi = G.character(G.character_table()[1])
sage: R.<x,y,z> = K[]
sage: G.reynolds_operator(x*y^5, chi)
1/3*x*y^5 + (2/3*izeta3^3 + izeta3^2 + 8/3*izeta3 + 1)*x^5*z + (-2/3*izeta3^3 - izeta3^2 - 8/3*izeta3 - 4/3)*y*z^5

sage: R.<x,y,z> = QQbar[]
sage: G.reynolds_operator(x*y^5, chi)
1/3*x*y^5 + (-0.1666666666666667? - 0.2886751345948129?*I)*x^5*z + (-0.1666666666666667? + 0.2886751345948129?*I)*y*z^5

sage: K.<i> = CyclotomicField(4)
sage: Tetra = MatrixGroup([(-1+i)/2,(-1+i)/2, (1+i)/2,(-1-i)/2], [0,i, -i,0])
sage: chi = Tetra.character(Tetra.character_table()[4])
sage: L.<v> = QuadraticField(-3)
sage: R.<x,y> = L[]
sage: Tetra.reynolds_operator(x^4)
0
sage: Tetra.reynolds_operator(x^4, chi)
1/4*x^4 + (1/2*v)*x^2*y^2 + 1/4*y^4

sage: R.<x,y,z,w> = QQ[]
sage: f = x^3*y
sage: G.reynolds_operator(f, chi)
1/8*x^3*y - 1/8*x*y^3 + 1/8*y^3*z - 1/8*y*z^3 - 1/8*x^3*w + 1/8*z^3*w + 1/8*x*z*w^3 - 1/8*x*w^3

Characteristic p>0 examples:

sage: G = MatrixGroup([[0,1,1,0]])
sage: R.<w,x> = GF(2)[]
sage: G.reynolds_operator(x)
Traceback (most recent call last):
... Not ImplementedError: only implemented for absolute fields

sage: i = GF(7)(3)
sage: G = MatrixGroup([[i^3,0,0,-i^3],[i^2,0,0,-i^2]])
sage: chi = G.character(G.character_table()[4])
sage: R.<w,x> = GF(7)[]
sage: f = w^5*x + x^6

(continues on next page)
\begin{verbatim}
sage: G.reynolds_operator(f, chi)
Traceback (most recent call last):
...
NotImplementedError: nontrivial characters not implemented for characteristic → 0
sage: G.reynolds_operator(f)
x^6

sage: K = GF(3^2,'t')
sage: G = MatrixGroup([matrix(K,2,2, [0,K.gen(),1,0])])
sage: R.<x,y> = GF(3)
x^8
sage: G.reynolds_operator(x^8)
-x^8 - y^8

sage: K = GF(3^2,'t')
sage: G = MatrixGroup([matrix(GF(3),2,2, [0,1,1,0])])
sage: R.<x,y> = K
sage: f = -K.gen()*x
sage: G.reynolds_operator(f)
(t)*x + (t)*y
\end{verbatim}

\textbf{class} \texttt{sage.groups.matrix_gps.finitely_generated.FinitelyGeneratedMatrixGroup_generic}\linebreak\texttt{(degree, base_ring, generator_matrices, category=None)}\linebreak

\textbf{Bases:} \texttt{sage.groups.matrix_gps.matrix_group.MatrixGroup_generic}\

\textbf{gen}(i)\linebreak
Return the \(i\)-th generator

\textbf{OUTPUT:}\linebreak
The \(i\)-th generator of the group.

\textbf{EXAMPLES:}\linebreak
\begin{verbatim}
sage: H = GL(2, GF(3))
sage: h1, h2 = H([[1,0],[2,1]]), H([[1,1],[0,1]])
sage: G = H.subgroup([h1, h2])
sage: G.gen(0)
[1 0]
[2 1]
sage: G.gen(0).matrix() == h1.matrix()
True
\end{verbatim}

\textbf{gens}()\linebreak
Return the generators of the matrix group.

\textbf{EXAMPLES:}\linebreak
\begin{verbatim}
sage: F = GF(3); MS = MatrixSpace(F,2,2)
sage: gens = [MS([[1,0],[0,1]]), MS([[1,1],[0,1]])]
\end{verbatim}
sage: G = MatrixGroup(gens)
sage: gens[0] in G
True
sage: gens = G.gens()
sage: gens[0] in G
True
sage: gens = [MS([[1,0],[0,1]]),MS([[1,1],[0,1]])]

sage: F = GF(5); MS = MatrixSpace(F,2,2)
sage: G = MatrixGroup([MS(1), MS([1,2,3,4])])
sage: G
Matrix group over Finite Field of size 5 with 2 generators ( [1 0] [1 2] [0 1], [3 4] )
sage: G.gens()
( [1 0] [1 2] [0 1], [3 4] )

ngens ()
Return the number of generators

OUTPUT:
An integer. The number of generators.

EXAMPLES:

sage: H = GL(2, GF(3))
sage: h1, h2 = H([[1,0],[2,1]]), H([[1,1],[0,1]])
sage: G = H.subgroup([h1, h2])
sage: G.ngens()
2

sage.groups.matrix_gps.finitely_generated.MatrixGroup(*gens, **kwds)
Return the matrix group with given generators.

INPUT:
- *gens – matrices, or a single list/tuple/iterable of matrices, or a matrix group.
- check – boolean keyword argument (optional, default: True). Whether to check that each matrix is invertible.

EXAMPLES:

sage: F = GF(5)
sage: gens = [matrix(F,2,[1,2, -1, 1]), matrix(F,2, [1,1, 0,1])]
sage: G = MatrixGroup(gens); G
Matrix group over Finite Field of size 5 with 2 generators ( [1 2] [4 1], [1 1] [0 1] )

In the second example, the generators are a matrix over \(\mathbb{Z}\), a matrix over a finite field, and the integer 2. Sage determines that they both canonically map to matrices over the finite field, so creates that matrix group there:
sage: gens = [matrix(2, [1, 2, -1, 1]), matrix(GF(7), 2, [1, 1, 0, 1]), 2]
          sage: G = MatrixGroup(gens); G
          Matrix group over Finite Field of size 7 with 3 generators 
          [ 1  2]  [1 1]  [2 0]
          [ 6  1], [0 1], [0 2]

Each generator must be invertible:

sage: G = MatrixGroup([matrix(ZZ,2,[1,2,3,4])])
Traceback (most recent call last):
...  ValueError: each generator must be an invertible matrix

sage: F = GF(5); MS = MatrixSpace(F,2,2)
sage: MatrixGroup([MS.0])
Traceback (most recent call last):
...  ValueError: each generator must be an invertible matrix
sage: MatrixGroup([MS.0], check=False)  # works formally but is mathematical nonsense
Matrix group over Finite Field of size 5 with 1 generators 
          [1 0]
          [0 0]

Some groups are not supported, or do not have much functionality implemented:

sage: G = SL(0, QQ)
Traceback (most recent call last):
...  ValueError: the degree must be at least 1

sage: SL2C = SL(2, CC); SL2C
Special Linear Group of degree 2 over Complex Field with 53 bits of precision
sage: SL2C gens()
Traceback (most recent call last):
...  AttributeError: 'LinearMatrixGroup_generic_with_category' object has no attribute 'gens'

sage.groups.matrix_gps.finitely_generated.QuaternionMatrixGroupGF3()
The quaternion group as a set of $2 \times 2$ matrices over $GF(3)$.

OUTPUT:

A matrix group consisting of $2 \times 2$ matrices with elements from the finite field of order 3. The group is the quaternion group, the nonabelian group of order 8 that is not isomorphic to the group of symmetries of a square (the dihedral group $D_4$).

Note: This group is most easily available via groups.matrix.QuaternionGF3().

EXAMPLES:

The generators are the matrix representations of the elements commonly called $I$ and $J$, while $K$ is the product of $I$ and $J$.  

sage: from sage.groups.matrix_gps.finitely_generated import QuaternionMatrixGroupGF3
sage: Q = QuaternionMatrixGroupGF3()
sage: Q.order()
8
sage: aye = Q.gens()[0]; aye
[1 1]
[1 2]
sage: jay = Q.gens()[1]; jay
[2 1]
[1 1]
sage: kay = aye*jay; kay
[0 2]
[1 0]

sage.groups.matrix_gps.finitely_generated.normalize_square_matrices(matrices)

Find a common space for all matrices.

OUTPUT:
A list of matrices, all elements of the same matrix space.

EXAMPLES:

sage: from sage.groups.matrix_gps.finitely_generated import normalize_square_matrices
sage: m1 = [[1,2],[3,4]]
sage: m2 = [2, 3, 4, 5]
sage: m3 = matrix(QQ, [[1/2,1/3],[1/4,1/5]])
sage: m4 = MatrixGroup(m3).gen(0)
sage: normalize_square_matrices([m1, m2, m3, m4])

25.5 Homomorphisms Between Matrix Groups

Deprecated May, 2018; use sage.groups.libgap_morphism instead.

sage.groups.matrix_gps.morphism.to_libgap(x)
Helper to convert x to a LibGAP matrix or matrix group element.

Deprecated; use the x.gap() method or libgap(x) instead.

EXAMPLES:

sage: from sage.groups.matrix_gps.morphism import to_libgap
sage: to_libgap(GL(2,3).gen(0))
doctest:...: DeprecationWarning: this function is deprecated.
Use x.gap() or libgap(x) instead.
See https://trac.sagemath.org/25444 for details.
[ [ Z(3), 0*Z(3) ], [ 0*Z(3), Z(3)^0 ] ]
sage: to_libgap(matrix(QQ, [[1,2],[3,4]]))
[ [ 1, 2 ], [ 3, 4 ] ]
25.6 Matrix Group Homsets

AUTHORS:

• William Stein (2006-05-07): initial version
• Volker Braun (2013-1) port to new Parent, libGAP

```python
sage.groups.matrix_gps.homset.is_MatrixGroupHomset(x)
Test whether x is a matrix group homset.

EXAMPLES:

sage: from sage.groups.matrix_gps.homset import is_MatrixGroupHomset
sage: is_MatrixGroupHomset(4)
False
sage: F = GF(5)
sage: gens = [matrix(F,2,[1,2,-1,1]), matrix(F,2,[1,1,0,1])]
sage: G = MatrixGroup(gens)
sage: from sage.groups.matrix_gps.homset import MatrixGroupHomset
sage: M = MatrixGroupHomset(G, G)
sage: is_MatrixGroupHomset(M)
True
```

25.7 Binary Dihedral Groups

AUTHORS:

• Travis Scrimshaw (2016-02): initial version

```python
class sage.groups.matrix_gps.binary_dihedral.BinaryDihedralGroup(n)
Bases:  
sage.structure.unique_representation.UniqueRepresentation,  
sage.groups.matrix_gps.finitely_generated.FinitelyGeneratedMatrixGroup_gap

The binary dihedral group \( BD_n \) of order \( 4n \).

Let \( n \) be a positive integer. The binary dihedral group \( BD_n \) is a finite group of order \( 4n \), and can be considered as the matrix group generated by

\[
g_1 = \begin{pmatrix} \zeta_{2n} & 0 \\ 0 & \zeta_{2n}^{-1} \end{pmatrix}, \quad g_2 = \begin{pmatrix} 0 & \zeta_4 \\ \zeta_4 & 0 \end{pmatrix},
\]

where \( \zeta_k = e^{2\pi i/k} \) is the primitive \( k \)-th root of unity. Furthermore, \( BD_n \) admits the following presentation (note that there is a typo in [Sun]):

\[
BD_n = \langle x, y, z | x^2 = y^2 = z^n = xyz \rangle.
\]

(The \( x, y \) and \( z \) in this presentations correspond to the \( g_2, g_2g_1^{-1} \) and \( g_1 \) in the matrix group avatar.)

REFERENCES:

• Wikipedia article Dicyclic_group#Binary_dihedral_group
```
cardinality()

Return the order of self, which is $4n$.

EXAMPLES:

```
sage: G = groups.matrix.BinaryDihedral(3)
sage: G.order()
12
```

order()

Return the order of self, which is $4n$.

EXAMPLES:

```
sage: G = groups.matrix.BinaryDihedral(3)
sage: G.order()
12
```

## 25.8 Coxeter Groups As Matrix Groups

This implements a general Coxeter group as a matrix group by using the reflection representation.

AUTHORS:

- Travis Scrimshaw (2013-08-28): Initial version

**class** `sage.groups.matrix_gps.coxeter_group.CoxeterMatrixGroup(coxeter_matrix, base_ring, index_set)`

Bases: `sage.structure.unique_representation.UniqueRepresentation`, `sage.groups.matrix_gps.finitely_generated.FinitelyGeneratedMatrixGroup_generic`

A Coxeter group represented as a matrix group.

Let $(W, S)$ be a Coxeter system. We construct a vector space $V$ over $\mathbb{R}$ with a basis of \{\alpha_s\}_{s \in S} and inner product

$$B(\alpha_s, \alpha_t) = \cos \left( \frac{\pi}{m_{st}} \right)$$

where we have $B(\alpha_s, \alpha_t) = -1$ if $m_{st} = \infty$. Next we define a representation $\sigma_s : V \rightarrow V$ by

$$\sigma_s \lambda = \lambda - 2B(\alpha_s, \lambda) \alpha_s.$$ 

This representation is faithful so we can represent the Coxeter group $W$ by the set of matrices $\sigma_s$ acting on $V$.

**INPUT:**

- `data` – a Coxeter matrix or graph or a Cartan type
- `base_ring` – (default: the universal cyclotomic field or a number field) the base ring which contains all values $\cos(\pi/m_{ij})$ where $(m_{ij})_{ij}$ is the Coxeter matrix
- `index_set` – (optional) an indexing set for the generators

For finite Coxeter groups, the default base ring is taken to be $\mathbb{Q}$ or a quadratic number field when possible.

For more on creating Coxeter groups, see `CoxeterGroup()`.
Todo: Currently the label ∞ is implemented as −1 in the Coxeter matrix.

EXAMPLES:

We can create Coxeter groups from Coxeter matrices:

```
sage: W = CoxeterGroup([[1, 6, 3], [6, 1, 10], [3, 10, 1]])
sage: W
Coxeter group over Universal Cyclotomic Field with Coxeter matrix:
[ 1  6  3]
[ 6  1 10]
[ 3 10  1]
sage: W.gens()
( [ -1 -E(12)^7 + E(12)^11 1]
 [  0          1 0],
 [  0          0 1],
 [  1  0  0  0]
 [  0  1  0  0]
 [  1 E(20) - E(20)^9 -1],
 [  1  0  0  0]
 [  0  1  0  0]
 [  1 E(20) - E(20)^9 -1],
 [  1  0  0  0]
 [  0  1  0  0]
 [  1 E(20) - E(20)^9 -1]
)
sage: m = matrix([[1,3,3,3], [3,1,3,2], [3,3,1,2], [3,2,2,1]])
sage: W = CoxeterGroup(m)
sage: W.gens()
( [ -1  1  1  1] [  1  0  0  0] [  1  0  0  0] [  1  0  0  0]
 [  0  1  0  0] [  1 -1  1  0] [  0  1  0  0] [  0  1  0  0]
 [  0  0  1  0] [  0  0  1  0] [  1  1 -1  0] [  0  0  1  0]
 [  0  0  0  1], [  0  0  0  1], [  1  1 -1  0], [  1  0  0  1] )
sage: a,b,c,d = W.gens()
sage: (a*b*c)^3
[ 5 1 -5 7]
[ 5 0 -4 5]
[ 4 1 -4 4]
[ 0 0 0 1]
sage: (a*b)^3
[ 1 0 0 0]
[ 0 1 0 0]
[ 0 0 1 0]
[ 0 0 0 1]
sage: b*d == d*b
True
sage: a*c*a == c*a*c
True
```

We can create the matrix representation over different base rings and with different index sets. Note that the base ring must contain all $2 \times \cos(\pi/m_{ij})$ where $(m_{ij})_{ij}$ is the Coxeter matrix:

```
sage: W = CoxeterGroup(m, base_ring=RR, index_set=['a','b','c','d'])
sage: W.base_ring()
```

(continues on next page)
Real Field with 53 bits of precision

```python
sage: W.index_set()
('a', 'b', 'c', 'd')
```

```python
sage: CoxeterGroup(m, base_ring=Z2)
Coxeter group over Integer Ring with Coxeter matrix:
[1 3 3 3]
[3 1 3 2]
[3 3 1 2]
[3 2 2 1]
```

```python
sage: CoxeterGroup([[1,4],[4,1]], base_ring=QQ)
Traceback (most recent call last):
...
TypeError: unable to convert sqrt(2) to a rational
```

Using the well-known conversion between Coxeter matrices and Coxeter graphs, we can input a Coxeter graph. Following the standard convention, edges with no label (i.e. labelled by `None`) are treated as 3:

```python
sage: G = Graph([(0,3,None), (1,3,15), (2,3,7), (0,1,3)])
```

```python
sage: W = CoxeterGroup(G); W
Coxeter group over Universal Cyclotomic Field with Coxeter matrix:
[ 1 3 -1 2]
[ 3 1 4 4]
[ -1 4 1 3]
```

Because there currently is no class for \( \mathbb{Z} \cup \{\infty\} \), labels of \( \infty \) are given by \(-1\) in the Coxeter matrix:

```python
sage: G = Graph([(0,1,None), (1,2,4), (0,2,oo)])
```

```python
sage: W = CoxeterGroup(G)
sage: W.coxeter_matrix()
[ 1 3 -1]
[ 3 1 4]
[ -1 4 1]
```

We can also create Coxeter groups from Cartan types using the `implementation` keyword:

```python
sage: W = CoxeterGroup(['D',5], implementation="reflection")
```

```python
sage: W
Finite Coxeter group over Integer Ring with Coxeter matrix:
[1 3 2 2 2]
[3 1 3 2 2]
[2 3 1 3 3]
[2 2 3 1 2]
[2 2 3 2 1]
```

```python
sage: W = CoxeterGroup(['H',3], implementation="reflection")
```

```python
sage: W
Finite Coxeter group over Number Field in a with defining polynomial
x^2 - 5 with Coxeter matrix:
[1 3 2]
[3 1 5]
[2 5 1]
```

```python
class Element
```
Bases: `sage.groups.matrix_gps.group_element.MatrixGroupElement_generic`

A Coxeter group element.

**action_on_root_indices** *(i, side='left')*

Return the action on the set of roots.

The roots are ordered as in the output of the method `roots`.

**EXAMPLES:**

```python
sage: W = CoxeterGroup(['A',3], implementation="reflection")
sage: w = W.w0
sage: w.action_on_root_indices(0)
11
```

**canonical_matrix**

Return the matrix of self in the canonical faithful representation, which is self as a matrix.

**EXAMPLES:**

```python
sage: W = CoxeterGroup(['A',3], implementation="reflection")
sage: a, b, c = W.gens()
sage: elt = a*b*c
sage: elt.canonical_matrix()
[ 0 0 -1]
[ 1 0 -1]
[ 0 1 -1]
```

**descents** *(side='right', index_set=None, positive=False)*

Return the descents of self, as a list of elements of the index_set.

**INPUT:**

- **index_set** – (default: all of them) a subset (as a list or iterable) of the nodes of the Dynkin diagram
- **side** – (default: 'right') 'left' or 'right'
- **positive** – (default: False) boolean

**EXAMPLES:**

```python
sage: W = CoxeterGroup(['A',3], implementation="reflection")
sage: a, b, c = W.gens()
sage: elt = b*a*c
sage: elt.descents()  # default
[1, 3]
sage: elt.descents(positive=True)  # positive=True
[2]
sage: elt.descents(index_set=[1,2])  # index_set=[1,2]
[1]
sage: elt.descents(side='left')  # side='left'
[2]
```

**first_descent** *(side='right', index_set=None, positive=False)*

Return the first left (resp. right) descent of self, as an element of index_set, or None if there is none.

See `descents()` for a description of the options.

**EXAMPLES:**
has_right_descent\( (i) \)

Return whether \( i \) is a right descent of \( \text{self} \).

A Coxeter system \((W, S)\) has a root system defined as \( \{w(\alpha_s)\}_{w \in W} \) and we define the positive (resp. negative) roots \( \alpha = \sum_{s \in S} c_s \alpha_s \) by all \( c_s \geq 0 \) (resp. \( c_s \leq 0 \)). In particular, we note that if \( \ell(ws) > \ell(w) \) then \( w(\alpha_s) > 0 \) and if \( \ell(ws) < \ell(w) \) then \( w(\alpha_s) < 0 \). Thus \( i \in I \) is a right descent if \( w(\alpha_s) < 0 \) or equivalently if the matrix representing \( w \) has all entries of the \( i \)-th column being non-positive.

INPUT:

- \( i \) – an element in the index set

EXAMPLES:

```python
sage: W = CoxeterGroup(['A',3], implementation="reflection")
sage: a,b,c = W.gens()
sage: elt = b*a*c
d... sage: [elt.has_right_descent(i) for i in [1, 2, 3]]
[True, False, True]
```

bilinear_form\()\)

Return the bilinear form associated to \( \text{self} \).

Given a Coxeter group \( G \) with Coxeter matrix \( M = (m_{ij})_{ij} \), the associated bilinear form \( A = (a_{ij})_{ij} \) is given by

\[
a_{ij} = -\cos\left(\frac{\pi}{m_{ij}}\right).
\]

If \( A \) is positive definite, then \( G \) is of finite type (and so the associated Coxeter group is a finite group). If \( A \) is positive semidefinite, then \( G \) is affine type.

EXAMPLES:

```python
sage: W = CoxeterGroup(['D',4])
sage: W.bilinear_form()
[ 1 -1/2 0 0]
[-1/2 1 -1/2 -1/2]
[ 0 -1/2 1 0]
[ 0 -1/2 0 1]
```

canonical_representation\()\)

Return the canonical faithful representation of \( \text{self} \), which is \( \text{self} \).

EXAMPLES:

```python
sage: W = CoxeterGroup([[1,3],[[3,1]])
sage: W.canonical_representation() is W
True
```

coxeter_matrix\()\)

Return the Coxeter matrix of \( \text{self} \).
EXAMPLES:

```
sage: W = CoxeterGroup([[1,3],[3,1]])
sage: W.coxeter_matrix()
[1 3]
[3 1]
sage: W = CoxeterGroup(['H',3])
sage: W.coxeter_matrix()
[1 3 2]
[3 1 5]
[2 5 1]
```

**fundamental_weight** (*i*)

Return the fundamental weight with index *i*.

See also:

**fundamental_weights()**

EXAMPLES:

```
sage: W = CoxeterGroup(['A',3], implementation='reflection')
sage: W.fundamental_weight(1)
(3/2, 1, 1/2)
```

**fundamental_weights()**

Return the fundamental weights for self.

This is the dual basis to the basis of simple roots.

The base ring must be a field.

See also:

**fundamental_weight()**

EXAMPLES:

```
sage: W = CoxeterGroup(['A',3], implementation='reflection')
sage: W.fundamental_weights()
Finite family {1: (3/2, 1, 1/2), 2: (1, 2, 1), 3: (1/2, 1, 3/2)}
```

**is_commutative()**

Return whether self is commutative.

EXAMPLES:

```
sage: CoxeterGroup(['A', 2]).is_commutative()
False
sage: W = CoxeterGroup(['I',2])
sage: W.is_commutative()
True
```

**is_finite()**

Return True if this group is finite.

EXAMPLES:

```
sage: [l for l in range(2, 9) if
.....: CoxeterGroup([[l,3,2],[3,l,1],[2,1,l]]).is_finite()]
(continues on next page)
```
order()  
Return the order of self.

If the Coxeter group is finite, this uses an iterator.

EXAMPLES:

sage: W = CoxeterGroup([[1,3],[3,1]])
sage: W.order()  
6
sage: W = CoxeterGroup([[1,1],[1,1]])
sage: W.order()  
+Infinity

positive_roots()  
Return the positive roots.

These are roots in the Coxeter sense, that all have the same norm. They are given by their coefficients in the base of simple roots, also taken to have all the same norm.

See also:

reflections()  

EXAMPLES:

sage: W = CoxeterGroup(['A',3], implementation='reflection')
sage: W.positive_roots()  
((1, 0, 0), (1, 1, 0), (1, 1, 1), (0, 1, 0), (0, 1, 1), (0, 0, 1))

sage: W = CoxeterGroup(['I',5], implementation='reflection')
sage: W.positive_roots()  
((1, 0),
 (-E(5)^2 - E(5)^3, 1),
 (-E(5)^2 - E(5)^3, -E(5)^2 - E(5)^3),
 (1, -E(5)^2 - E(5)^3),
(0, 1))
reflections()

Return the set of reflections.

The order is the one given by positive_roots().

EXAMPLES:

```python
sage: W = CoxeterGroup(['A',2], implementation='reflection')
sage: list(W.reflections())
[[-1 1]  [ 0 -1]  [ 1 0]
 [ 0 1], [-1 0], [ 1 -1]]
```

roots()

Return the roots.

These are roots in the Coxeter sense, that all have the same norm. They are given by their coefficients in the base of simple roots, also taken to have all the same norm.

The positive roots are listed first, then the negative roots in the same order. The order is the one given by roots().

EXAMPLES:

```python
sage: W = CoxeterGroup(['A',3], implementation='reflection')
sage: W.roots()
((1, 0, 0),
 (1, 1, 0),
 (0, 1, 0),
 (1, 1, 1),
 (0, 1, 1),
 (0, 0, 1),
 (-1, 0, 0),
 (-1, -1, 0),
 (0, -1, 0),
 (-1, -1, -1),
 (0, -1, -1),
 (0, 0, -1))
sage: W = CoxeterGroup(['I',5], implementation='reflection')
sage: len(W.roots())
10
```

simple_reflection(i)

Return the simple reflection $s_i$.

INPUT:

- $i$ – an element from the index set

EXAMPLES:

```python
sage: W = CoxeterGroup(['A',3], implementation='reflection')
sage: W.simple_reflection(1)
[-1 1 0]
[ 0 1 0]
[ 0 0 1]
sage: W.simple_reflection(2)
[ 1 0 0]
[ 1 -1 1]
```
simple_root_index($i$)

Return the index of the simple root $\alpha_i$.

This is the position of $\alpha_i$ in the list of all roots as given by \texttt{roots()}.

EXAMPLES:

```python
sage: W = CoxeterGroup(['A',3], implementation='reflection')
sage: [W.simple_root_index(i) for i in W.index_set()]
[0, 2, 5]
```

25.9 Linear Groups

EXAMPLES:

```python
sage: GL(4,QQ)
General Linear Group of degree 4 over Rational Field
sage: GL(1,ZZ)
General Linear Group of degree 1 over Integer Ring
sage: GL(100,RR)
General Linear Group of degree 100 over Real Field with 53 bits of precision
sage: GL(3,GF(49,'a'))
General Linear Group of degree 3 over Finite Field in a of size 7^2
sage: SL(2, ZZ)
Special Linear Group of degree 2 over Integer Ring
sage: G = SL(2,GF(3)); G
Special Linear Group of degree 2 over Finite Field of size 3
sage: G.is_finite()
True
sage: G.conjugacy_classes_representatives()

\[
\begin{bmatrix} 1 & 0 \\ 0 & 2 \end{bmatrix}, \begin{bmatrix} 1 & 1 \\ 2 & 1 \end{bmatrix}, \begin{bmatrix} 2 & 2 \\ 1 & 0 \end{bmatrix}
\]

sage: G = SL(6,GF(5))
sage: G.gens()

\[
\begin{bmatrix} 2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \begin{bmatrix} 4 & 0 & 0 & 0 & 0 & 1 \\ 0 & 4 & 0 & 0 & 0 & 0 \\ 0 & 0 & 4 & 0 & 0 & 0 \\ 0 & 0 & 0 & 4 & 0 & 0 \\ 0 & 0 & 0 & 0 & 4 & 0 \end{bmatrix}
\]

AUTHORS:

- William Stein: initial version
• David Joyner: degree, base_ring, random, order methods; examples
• David Joyner (2006-05): added center, more examples, renamed random attributes, bug fixes.
• William Stein (2006-12): total rewrite
• Volker Braun (2013-1) port to new Parent, libGAP, extreme refactoring.

REFERENCES: See [KL1990] and [Car1972].

```
sage.groups.matrix_gps.linear.GL(n, R, var='a')
```

Return the general linear group.

The general linear group \( GL(d, R) \) consists of all \( d \times d \) matrices that are invertible over the ring \( R \).

**Note:** This group is also available via `groups.matrix.GL()`.

**INPUT:**

- \( n \) – a positive integer.
- \( R \) – ring or an integer. If an integer is specified, the corresponding finite field is used.
- \( \text{var} \) – variable used to represent generator of the finite field, if needed.

**EXAMPLES:**

```
sage: G = GL(6,GF(5))
sage: G.order()
110644754220000000000000000000000
sage: G.base_ring()
Finite Field of size 5
sage: G.category()
Category of finite groups
sage: TestSuite(G).run()

sage: G = GL(6, QQ)
```

**Here is the Cayley graph of (relatively small) finite General Linear Group:**

```
sage: g = GL(2,3)
sage: d = g.cayley_graph(); d
Digraph on 48 vertices
sage: d.plot(color_by_label=True, vertex_size=0.03, vertex_labels=False)  # long time
Graphics object consisting of 144 graphics primitives
sage: d.plot3d(color_by_label=True)  # long time
Graphics3d Object
```

```
sage: F = GF(3); MS = MatrixSpace(F,2,2)
sage: gens = [MS([[2,0],[0,1]]), MS([[2,1],[2,0]])]
sage: G = MatrixGroup(gens)
sage: G.order()
48
sage: G.cardinality()
48
```

(continues on next page)
```python
sage: H.order()
48
sage: H == G
True
sage: H.gens() == G.gens()
True
sage: H.as_matrix_group() == H
True
sage: H.gens()
[[2 0]
 [2 1]], [[2 0]
 [0 1]], [[2 0]
 [0 1]]
```

```python
class sage.groups.matrix_gps.linear.LinearMatrixGroup_gap(degree, base_ring, special, sage_name, latex_string, gap_command_string, category=None)


The general or special linear group in GAP.

class sage.groups.matrix_gps.linear.LinearMatrixGroup_generic(degree, base_ring, special, sage_name, latex_string, category=None, invariant_form=None)

Bases: sage.groups.matrix_gps.named_group.NamedMatrixGroup_generic

sage.groups.matrix_gps.linear.SL(n, R, var='a')

Return the special linear group.

The special linear group $SL(d, R)$ consists of all $d \times d$ matrices that are invertible over the ring $R$ with determinant one.

**Note:** This group is also available via groups.matrix.SL().

**INPUT:**

- $n$ – a positive integer.
- $R$ – ring or an integer. If an integer is specified, the corresponding finite field is used.
- $var$ – variable used to represent generator of the finite field, if needed.

**EXAMPLES:**

```python
sage: SL(3, GF(2))
Special Linear Group of degree 3 over Finite Field of size 2
sage: G = SL(15, GF(7)); G
Special Linear Group of degree 15 over Finite Field of size 7
```
Next we compute generators for $\text{SL}_3(\mathbb{Z})$

$$\text{sage: G = SL(3, ZZ); G}$$
Special Linear Group of degree 3 over Integer Ring

$$\text{sage: G.gens()}$$
\[
\begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix}, \begin{pmatrix} 1 & 1 \\ -1 & 0 \\ 0 & 0 \end{pmatrix}, \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix}
\]

$$\text{sage: TestSuite(G).run()}$$

## 25.10 Orthogonal Linear Groups

The general orthogonal group $GO(n, R)$ consists of all $n \times n$ matrices over the ring $R$ preserving an $n$-ary positive definite quadratic form. In cases where there are multiple non-isomorphic quadratic forms, additional data needs to be specified to disambiguate. The special orthogonal group is the normal subgroup of matrices of determinant one.

In characteristics different from 2, a quadratic form is equivalent to a bilinear symmetric form. Furthermore, over the real numbers a positive definite quadratic form is equivalent to the diagonal quadratic form, equivalent to the bilinear symmetric form defined by the identity matrix. Hence, the orthogonal group $GO(n, \mathbb{R})$ is the group of orthogonal matrices in the usual sense.

In the case of a finite field and if the degree $n$ is even, then there are two inequivalent quadratic forms and a third parameter $e$ must be specified to disambiguate these two possibilities. The index of $SO(e, d, q)$ in $GO(e, d, q)$ is 2 if $q$ is odd, but $SO(e, d, q) = GO(e, d, q)$ if $q$ is even.

**Warning:** GAP and Sage use different notations:

- GAP notation: The optional $e$ comes first, that is, $GO([e,] d, q), SO([e,] d, q)$.
- Sage notation: The optional $e$ comes last, the standard Python convention: $GO(d, GF(q), e=0), SO(d, GF(q), e=0)$.

**EXAMPLES:**

1. $G = \text{SL}(2, \mathbb{Z})$,
   $\text{category()}$ = Category of finite groups
   $\text{G.order()}$ = 19567125956814696201521906242958634112401800718204947891606736963871306673788236339351996634365767743090701127020626583481909204625023204918796771814955813422677465084565879186574540800000000
   $\text{len(G.gens())}$ = 2

2. $G = \text{SL}(3, \mathbb{Z})$,
   $\text{G.category()}$ = Category of infinite groups
   $\text{G.gens()}$ = \[
   \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix}, \begin{pmatrix} 1 & 1 \\ -1 & 0 \\ 0 & 0 \end{pmatrix}, \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix}
   \]

3. $G = \text{GO}(2, \mathbb{Z})$,
   $\text{G.category()}$ = Category of finite groups
   $\text{G.order()}$ = 19567125956814696201521906242958634112401800718204947891606736963871306673788236339351996634365767743090701127020626583481909204625023204918796771814955813422677465084565879186574540800000000

4. $G = \text{GO}(3, \mathbb{Z})$,
   $\text{G.category()}$ = Category of infinite groups
   $\text{G.gens()}$ = \[
   \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}, \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}
   \]

5. $G = \text{SO}(2, \mathbb{Z})$,
   $\text{G.category()}$ = Category of finite groups
   $\text{G.order()}$ = 19567125956814696201521906242958634112401800718204947891606736963871306673788236339351996634365767743090701127020626583481909204625023204918796771814955813422677465084565879186574540800000000

6. $G = \text{SO}(3, \mathbb{Z})$,
   $\text{G.category()}$ = Category of infinite groups
   $\text{G.gens()}$ = \[
   \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix}, \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}
   \]

7. $G = \text{GO}(4, \mathbb{Z})$,
   $\text{G.category()}$ = Category of finite groups
   $\text{G.order()}$ = 19567125956814696201521906242958634112401800718204947891606736963871306673788236339351996634365767743090701127020626583481909204625023204918796771814955813422677465084565879186574540800000000

8. $G = \text{SO}(4, \mathbb{Z})$,
   $\text{G.category()}$ = Category of infinite groups
   $\text{G.gens()}$ = \[
   \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix}, \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{pmatrix}, \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}, \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix}
   \]
sage: GO(3,7)
General Orthogonal Group of degree 3 over Finite Field of size 7
sage: G = SO( 4, GF(7), 1); G
Special Orthogonal Group of degree 4 and form parameter 1 over Finite Field of size 7
sage: G.random_element()  # random
[4 3 5 2]
[6 6 4 0]
[0 4 6 0]
[4 4 5 1]

AUTHORS:

- David Joyner (2006-03): initial version
- David Joyner (2006-05): added examples, _latex_, __str__, gens, as_matrix_group
- William Stein (2006-12-09): rewrite
- Volker Braun (2013-1) port to new Parent, libGAP, extreme refactoring.
- Sebastian Oehms (2018-8) add invariant_form() (as alias), _OG, option for user defined invariant bilinear form, and bug-fix in cmd-string for calling GAP (see trac ticket #26028)

sage.groups.matrix_gps.orthogonal.GO(n, R, e=0, var='a', invariant_form=None)

Return the general orthogonal group.

The general orthogonal group \( GO(n, R) \) consists of all \( n \times n \) matrices over the ring \( R \) preserving an \( n \)-ary positive definite quadratic form. In cases where there are multiple non-isomorphic quadratic forms, additional data needs to be specified to disambiguate.

In the case of a finite field and if the degree \( n \) is even, then there are two inequivalent quadratic forms and a third parameter \( e \) must be specified to disambiguate these two possibilities.

**Note:** This group is also available via groups.matrix.GO().

**INPUT:**

- \( n \) – integer; the degree
- \( R \) – ring or an integer; if an integer is specified, the corresponding finite field is used
- \( e = +1 \) or \(-1\), and ignored by default; only relevant for finite fields and if the degree is even: a parameter that distinguishes inequivalent invariant forms
- \( \text{var} \) – (optional, default: 'a') variable used to represent generator of the finite field, if needed
- \( \text{invariant\_form} \) – (optional) instances being accepted by the matrix-constructor which define an \( n \times n \) square matrix over \( R \) describing the symmetric form to be kept invariant by the orthogonal group; the form is checked to be non-degenerate and symmetric but not to be positive definite

**OUTPUT:**

The general orthogonal group of given degree, base ring, and choice of invariant form.

**EXAMPLES:**

```
sage: GO( 3, GF(7))
General Orthogonal Group of degree 3 over Finite Field of size 7
sage: GO( 3, GF(7)).order()
672
```

(continues on next page)
Using the `invariant_form` option:

```sage
sage: m = matrix(QQ, 3,3, 
              [[0, 1, 0], 
               [1, 0, 0], 
               [0, 0, 3]])
sage: GO3 = GO(3,QQ)
sage: GO3m = GO(3,QQ, invariant_form=m)
sage: GO3 == GO3m
False
sage: GO3.invariant_form()
[1 0 0]
[0 1 0]
[0 0 1]
sage: GO3m.invariant_form()
[0 1 0]
[1 0 0]
[0 0 3]
sage: pm = Permutation([2,3,1]).to_matrix()
sage: g = GO3(pm); g in GO3; g
True
[0 0 1]
[1 0 0]
[0 1 0]
sage: GO3m(pm)
Traceback (most recent call last):
  ...
TypeError: matrix must be orthogonal with respect to the symmetric form
[0 1 0]
[1 0 0]
[0 0 3]
sage: GO(3,3, invariant_form=[[1,0,0],[0,2,0],[0,0,1]])
Traceback (most recent call last):
  ...
NotImplementedError: invariant_form for finite groups is fixed by GAP
sage: 5+5
10
sage: R.<x> = ZZ[]
sage: GO(2, R, invariant_form=[[x,0],[0,1]])
General Orthogonal Group of degree 2 over Univariate Polynomial Ring in x over Integer Ring with respect to symmetric form
[x 0]
[0 1]
```

340 Chapter 25. Matrix and Affine Groups
class sage.groups.matrix_gps.orthogonal.OrthogonalMatrixGroup_gap(degree, base_ring, special, sage_name, latex_string, gap_command_string, category=None)


The general or special orthogonal group in GAP.

invariant_bilinear_form()

Return the symmetric bilinear form preserved by the orthogonal group.

OUTPUT:

A matrix $M$ such that, for every group element $g$, the identity $gmg^T = m$ holds. In characteristic different from two, this uniquely determines the orthogonal group.

EXAMPLES:

```python
sage: G = GO(4, GF(7), -1)
sage: G.invariant_bilinear_form()
[0 1 0 0]
[1 0 0 0]
[0 0 2 0]
[0 0 0 2]
sage: G = GO(4, GF(7), +1)
sage: G.invariant_bilinear_form()
[0 1 0 0]
[1 0 0 0]
[0 0 6 0]
[0 0 0 2]
sage: G = SO(4, GF(7), -1)
sage: G.invariant_bilinear_form()
[0 1 0 0]
[1 0 0 0]
[0 0 2 0]
[0 0 0 2]
```

invariant_form()

Return the symmetric bilinear form preserved by the orthogonal group.

OUTPUT:

A matrix $M$ such that, for every group element $g$, the identity $gmg^T = m$ holds. In characteristic different from two, this uniquely determines the orthogonal group.

EXAMPLES:

```python
sage: G = GO(4, GF(7), -1)
sage: G.invariant_bilinear_form()
[0 1 0 0]
[1 0 0 0]
[0 0 2 0]
[0 0 0 2]
```
invariant_quadratic_form()

Return the quadratic form preserved by the orthogonal group.

OUTPUT:

The matrix $Q$ defining “orthogonal” as follows. The matrix determines a quadratic form $q$ on the natural vector space $V$, on which $G$ acts, by $q(v) = vQv^t$. A matrix $M$ is an element of the orthogonal group if $q(v) = q(vM)$ for all $v \in V$.

EXAMPLES:

\begin{verbatim}
sage: G = GO(4, GF(7), -1)
sage: G.invariant_quadratic_form()
[0 1 0 0]
[0 0 0 0]
[0 0 1 0]
[0 0 0 1]
sage: G = GO(4, GF(7), +1)
sage: G.invariant_quadratic_form()
[0 1 0 0]
[0 0 0 0]
[0 0 3 0]
[0 0 0 1]
sage: G = GO(4, QQ)
sage: G.invariant_quadratic_form()
[1 0 0 0]
[0 1 0 0]
[0 0 1 0]
[0 0 0 1]
sage: G = SO(4, GF(7), -1)
sage: G.invariant_quadratic_form()
[0 1 0 0]
[0 0 0 0]
[0 0 1 0]
[0 0 0 1]
\end{verbatim}
class sage.groups.matrix_gps.orthogonal.OrthogonalMatrixGroup_generic(
    degree, base_ring, special, sage_name, latex_string, category=None, invariant_form=None)

Bases: sage.groups.matrix_gps.named_group.NamedMatrixGroup_generic

General Orthogonal Group over arbitrary rings.

EXAMPLES:

```python
sage: G = GO(3, GF(7)); G
General Orthogonal Group of degree 3 over Finite Field of size 7
sage: latex(G)
\text{GO}_{3}(\Bold{F}_{7})

sage: G = SO(3, GF(5)); G
Special Orthogonal Group of degree 3 over Finite Field of size 5
sage: latex(G)
\text{SO}_{3}(\Bold{F}_{5})

sage: CF3 = CyclotomicField(3); e3 = CF3.gen()
sage: m=matrix(CF3, 3,3, \[
[1,e3,0],
[e3,2,0],[0,0,1]\]
)sage: G = SO(3, CF3, invariant_form=m)
sage: latex(G)
\text{SO}_{3}(\Bold{Q}(\zeta_{3}))\text{ with respect to non positive definite symmetric form }
\left(
\begin{array}{rrr}
1 & \zeta_{3} & 0 \\
\zeta_{3} & 2 & 0 \\
0 & 0 & 1
\end{array}
\right)
```

invariant_bilinear_form()

Return the symmetric bilinear form preserved by self.

OUTPUT:

A matrix.

EXAMPLES:

```python
sage: GO(2,3,+1).invariant_bilinear_form()
[0 1]
[1 0]
sage: GO(2,3,-1).invariant_bilinear_form()
[2 1]
[1 1]
sage: G = GO(4, QQ)
sage: G.invariant_bilinear_form()
[1 0 0 0]
[0 1 0 0]
[0 0 1 0]
```

(continues on next page)
invariant_form()
Return the symmetric bilinear form preserved by self.

OUTPUT:
A matrix.

EXAMPLES:

```python
sage: GO(2,3,+1).invariant_bilinear_form()
[0 1]
[1 0]
sage: GO(2,3,-1).invariant_bilinear_form()
[2 1]
[1 1]
sage: G = GO(4, QQ)
sage: G.invariant_bilinear_form()
[1 0 0 0]
[0 1 0 0]
[0 0 1 0]
[0 0 0 1]
sage: GO3m = GO(3,QQ, invariant_form=(1,0,0,0,2,0,0,0,3))
sage: GO3m.invariant_bilinear_form()
[1 0 0]
[0 2 0]
[0 0 3]
```

invariant_quadratic_form()
Return the symmetric bilinear form preserved by self.

OUTPUT:
A matrix.

EXAMPLES:

```python
sage: GO(2,3,+1).invariant_bilinear_form()
[0 1]
[1 0]
sage: GO(2,3,-1).invariant_bilinear_form()
[2 1]
[1 1]
sage: G = GO(4, QQ)
sage: G.invariant_bilinear_form()
[1 0 0 0]
[0 1 0 0]
[0 0 1 0]
[0 0 0 1]
sage: GO3m = GO(3,QQ, invariant_form=(1,0,0,0,2,0,0,0,3))
sage: GO3m.invariant_bilinear_form()
[1 0 0]
[0 2 0]
[0 0 3]
```
Return the special orthogonal group.

The special orthogonal group $GO(n, R)$ consists of all $n \times n$ matrices with determinant one over the ring $R$ preserving an $n$-ary positive definite quadratic form. In cases where there are multiple non-isomorphic quadratic forms, additional data needs to be specified to disambiguate.

**Note:** This group is also available via `groups.matrix.SO()`.

**INPUT:**

- $n$ – integer; the degree
- $R$ – ring or an integer; if an integer is specified, the corresponding finite field is used
- $e$ – $+1$ or $-1$, and ignored by default; only relevant for finite fields and if the degree is even: a parameter that distinguishes inequivalent invariant forms
- $var$ – (optional, default: 'a') variable used to represent generator of the finite field, if needed
- $invariant_form$ – (optional) instances being accepted by the matrix-constructor which define a $n \times n$ square matrix over $R$ describing the symmetric form to be kept invariant by the orthogonal group; the form is checked to be non-degenerate and symmetric but not to be positive definite

**OUTPUT:**

The special orthogonal group of given degree, base ring, and choice of invariant form.

**EXAMPLES:**

```python
sage: G = SO(3,GF(5))
sage: G
Special Orthogonal Group of degree 3 over Finite Field of size 5
```

```python
sage: G = SO(3,GF(5))
sage: G.gens()
\([\begin{array}{ccc}2 & 0 & 0 \\ 0 & 3 & 0 \\ 0 & 0 & 1 \end{array}], \begin{array}{ccc}3 & 2 & 3 \\ 0 & 2 & 0 \\ 0 & 3 & 1 \end{array}], \begin{array}{ccc}1 & 4 & 4 \\ 4 & 0 & 0 \\ 2 & 0 & 4 \end{array}\)\)
```

```python
sage: G = SO(3,GF(5))
sage: G.as_matrix_group()
Matrix group over Finite Field of size 5 with 3 generators ( 
\([\begin{array}{ccc}2 & 0 & 0 \\ 0 & 3 & 0 \\ 0 & 0 & 1 \end{array}], \begin{array}{ccc}3 & 2 & 3 \\ 0 & 2 & 0 \\ 0 & 3 & 1 \end{array}], \begin{array}{ccc}1 & 4 & 4 \\ 4 & 0 & 0 \\ 2 & 0 & 4 \end{array}\)\)
```

Using the `invariant_form` option:

```python
sage: CF3 = CyclotomicField(3); e3 = CF3.gen()
sage: m=matrix(CF3, 3,3,=[[1,e3,0],[e3,2,0],[0,0,1]])
sage: SO3 = SO(3, CF3)
sage: SO3m = SO(3, CF3, invariant_form=m)
```

(continues on next page)
sage: SO3 == SO3m
False
sage: SO3.invariant_form()
[1 0 0]
[0 1 0]
[0 0 1]
sage: SO3m.invariant_form()
[ 1 zeta3 0]
[zeta3 2 0]
[ 0 0 1]

sage: pm = Permutation([2,3,1]).to_matrix()
sage: g = SO3(pm); g in SO3; g
True
[0 0 1]
[1 0 0]
[0 1 0]
sage: SO3m(pm)
Traceback (most recent call last):
...  
TypeError: matrix must be orthogonal with respect to the symmetric form
[ 1 zeta3 0]
[zeta3 2 0]
[ 0 0 1]

sage: SO(3,5, invariant_form=[[1,0,0],[0,2,0],[0,0,3]])
Traceback (most recent call last):
...  
NotImplementedError: invariant_form for finite groups is fixed by GAP
sage: 5+5
10

sage.groups.matrix_gps.orthogonal.normalize_args_e(degree, ring, e)

Normalize the arguments that relate the choice of quadratic form for special orthogonal groups over finite fields.

INPUT:

- **degree** – integer. The degree of the affine group, that is, the dimension of the affine space the group is acting on.
- **ring** – a ring. The base ring of the affine space.
- **e** – integer, one of +1, 0, −1. Only relevant for finite fields and if the degree is even. A parameter that distinguishes inequivalent invariant forms.

OUTPUT:

The integer e with values required by GAP.

### 25.11 Groups of isometries.

Let $M = \mathbb{Z}^n$ or $\mathbb{Q}^n$, $b : M \times M \to \mathbb{Q}$ a bilinear form and $f : M \to M$ a linear map. We say that $f$ is an isometry if for all elements $x, y$ of $M$ we have that $b(x, y) = b(f(x), f(y))$. A group of isometries is a subgroup of $GL(M)$ consisting of isometries.

EXAMPLES:
```sage
sage: L = IntegralLattice("D4")
sage: O = L.orthogonal_group()
sage: O
Group of isometries with 5 generators (-1 0 0 0) [0 0 0 1] [-1 -1 -1 -1] [1 1 0 0] [1 0 0 0]
[-1 0 0 0] [0 1 0 0] [0 0 1 0] [-1 -1 -1 -1]
[0 0 -1 0] [0 0 1 0] [0 1 0 1] [0 1 0 1] [0 0 1 0]
[0 0 0 -1], [1 0 0 0], [0 -1 -1 0], [0 -1 -1 0], [0 0 0 1]
```

Basic functionality is provided by GAP:

```sage
sage: O.cardinality()
1152
sage: len(O.conjugacy_classes_representatives())
25
```

AUTHORS:

• Simon Brandhorst (2018-02): First created

```python
class sage.groups.matrix_gps.isometries.GroupActionOnQuotientModule(MatrixGroup, quotient_module, is_left=False)

Bases: sage.categories.action.Action

Matrix group action on a quotient module from the right.

INPUT:

• MatrixGroup – the group acting GroupOfIsometries

• submodule – an invariant quotient module

• is_left – bool (default: False)

EXAMPLES:

```sage
sage: from sage.groups.matrix_gps.isometries import GroupOfIsometries
sage: S = span(ZZ,[[0,1]])
sage: Q = S/(6*S)
sage: g = Matrix(QQ,2,[[1,0],[0,-1]])
sage: G = GroupOfIsometries(2, ZZ, [g], invariant_bilinear_form=matrix.
\rightarrow identity(2), invariant_quotient_module=Q)
sage: g = G.an_element()
sage: x = Q.an_element()
sage: x*g
5
(x*g).parent()
Finitely generated module V/W over Integer Ring with invariants (6)
```
```
class sage.groups.matrix_gps.isometries.GroupActionOnSubmodule(MatrixGroup, submodule, is_left=False)

Bases: sage.categories.action.Action

Matrix group action on a submodule from the right.

INPUT:

• MatrixGroup – an instance of GroupOfIsometries
```
```
• submodule – an invariant submodule
• is_left – bool (default: False)

EXAMPLES:

```python
sage: from sage.groups.matrix_gps.isometries import GroupOfIsometries
sage: S = span(ZZ,[[0,1]])
sage: g = Matrix(QQ,2,[[1,0],[0,-1]])
sage: G = GroupOfIsometries(2, ZZ, [g], invariant_bilinear_form=matrix.
˓→identity(2), invariant_submodule=S)
sage: g = G.an_element()
sage: x = S.an_element()
sage: x*g
(0, -1)
sage: (x*g).parent()
Free module of degree 2 and rank 1 over Integer Ring
Echelon basis matrix:
[0 1]
```

```python
class sage.groups.matrix_gps.isometries.GroupOfIsometries(degree,
 gens, invariant_bilinear_form,
 category=None, check=True, invariant_submodule=None,
 invariant_quotient_module=None)

Bases: sage.groups.matrix_gps.finitely_generated.FinitelyGeneratedMatrixGroup_gap
```

A base class for Orthogonal matrix groups with a gap backend.

Main difference to OrthogonalMatrixGroup_gap is that we can specify generators and a bilinear form. Following gap the group action is from the right.

INPUT:

• degree – integer, the degree (matrix size) of the matrix
• base_ring – ring, the base ring of the matrices
• gens – a list of matrices over the base ring
• invariant_bilinear_form – a symmetric matrix
• category – (default: None) a category of groups
• check – bool (default: True) check if the generators preserve the bilinear form
• invariant_submodule – a submodule preserved by the group action (default: None) registers an action on this submodule.
• invariant_quotient_module – a quotient module preserved by the group action (default: None) registers an action on this quotient module.

EXAMPLES:

```python
sage: from sage.groups.matrix_gps.isometries import GroupOfIsometries
sage: bil = Matrix(ZZ,2,[3,2,2,3])
sage: gens = [-Matrix(ZZ,2,[0,1,1,0])]
sage: G = GroupOfIsometries(2,ZZ,gens,bil)
sage: G
```

(continues on next page)
Group of isometries with 1 generator (  
[ 0 -1]  
[-1 0]  
)
sage: O.order()  
2

Infinite groups are O.K. too:
sage: bil = Matrix(ZZ,4,[0, 1, 1, 1, 1, 0, 1, 1, 1, 0, 1, 1, 1, 0])
sage: f = Matrix(ZZ,4,[0, 1, 0, 0, 0, 0, 1, 0, 0, 0, 0, 1, -1, 1, 1, 1])
sage: O = GroupOfIsometries(2,ZZ,[f],bil)
sage: O.cardinality()  
+Infinity

**invariant_bilinear_form()**

Return the symmetric bilinear form preserved by the orthogonal group.

**OUTPUT:**

- the matrix defining the bilinear form

**EXAMPLES:**

```python
sage: from sage.groups.matrix_gps.isometries import GroupOfIsometries
sage: bil = Matrix(ZZ,2,[3,2,2,3])
sage: gens = [-Matrix(ZZ,2,[0,1,1,0])]
```

25.12 Symplectic Linear Groups

**EXAMPLES:**

```python
sage: G = Sp(4,GF(7)); G  
Symplectic Group of degree 4 over Finite Field of size 7
sage: g = prod(G.gens()); g  
[3 0 3 0]
[1 0 0 0]
[0 1 0 1]
[0 2 0 0]
sage: m = g.matrix()  
sage: m * G.invariant_form() * m.transpose() == G.invariant_form()  
True
sage: G.order()  
276595200
```

**AUTHORS:**

- David Joyner (2006-03): initial version, modified from special_linear (by W. Stein)
- Volker Braun (2013-1) port to new Parent, libGAP, extreme refactoring.
- Sebastian Oehms (2018-8) add option for user defined invariant bilinear form and bug-fix in `invariant_form()` (see trac ticket #26028)
Return the symplectic group.

The special linear group $GL(d, R)$ consists of all $d \times d$ matrices that are invertible over the ring $R$ with determinant one.

**Note:** This group is also available via `groups.matrix.Sp()`.

**INPUT:**
- $n$ – a positive integer
- $R$ – ring or an integer; if an integer is specified, the corresponding finite field is used
- $\text{var}$ – (optional, default: 'a') variable used to represent generator of the finite field, if needed
- $\text{invariant\_form}$ – (optional) instances being accepted by the matrix-constructor which define a $n \times n$ square matrix over $R$ describing the alternating form to be kept invariant by the symplectic group

**EXAMPLES:**

```
sage: Sp(4, 5)
Symplectic Group of degree 4 over Finite Field of size 5
sage: Sp(4, IntegerModRing(15))
Symplectic Group of degree 4 over Ring of integers modulo 15
sage: Sp(3, GF(7))
Traceback (most recent call last):...
ValueError: the degree must be even
```

Using the `invariant_form` option:

```
sage: m = matrix(QQ, 4,4, [[0, 0, 1, 0], [0, 0, 0, 2], [-1, 0, 0, 0], [0, -2, 0, 0]])
sage: Sp4m = Sp(4, QQ, invariant_form=m)
sage: Sp4 = Sp(4, QQ)
sage: Sp4 == Sp4m
False
sage: Sp4.invariant_form()
[ 0 0 0 1]
[ 0 0 1 0]
[ 0 -1 0 0]
[-1 0 0 0]
sage: Sp4m.invariant_form()
[ 0 0 1 0]
[ 0 0 0 2]
[-1 0 0 0]
[ 0 -2 0 0]
sage: pm = Permutation([2,1,4,3]).to_matrix()
sage: g = Sp4(pm); g in Sp4; g
True
[0 1 0 0]
[1 0 0 0]
[0 0 1 0]
[0 0 0 1]
sage: Sp4m(pm)
```

(continues on next page)
Traceback (most recent call last):
...
TypeError: matrix must be symplectic with respect to the alternating form
[ 0 0 0 1]
[ 0 0 0 2]
[-1 0 0 0]
[ 0 -2 0 0]

sage: Sp(4,3, invariant_form=[[0,0,0,1],[0,0,1,0],[0,2,0,0], [2,0,0,0])
Traceback (most recent call last):
...
NotImplementedError: invariant_form for finite groups is fixed by GAP

class sage.groups.matrix_gps.symplectic.SymplecticMatrixGroup_gap(degree, base_ring, special, sage_name, latex_string, gap_command_string, category=None)


Symplectic group in GAP.

EXAMPLES:

sage: Sp(2,4)
Symplectic Group of degree 2 over Finite Field in a of size 2^2
sage: latex(Sp(4,5))
\text{Sp}_{4}(<5>)

invariant_form()

Return the quadratic form preserved by the symplectic group.

OUTPUT:

A matrix.

EXAMPLES:

sage: Sp(4, GF(3)).invariant_form()
[0 0 0 1]
[0 0 1 0]
[0 2 0 0]
[2 0 0 0]
class sage.groups.matrix_gps.symplectic.SymplecticMatrixGroup_generic

Bases: sage.groups.matrix_gps.named_group.NamedMatrixGroup_generic

Symplectic Group over arbitrary rings.

EXAMPLES:

```python
sage: Sp43 = Sp(4,3); Sp43
Symplectic Group of degree 4 over Finite Field of size 3
sage: latex(Sp43)
\text{Sp}_{4} (\Bold{F}_{3})
```

```python
sage: Sp4m = Sp(4,QQ, invariant_form=(0, 0, 1, 0, 0, 0, 0, 2, -1, 0, 0, 0, -2, \rightarrow 0, 0)); Sp4m
Symplectic Group of degree 4 over Rational Field with respect to alternating bilinear form
```

```python
sage: latex(Sp4m)
\text{Sp}_{4} (\Bold{Q}) \text{ with respect to alternating bilinear form}
```

```python
invariant_form()

Return the quadratic form preserved by the symplectic group.

OUTPUT:

A matrix.

EXAMPLES:

```python
sage: Sp4(4, QQ).invariant_form()
[ 0 0 0 1]
[ 0 0 1 0]
[ 0 -1 0 0]
[ -1 0 0 0]
```
25.13 Unitary Groups $GU(n, q)$ and $SU(n, q)$

These are $n \times n$ unitary matrices with entries in $GF(q^2)$.

EXAMPLES:

```python
sage: G = SU(3,5)
sage: G.order()
378000
sage: G
Special Unitary Group of degree 3 over Finite Field in a of size 5^2
sage: G.gens()

\[
\begin{bmatrix}
    a & 0 & 0 \\
    0 & 2a + 2 & 0 \\
    0 & 0 & 3a
\end{bmatrix},
\begin{bmatrix}
    4a & 4 & 1 \\
    4 & 4 & 0 \\
    1 & 0 & 0
\end{bmatrix}
\]

sage: G.base_ring()
Finite Field in a of size 5^2
```

AUTHORS:

- David Joyner (2006-03): initial version, modified from special_linear (by W. Stein)
- David Joyner (2006-05): minor additions (examples, _latex_, __str__, gens)
- William Stein (2006-12): rewrite
- Volker Braun (2013-1) port to new Parent, libGAP, extreme refactoring.
- Sebastian Oehms (2018-8) add _UG, invariant_form(), option for user defined invariant bilinear form, and bug-fix in _check_matrix (see trac ticket #26028)

```
sage.groups.matrix_gps.unitary.GU(n, R, var='a', invariant_form=None)
```

Return the general unitary group.

The general unitary group $GU(d, R)$ consists of all $d \times d$ matrices that preserve a nondegenerate sesquilinear form over the ring $R$.

**Note:** For a finite field the matrices that preserve a sesquilinear form over $F_q$ live over $F_{q^2}$. So $GU(n, q)$ for a prime power $q$ constructs the matrix group over the base ring $GF(q^2)$.

Note: This group is also available via `groups.matrix.GU()`.

INPUT:

- $n$ – a positive integer
- $R$ – ring or an integer; if an integer is specified, the corresponding finite field is used
- $\text{var}=$ (optional, default: 'a') variable used to represent generator of the finite field, if needed
- $\text{invariant\_form}=$ (optional) instances being accepted by the matrix-constructor which define a $n \times n$ square matrix over $R$ describing the hermitian form to be kept invariant by the unitary group; the form is checked to be non-degenerate and hermitian but not to be positive definite

OUTPUT:

Return the general unitary group.
EXAMPLES:

```python
sage: G = GU(3, 7); G
General Unitary Group of degree 3 over Finite Field in a of size 7^2
sage: G.gens()
( [ a 0 0 ] [6*a 6 1]
 [ 0 1 0 ] [ 6 6 0]
 [ 0 0 5*a], [ 1 0 0]
 )
sage: GU(2, QQ)
General Unitary Group of degree 2 over Rational Field
sage: G = GU(3, 5, var='beta')
sage: G.base_ring()
Finite Field in beta of size 5^2
sage: G.gens()
( [ beta 0 0 ] [4*beta 4 1]
 [ 0 1 0 ] [ 4 4 0]
 [ 0 0 3*beta], [ 1 0 0]
 )
```

Using the `invariant_form` option:

```python
sage: UCF = UniversalCyclotomicField(); e5=UCF.gen(5)
sage: m=matrix(UCF, 3,3, 
 [ [1,e5,0],
   [e5.conjugate(),2,0],
   [0,0,1]
  ])
sage: G = GU(3, UCF)
sage: Gm = GU(3, UCF, invariant_form=m)
sage: G == Gm
False
sage: G.invariant_form()
[1 0 0]
[0 1 0]
[0 0 1]
sage: Gm.invariant_form()
[ 1 E(5) 0]
[E(5)^4 2 0]
[ 0 0 1]
sage: pm=Permutation((1,2,3)).to_matrix()
sage: g = G(pm); g in G; g
True
[0 0 1]
[1 0 0]
[0 1 0]
sage: Gm(pm)
Traceback (most recent call last):
  ...
TypeError: matrix must be unitary with respect to the hermitian form
[ 1 E(5) 0]
[E(5)^4 2 0]
[ 0 0 1]
sage: GU(3,3, invariant_form=[[1,0,0],[0,2,0],[0,0,1]])
Traceback (most recent call last):
  ...
NotImplementedError: invariant_form for finite groups is fixed by GAP
```

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The special unitary group \( SU(d, R) \) consists of all \( d \times d \) matrices that preserve a nondegenerate sesquilinear form over the ring \( R \) and have determinant 1.

**Note:** For a finite field the matrices that preserve a sesquilinear form over \( F_q \) live over \( F_{q^2} \). So \( SU(n, q) \) for a prime power \( q \) constructs the matrix group over the base ring \( GF(q^2) \).

**Note:** This group is also available via `groups.matrix.SU()`.

**INPUT:**
- \( n \) – a positive integer
- \( R \) – ring or an integer; if an integer is specified, the corresponding finite field is used
- \( \text{var} \) – (optional, default: 'a') variable used to represent generator of the finite field, if needed
- \( \text{invariant\_form} \) – (optional) instances being accepted by the matrix-constructor which define a \( n \times n \) square matrix over \( R \) describing the hermitian form to be kept invariant by the unitary group; the form is checked to be non-degenerate and hermitian but not to be positive definite

**OUTPUT:**
Return the special unitary group.

**EXAMPLES:**

```
sage: SU(3,5)
Special Unitary Group of degree 3 over Finite Field in a of size 5^2
sage: SU(3, GF(5))
Special Unitary Group of degree 3 over Finite Field in a of size 5^2
sage: SU(3,QQ)
Special Unitary Group of degree 3 over Rational Field
```

Using the `invariant_form` option:

```
sage: CF3 = CyclotomicField(3); e3 = CF3.gen()
sage: m=matrix(CF3, 3,3, [[1,e3,0],[e3.conjugate(),2,0],[0,0,1]])
sage: G = SU(3, CF3)
sage: Gm = SU(3, CF3, invariant_form=m)
sage: G == Gm
False
sage: G.invariant_form()
[1 0 0]
[0 1 0]
[0 0 1]
sage: Gm.invariant_form()
[ 1 zeta3 0]
[-zeta3 - 1 2 0]
[ 0 0 1]
```
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```python
sage: pm=Permutation((1,2,3)).to_matrix()
sage: G(pm)
[0 0 1]
[1 0 0]
[0 1 0]
sage: Gm(pm)
Traceback (most recent call last):
...  
TypeError: matrix must be unitary with respect to the hermitian form
[ 1 zeta3 0]
[-zeta3 - 1 2 0]
[ 0 0 1]
sage: SU(3,5, invariant_form=[1,0,0],[0,2,0],[0,0,3])
Traceback (most recent call last):
...  
NotImplementedError: invariant_form for finite groups is fixed by GAP
```

```python
class sage.groups.matrix_gps.unitary.UnitaryMatrixGroup_gap(degree, base_ring, special, sage_name, latex_string, gap_command_string, category=None)


The general or special unitary group in GAP.

**invariant_form()**

Return the hermitian form preserved by the unitary group.

**OUTPUT:**

A square matrix describing the bilinear form

**EXAMPLES:**

```python
sage: G32=GU(3,2)
sage: G32.invariant_form()
[0 0 1]
[0 1 0]
[1 0 0]
```

```python
class sage.groups.matrix_gps.unitary.UnitaryMatrixGroup_generic(degree, base_ring, special, sage_name, latex_string, gap_command_string, category=None, invariant_form=None)

Bases: sage.groups.matrix_gps.named_group.NamedMatrixGroup_generic

General Unitary Group over arbitrary rings.

**EXAMPLES:**
```
```
sage: G = GU(3, GF(7)); G
General Unitary Group of degree 3 over Finite Field in a of size 7^2
sage: latex(G)
\text{GU}_{3}(\Bold{F}_{7^{2}})

sage: G = SU(3, GF(5)); G
Special Unitary Group of degree 3 over Finite Field in a of size 5^2
sage: latex(G)
\text{SU}_{3}(\Bold{F}_{5^{2}})

sage: CF3 = CyclotomicField(3); e3 = CF3.gen()
sage: m=matrix(CF3, 3,3, 
\begin{bmatrix}
1 & e3 & 0 \\
e3.conjugate() & 2 & 0 \\
0 & 0 & 1
\end{bmatrix})
sage: G = SU(3, CF3, invariant_form=m)
sage: latex(G)
\text{SU}_{3}(\Bold{Q}(\zeta_{3})) with respect to positive definite hermitian form 
\left(
\begin{array}{rrr}
1 & \zeta_{3} & 0 \\
-\zeta_{3} - 1 & 2 & 0 \\
0 & 0 & 1
\end{array}
\right)

invariant_form()
Return the hermitian form preserved by the unitary group.

OUTPUT:
A square matrix describing the bilinear form

EXAMPLES:
```
```
sage: SU4 = SU(4, QQ)
sage: SU4.invariant_form()
[1 0 0 0]
[0 1 0 0]
[0 0 1 0]
[0 0 0 1]
```

sage.groups.matrix_gps.unitary.finite_field_sqrt(ring)
Helper function.

INPUT:
A ring.

OUTPUT:
Integer q such that ring is the finite field with q^2 elements.

EXAMPLES:
```
sage: from sage.groups.matrix_gps.unitary import finite_field_sqrt
sage: finite_field_sqrt(GF(4, 'a'))
2
```

25.14 Heisenberg Group

AUTHORS:
- Hilder Vitor Lima Pereira (2017-08): initial version
class sage.groups.matrix_gps.heisenberg.HeisenbergGroup(n=1, R=0)
Bases:  sage.structure.unique_representation.UniqueRepresentation,  sage.
groups.matrix_gps.finitely_generated.FinitelyGeneratedMatrixGroup_gap

The Heisenberg group of degree $n$.

Let $R$ be a ring, and let $n$ be a positive integer. The Heisenberg group of degree $n$ over $R$ is a multiplicative
group whose elements are matrices with the following form:
\[
\begin{pmatrix}
1 & x^T & z \\
0 & I_n & y \\
0 & 0 & 1
\end{pmatrix},
\]
where $x$ and $y$ are column vectors in $R^n$, $z$ is a scalar in $R$, and $I_n$ is the identity matrix of size $n$.

INPUT:

- $n$ – the degree of the Heisenberg group
- $R$ – (default: $\mathbb{Z}$) the ring $R$ or a positive integer as a shorthand for the ring $\mathbb{Z}/R\mathbb{Z}$

EXAMPLES:

```
sage: H = groups.matrix.Heisenberg(); H
Heisenberg group of degree 1 over Integer Ring
sage: H.gens()
(\[1 1 0\], \[1 0 0\], \[1 0 1\], \[0 1 0\], \[0 1 1\], \[0 1 0\], \[0 0 1\], \[0 0 1\], \[0 0 1\])
sage: X, Y, Z = H.gens()
sage: Z * X * Y**-1
\[1 1 0\]
\[0 1 -1\]
\[0 0 1\]
sage: X * Y * X**-1 * Y**-1 == Z
True
```

REFERENCES:

- Wikipedia article Heisenberg_group

cardinality()

Return the order of self.

EXAMPLES:

```
sage: H = groups.matrix.Heisenberg()
sage: H.order()
+Infinity
sage: H = groups.matrix.Heisenberg(n=4)
sage: H.order()
+Infinity
sage: H = groups.matrix.Heisenberg(R=3)
sage: H.order()
```

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order()

Return the order of self.

EXAMPLES:

sage: H = groups.matrix.Heisenberg()
sage: H.order()
+Infinity
sage: H = groups.matrix.Heisenberg(n=4)
sage: H.order()
+Infinity
sage: H = groups.matrix.Heisenberg(R=3)
sage: H.order()
27
sage: H = groups.matrix.Heisenberg(n=2, R=3)
sage: H.order()
243
sage: H = groups.matrix.Heisenberg(n=2, R=GF(4))
sage: H.order()
1024

25.15 Affine Groups

AUTHORS:

- Volker Braun: initial version

class sage.groups.affine_gps.affine_group.AffineGroup(degree, ring)

An affine group.

The affine group $\text{Aff}(A)$ (or general affine group) of an affine space $A$ is the group of all invertible affine transformations from the space into itself.

If we let $A_V$ be the affine space of a vector space $V$ (essentially, forgetting what is the origin) then the affine group $\text{Aff}(A_V)$ is the group generated by the general linear group $GL(V)$ together with the translations. Recall that the group of translations acting on $A_V$ is just $V$ itself. The general linear and translation subgroups do not quite commute, and in fact generate the semidirect product

$$\text{Aff}(A_V) = GL(V) \ltimes V.$$ 

As such, the group elements can be represented by pairs $(A, b)$ of a matrix and a vector. This pair then represents the transformation

$$x \mapsto Ax + b.$$
We can also represent affine transformations as linear transformations by considering \( \dim(V) + 1 \) dimensional space. We take the affine transformation \((A, b)\) to

\[
\begin{pmatrix}
A & b \\
0 & 1
\end{pmatrix}
\]

and lifting \( x = (x_1, \ldots, x_n) \) to \((x_1, \ldots, x_n, 1)\). Here the \((n + 1)\)-th component is always 1, so the linear representations acts on the affine hyperplane \( x_{n+1} = 1 \) as affine transformations which can be seen directly from the matrix multiplication.

**INPUT:**

Something that defines an affine space. For example

- An affine space itself:
  - \( A \) – affine space
- A vector space:
  - \( V \) – a vector space
- Degree and base ring:
  - degree – An integer. The degree of the affine group, that is, the dimension of the affine space the group is acting on.
  - ring – A ring or an integer. The base ring of the affine space. If an integer is given, it must be a prime power and the corresponding finite field is constructed.
  - var – (default: 'a') Keyword argument to specify the finite field generator name in the case where ring is a prime power.

**EXAMPLES:**

```sage
sage: F = AffineGroup(3, QQ); F
Affine Group of degree 3 over Rational Field
sage: F(matrix(QQ,[[1,2,3],[4,5,6],[7,8,0]]), vector(QQ,[10,11,12]))
   [1 2 3]
   [7 8 0]
```

```sage
sage: F([[1,2,3],[4,5,6],[7,8,0]], [10,11,12])
   [1 2 3]
   [7 8 0]
```

```sage
sage: F([[1,2,3,4,5,6,7,8,0], [10,11,12]])
   [1 2 3]
   [7 8 0]
```

Instead of specifying the complete matrix/vector information, you can also create special group elements:

```sage
sage: F.linear([[1,2,3,4,5,6,7,8,0]])
   [1 2 3]
x |-> [4 5 6] x + [0]
   [7 8 0]
```

```sage
sage: F.translation([1,2,3])
   [1 0 0]
x |-> [0 1 0] x + [2]
   [0 0 1]
```

Some additional ways to create affine groups:
```python
sage: A = AffineSpace(2, GF(4,'a')); A
Affine Space of dimension 2 over Finite Field in a of size 2^2
sage: G = AffineGroup(A); G
Affine Group of degree 2 over Finite Field in a of size 2^2
sage: G is AffineGroup(2,4) # shorthand
True
sage: V = ZZ^3; V
Ambient free module of rank 3 over the principal ideal domain Integer Ring
sage: AffineGroup(V)
Affine Group of degree 3 over Integer Ring
```

REFERENCES:

- Wikipedia article Affine_group

Element

alias of `sage.groups.affine_gps.group_element.AffineGroupElement`

degree()

Return the dimension of the affine space.

OUTPUT:

An integer.

EXAMPLES:

```python
sage: G = AffineGroup(6, GF(5))
sage: g = G.an_element()
sage: G.degree()
6
sage: G.degree() == g.A().nrows() == g.A().ncols() == g.b().degree()
True
```

linear(A)

Construct the general linear transformation by A.

INPUT:

- A – anything that determines a matrix

OUTPUT:

The affine group element \( x \mapsto Ax \).

EXAMPLES:

```python
sage: G = AffineGroup(3, GF(5))
sage: G.linear([1,2,3,4,5,6,7,8,0])
[1 2 3]
x |-> [4 0 1] x + [0]
[2 3 0] [0]
```

linear_space()

Return the space of the affine transformations represented as linear transformations.

We can represent affine transformations \( Ax + b \) as linear transformations by

\[
\begin{pmatrix}
A & b \\
0 & 1
\end{pmatrix}
\]
and lifting \(x = (x_1, \ldots, x_n)\) to \((x_1, \ldots, x_n, 1)\).

See also:

- \texttt{sage.groups.affine_gps.group_element.AffineGroupElement.matrix()}

### EXAMPLES:

```python
sage: G = AffineGroup(3, GF(5))
sage: G.linear_space()
Full MatrixSpace of 4 by 4 dense matrices over Finite Field of size 5
```

### matrix_space()

Return the space of matrices representing the general linear transformations.

**OUTPUT:**

The parent of the matrices \(A\) defining the affine group element \(Ax + b\).

**EXAMPLES:**

```python
sage: G = AffineGroup(3, GF(5))
sage: G.matrix_space()
Full MatrixSpace of 3 by 3 dense matrices over Finite Field of size 5
```

### random_element()

Return a random element of this group.

**EXAMPLES:**

```python
sage: G = AffineGroup(4, GF(3))
sage: G.random_element() # random
[2 0 1 2]  [1]
[2 1 1 2]  [2]
x |-> [1 0 2 2] x + [2].[1 1 1 1]  [2]
sage: G.random_element() in G
True
```

### reflection(v)

Construct the Householder reflection.

A Householder reflection (transformation) is the affine transformation corresponding to an elementary reflection at the hyperplane perpendicular to \(v\).

**INPUT:**

- \(v\) — a vector, or something that determines a vector.

**OUTPUT:**

The affine group element that is just the Householder transformation (a.k.a. Householder reflection, elementary reflection) at the hyperplane perpendicular to \(v\).

**EXAMPLES:**

```python
sage: G = AffineGroup(3, QQ)
sage: G.reflection([1,0,0])
[-1 0 0]  [0]
[2 1 1 2]  [2]
x |-> [0 1 0] x + [0]
[1 1 1 1]  [2]
sage: G.random_element() in G
True
```

(continues on next page)
sage: G.reflection([3,4,-5])
[ 16/25 -12/25  3/5] [0]
x |→ [ -12/25  9/25  4/5] x + [0]
     [ 3/5  4/5  0] [0]

**translation** *(b)*

Construct the translation by *b*.

**INPUT:**

- *b* – anything that determines a vector

**OUTPUT:**

The affine group element \( x \mapsto x + b \).

**EXAMPLES:**

```sage
sage: G = AffineGroup(3, GF(5))
sage: G.translation([1,4,8])
[1 0 0] [1]
x |→ [0 1 0] x + [4]
     [0 0 1] [3]
```

**vector_space()**

Return the vector space of the underlying affine space.

**EXAMPLES:**

```sage
sage: G = AffineGroup(3, GF(5))
sage: G.vector_space()
Vector space of dimension 3 over Finite Field of size 5
```

## 25.16 Euclidean Groups

**AUTHORS:**

- Volker Braun: initial version

**class** `sage.groups.affine_gps.euclidean_group.EuclideanGroup*(degree, ring)*

Bases: `sage.groups.affine_gps.euclidean_group.AffineGroup`

an Euclidean group.

The Euclidean group \( E(A) \) (or general affine group) of an affine space \( A \) is the group of all invertible affine transformations from the space into itself preserving the Euclidean metric.

If we let \( A_V \) be the affine space of a vector space \( V \) (essentially, forgetting what is the origin) then the Euclidean group \( E(A_V) \) is the group generated by the general linear group \( SO(V) \) together with the translations. Recall that the group of translations acting on \( A_V \) is just \( V \) itself. The general linear and translation subgroups do not quite commute, and in fact generate the semidirect product

\[
E(A_V) = SO(V) \ltimes V.
\]

As such, the group elements can be represented by pairs \((A, b)\) of a matrix and a vector. This pair then represents the transformation

\[
x \mapsto Ax + b.
\]
We can also represent this as a linear transformation in \(\dim(V) + 1\) dimensional space as

\[
\begin{pmatrix}
A & b \\
0 & 1
\end{pmatrix}
\]

and lifting \(x = (x_1, \ldots, x_n)\) to \((x_1, \ldots, x_n, 1)\).

See also:
- \texttt{AffineGroup}

**INPUT:**

Something that defines an affine space. For example

- An affine space itself:
  - \(A\) – affine space
- A vector space:
  - \(V\) – a vector space
- Degree and base ring:
  - degree – An integer. The degree of the affine group, that is, the dimension of the affine space the group is acting on.
  - ring – A ring or an integer. The base ring of the affine space. If an integer is given, it must be a prime power and the corresponding finite field is constructed.
  - var – (default: 'a') Keyword argument to specify the finite field generator name in the case where ring is a prime power.

**EXAMPLES:**

```python
sage: E3 = EuclideanGroup(3, QQ); E3
Euclidean Group of degree 3 over Rational Field
sage: E3(matrix(QQ,[(6/7, -2/7, 3/7), (-2/7, 3/7, 6/7), (3/7, 6/7, -2/7)]), vector(QQ,[10,11,12]))
[ 3/7 6/7 -2/7] [12]
```

Instead of specifying the complete matrix/vector information, you can also create special group elements:

```python
sage: E3.linear([6/7, -2/7, 3/7, -2/7, 3/7, 6/7, 3/7, 6/7, -2/7])
[ 6/7 -2/7 3/7] x |-> [-2/7 3/7 6/7] x + [0]
[ 3/7 6/7 -2/7] [0]
```

(continues on next page)
Some additional ways to create Euclidean groups:

```
sage: A = AffineSpace(2, GF(4,'a')); A
Affine Space of dimension 2 over Finite Field in a of size 2^2
sage: G = EuclideanGroup(A); G
Euclidean Group of degree 2 over Finite Field in a of size 2^2
sage: G is EuclideanGroup(2,4) # shorthand
True
sage: V = ZZ^3; V
Ambient free module of rank 3 over the principal ideal domain Integer Ring
sage: EuclideanGroup(V)
Euclidean Group of degree 3 over Integer Ring
sage: EuclideanGroup(2, QQ)
Euclidean Group of degree 2 over Rational Field
```

REFERENCES:

• Wikipedia article Euclidean_group

random_element()

Return a random element of this group.

EXAMPLES:

```
sage: G = EuclideanGroup(4, GF(3))
sage: G.random_element() # random
[2 1 2 1] [1]
[1 2 2 1] [0]
x |-> [2 2 2 1] x + [1]
[1 1 2 2] [2]
sage: G.random_element() in G
True
```

25.17 Elements of Affine Groups

The class in this module is used to represent the elements of `AffineGroup()` and its subgroups.

EXAMPLES:

```
sage: F = AffineGroup(3, QQ)
sage: F([[1,2,3,4,5,6,7,8,0], [10,11,12])
[1 2 3] [10]
[7 8 0] [12]
sage: G = AffineGroup(2, ZZ)
sage: g = G([[1,1],[0,1]], [1,0])
```

(continues on next page)
AUTHORS:

• Volker Braun

class sage.groups.affine_gps.group_element.AffineGroupElement (parent, A, b=0, convert=True, check=True)

Bases: sage.structure.element.MultiplicativeGroupElement

An affine group element.

INPUT:

• A – an invertible matrix, or something defining a matrix if convert=True.
• b – a vector, or something defining a vector if convert=True (default: 0, defining the zero vector).
• parent – the parent affine group.
• convert - bool (default: True). Whether to convert A into the correct matrix space and b into the correct vector space.
• check - bool (default: True). Whether to do some checks or just accept the input as valid.

As a special case, A can be a matrix obtained from matrix(), that is, one row and one column larger. In that case, the group element defining that matrix is reconstructed.

OUTPUT:

The affine group element $x \mapsto Ax + b$

EXAMPLES:

Conversion from a matrix and a matrix group element:

```
sage: M = Matrix(4, 4, [0, 0, -1, 1, 0, -1, 0, 1, -1, 0, 1, 0, 1, 0, 0, 1])
sage: A = AffineGroup(3, ZZ)
sage: A(M)
[ 0  0 -1]  [1]
\rightarrow [ 0 -1  0] x + [1]
```
A()

Return the general linear part of an affine group element.

OUTPUT:

The matrix $A$ of the affine group element $Ax + b$.

EXAMPLES:

```sage
sage: G = AffineGroup(3, QQ)
sage: g = G([1,2,3,4,5,6,7,8,0], [10,11,12])
sage: g.A()
[1 2 3]
[4 5 6]
[7 8 0]
```

b()

Return the translation part of an affine group element.

OUTPUT:

The vector $b$ of the affine group element $Ax + b$.

EXAMPLES:

```sage
sage: G = AffineGroup(3, QQ)
sage: g = G([1,2,3,4,5,6,7,8,0], [10,11,12])
sage: g.b()
(10, 11, 12)
```

inverse()

Return the inverse group element.

OUTPUT:

Another affine group element.

EXAMPLES:

```sage
sage: G = AffineGroup(2, GF(3))
sage: g = G([1,2,3,4], [5,6])
sage: g
[1 2] [2]
x |-> [0 1] x + [0]
sage: ~g
[1 1] [1]
x |-> [0 1] x + [0]
sage: g * g.inverse()
[1 0] [0]
x |-> [0 1] x + [0]
sage: g * g.inverse() == g.inverse() * g == G(1)
True
```
list()

Return list representation of self.

EXAMPLES:

```
sage: F = AffineGroup(3, QQ)
sage: g = F([1,2,3,4,5,6,7,8,0], [10,11,12])
sage: g
[ 1  2  3| 10]
x |-> [ 4  5  6| 11]
    [ 7  8  0| 12]
sage: g.list()
[[1, 2, 3, 10], [4, 5, 6, 11], [7, 8, 0, 12], [0, 0, 0, 1]]
```

matrix()

Return the standard matrix representation of self.

See also:

• AffineGroup.linear_space()

EXAMPLES:

```
sage: G = AffineGroup(3, GF(7))
sage: g = G([1,2,3,4,5,6,7,8,0], [10,11,12])
sage: g
[ 1  2  3| 3]
x |-> [ 4  5  6| 4]
    [ 0  1  0| 5]
sage: g.matrix()
[1  2  3| 3]
[ 4  5  6| 4]
[ 0  1  0| 5]
[-------+-]
[ 0  0  0| 1]
sage: parent(g.matrix())
Full MatrixSpace of 4 by 4 dense matrices over Finite Field of size 7
sage: g.matrix() == matrix(g)
True
```

Composition of affine group elements equals multiplication of the matrices:

```
sage: g1 = G.random_element()
sage: g2 = G.random_element()
sage: g1.matrix() * g2.matrix() == (g1*g2).matrix()
True
```
26.1 Nilpotent Lie groups

AUTHORS:

• Eero Hakavuori (2018-09-25): initial version of nilpotent Lie groups

```python
class sage.groups.lie_gps.nilpotent_lie_group.NilpotentLieGroup(L, name, **kwds):
    Bases: sage.groups.group.Group, sage.manifolds.differentiable.manifold.DifferentiableManifold
```

A nilpotent Lie group.

INPUT:

• $L$ – the Lie algebra of the Lie group; must be a finite dimensional nilpotent Lie algebra with basis over a topological field, e.g. $\mathbb{Q}$ or $\mathbb{R}$

• $name$ – a string; name (symbol) given to the Lie group

Two types of exponential coordinates are defined on any nilpotent Lie group using the basis of the Lie algebra, see `chart_exp1()` and `chart_exp2()`.

EXAMPLES:

Creation of a nilpotent Lie group:

```python
sage: L = lie_algebras.Heisenberg(QQ, 1)
sage: G = L.lie_group(); G
Lie group G of Heisenberg algebra of rank 1 over Rational Field
```

Giving a different name to the group:

```python
sage: L.lie_group('H')
```

```
Lie group H of Heisenberg algebra of rank 1 over Rational Field
```

Elements can be created using the exponential map:

```python
sage: p, q, z = L.basis()
sage: g = G.exp(p); g
exp(p1)
sage: h = G.exp(q); h
exp(q1)
```

Lie group multiplication has the usual product syntax:
The identity element is given by `one()`:

```python
sage: e = G.one(); e
exp(0)
sage: e*k == k and k*e == k
True
```

The default coordinate system is exponential coordinates of the first kind:

```python
sage: G.default_chart() == G.chart_exp1()
True
sage: G.chart_exp1()
Chart (G, (x_0, x_1, x_2))
```

Changing the default coordinates to exponential coordinates of the second kind will change how elements are printed:

```python
sage: G.set_default_chart(G.chart_exp2())
sage: G.set_default_chart(G.chart_exp1())
sage: k
exp(z)exp(q1)exp(p1)
```

A vector field can be displayed with respect to a coordinate frame:

```python
sage: expl1_frame = G.chart_exp1().frame()
sage: exp2_frame = G.chart_exp2().frame()
sage: X[0].display(expl1_frame)
X_0 = d/dx_0 - 1/2*x_1 d/dx_2
sage: X[0].display(exp2_frame)
X_0 = d/dy_0
```

Defining a left translation by a generic point:

```python
sage: g = G.point([var('a'), var('b'), var('c')]); g
exp(a*p1 + b*q1 + c*z)
sage: L_g = G.left_translation(g); L_g
Diffeomorphism of the Lie group G of Heisenberg algebra of rank 1 over Rational Field
```

(continues on next page)
G --> G
(x_0, x_1, x_2) |--> (a + x_0, b + x_1, -1/2*b*x_0 + 1/2*a*x_1 + c + x_2)
(x_0, x_1, x_2) |--> (y_0, y_1, y_2) = (a + x_0, b + x_1, 1/2*a*b + 1/2*(2*a
-+ x_0)*x_1 + c + x_2)
(y_0, y_1, y_2) |--> (x_0, x_1, x_2) = (a + y_0, b + y_1, -1/2*b*y_0 + 1/2*(a
-y_0)*y_1 + c + y_2)
(y_0, y_1, y_2) |--> (a + y_0, b + y_1, 1/2*a*b + a*y_1 + c + y_2)

Verifying the left-invariance of the left-invariant frame:

```
sage: x = G(G.chart_exp1()[:])
sage: L_g.differential(x)(X[0].at(x)) == X[0].at(L_g(x))
True
sage: L_g.differential(x)(X[1].at(x)) == X[1].at(L_g(x))
True
sage: L_g.differential(x)(X[2].at(x)) == X[2].at(L_g(x))
True
```

An element of the Lie algebra can be extended to a left or right invariant vector field:

```
sage: X_L = G.left_invariant_extension(p + 3*q); X_L
Vector field p1 + 3*q1 on the Lie group G of Heisenberg algebra of rank 1 over Rational Field
sage: X_L.display(exp1_frame)
p1 + 3*q1 = d/dx_0 + 3 d/dx_1 + (3/2 *x_0 - 1/2*x_1) d/dx_2
sage: X_R = G.right_invariant_extension(p + 3*q)
sage: X_R.display(exp2_frame)
p1 + 3*q1 = d/dx_0 + 3 d/dx_1 + (-3/2*x_0 + 1/2*x_1) d/dx_2
```

The nilpotency step of the Lie group is the nilpotency step of its algebra. Nilpotency for Lie groups means that group commutators that are longer than the nilpotency step vanish:

```
sage: G.step()
2
sage: g = G.exp(p); h = G.exp(q)
sage: c = g*h*~g*~h; c
exp(z)
sage: g*c*~g*~c
exp(0)
```

```
class Element (parent, **kwds)

Bases: sage.manifolds.point.ManifoldPoint, sage.structure.element.MultiplicativeGroupElement

A base class for an element of a Lie group.

EXAMPLES:

Elements of the group are printed in the default exponential coordinates:
```
sage: L.<X,Y,Z> = LieAlgebra(QQ, 2, step=2)
sage: G = L.lie_group()
sage: g = G.exp(2*X + 3*Z); g
exp(2*X + 3*Z)
sage: h = G.point([ var('a'), var('b'), 0]); h
exp(a*Z + b*Y)
sage: G.set_default_chart(G.chart_exp2())
```
Multiplication of two elements uses the usual product syntax:

```plaintext
gexp(3*Z)exp(2*X)
hexp(1/2*a*b*Z)exp(b*Y)exp(a*X)
```

```
sage: G.exp(Y)*G.exp(X)
sage: G.exp(X)*G.exp(Y)
```

```plaintext
gexp(2*X)exp(2*Y)
```

```plaintext
adjoint (g)
Return the adjoint map as an automorphism of the Lie algebra of self.

INPUT:

• g – an element of self

For a Lie group element \( g \), the adjoint map \( \text{Ad}_g \) is the map on the Lie algebra \( g \) given by the differential of the conjugation by \( g \) at the identity.

If the Lie algebra of \( \text{self} \) does not admit symbolic coefficients, the adjoint is not in general defined for abstract points.

EXAMPLES:

An example of an adjoint map:

```plaintext
sage: L = LieAlgebra(QQ, 2, step=3)
sage: G = L.lie_group()
sage: g = G.exp(L.basis().list()[0]); g
exp(X_1)
sage: Ad_g = G.adjoint(g); Ad_g
Lie algebra endomorphism of Free Nilpotent Lie algebra on 5 generators (X_1, X_2, X_12, X_112, X_122) over Rational Field
Defn: X_1 |--> X_1
X_2 |--> X_2 + X_12 + 1/2*X_112
X_12 |--> X_12 + X_112
X_112 |--> X_112
X_122 |--> X_122
```

Usually the adjoint map of a symbolic point is not defined:

```plaintext
sage: L = LieAlgebra(QQ, 2, step=2)
sage: G = L.lie_group()
sage: g = G.point([var('a'), var('b'), var('c')]); g
exp(a*X_1 + b*X_2 + c*X_12)
sage: G.adjoint(g)
Traceback (most recent call last):
  ...
TypeError: unable to convert -b to a rational
```

However, if the adjoint map is independent from the symbolic terms, the map is still well defined:
sage: g = G.point([0, 0, var('a')]); g
exp(a*X_12)
sage: G.adjoint(g)

Lie algebra endomorphism of Free Nilpotent Lie algebra on 3 generators (X_1, →X_2, X_12) over Rational Field
Defn: X_1 |--> X_1
X_2 |--> X_2
X_12 |--> X_12

chart_exp1()
Return the chart of exponential coordinates of the first kind.

Exponential coordinates of the first kind are

\[ \exp(x_1 X_1 + \cdots + x_n X_n) \mapsto (x_1, \ldots, x_n). \]

EXAMPLES:

sage: L = LieAlgebra(QQ, 2, step=2)
sage: G = L.lie_group()
sage: G.chart_exp1()
Chart (G, (x_1, x_2, x_12))

chart_exp2()
Return the chart of exponential coordinates of the second kind.

Exponential coordinates of the second kind are

\[ \exp(x_n X_n) \cdots \exp(x_1 X_1) \mapsto (x_1, \ldots, x_n). \]

EXAMPLES:

sage: L = LieAlgebra(QQ, 2, step=2)
sage: G = L.lie_group()
sage: G.chart_exp2()
Chart (G, (y_1, y_2, y_12))

conjugation(g)
Return the conjugation by \( g \) as an automorphism of \( \text{self} \).

The conjugation by \( g \) on a Lie group \( G \) is the map

\[ G \to G, \quad h \mapsto ghg^{-1}. \]

INPUT:

- \( g \) – an element of \( \text{self} \)

EXAMPLES:

A generic conjugation in the Heisenberg group:

sage: H = lie_algebras.Heisenberg(QQ, 1)
sage: p, q, z = H.basis()
sage: G = H.lie_group()
sage: g = G.point([var('a'), var('b'), var('c')])
sage: C_g = G.conjugation(g); C_g
Diffeomorphism of the Lie group G of Heisenberg algebra of rank 1 over Rational Field

(continues on next page)
\begin{verbatim}
sage: G = L.lie_group()
sage: G.exp(X)
exp(X)
sage: G.exp(Y)
exp(Y)
sage: G.exp(X + Y)
exp(X + Y)
\end{verbatim}

\section*{gens()}

Return a tuple of elements whose one-parameter subgroups generate the Lie group.

**EXAMPLES:**

\begin{verbatim}
sage: H = L.lie_group()
sage: H.gens()
(exp(p1), exp(q1), exp(z))
\end{verbatim}

\section*{left_invariant_extension(X, name=None)}

Return the left-invariant vector field that has the value \( X \) at the identity.

**INPUT:**

- \( X \) – an element of the Lie algebra of \texttt{self}
- \( name \) – (optional) a string to use as a name for the vector field; if nothing is given, the name of the vector \( X \) is used

**EXAMPLES:**

A left-invariant extension in the Heisenberg group:

\begin{verbatim}
sage: H = H.left_invariant_extension(p); X
Vector field p1 on the Lie group H of Heisenberg algebra of rank 1 over \(--Rational Field
sage: X.display(H.chart_exp1().frame())
p1 = d/dx_0 - 1/2*x_1 d/dx_2
\end{verbatim}

Default vs. custom naming for the invariant vector field:

\begin{verbatim}
sage: Y = H.left_invariant_extension(p + q); Y
Vector field p1 + q1 on the Lie group H of Heisenberg algebra of rank 1 over \(--Rational Field
\end{verbatim}
sage: Z = H.left_invariant_extension(p + q, 'Z'); Z
Vector field Z on the Lie group H of Heisenberg algebra of rank 1 over \mathbb{Q} → \mathbb{R}ational Field

left_invariant_frame(**kwds)

Return the frame of left-invariant vector fields of self.

The labeling of the frame and the dual frame can be customized using keyword parameters as described in sage.manifolds.differentiable.manifold.DifferentiableManifold.vector_frame().

EXAMPLES:

The default left-invariant frame:

sage: L = LieAlgebra(QQ, 2, step=2)
sage: G = L.lie_group()
sage: livf = G.left_invariant_frame(); livf
Vector frame (G, (X_1,X_2,X_12))
sage: coord_frame = G.chart_exp1().frame()
sage: livf[0].display(coord_frame)
X_1 = d/dx_1 - 1/2*x_2 d/dx_12
sage: livf[1].display(coord_frame)
X_2 = d/dx_2 + 1/2*x_1 d/dx_12
sage: livf[2].display(coord_frame)
X_12 = d/dx_12

Examples of custom labeling for the frame:

sage: G.left_invariant_frame(symbol='Y')
Vector frame (G, (Y_1,Y_2,Y_12))
sage: G.left_invariant_frame(symbol='Z', indices=None)
Vector frame (G, (Z_0,Z_1,Z_2))
sage: G.left_invariant_frame(symbol='W', indices=('a','b','c'))
Vector frame (G, (W_a,W_b,W_c))

left_translation(g)

Return the left translation by g as an automorphism of self.

The left translation by g on a Lie group G is the map

\[ G \to G, \quad h \mapsto gh. \]

INPUT:

* g – an element of self

EXAMPLES:

A left translation in the Heisenberg group:

sage: H = lie_algebras.Heisenberg(QQ, 1)
sage: p,q,z = H.basis()
sage: G = H.lie_group()
sage: g = G.exp(p)
sage: L_g = G.left_translation(g); L_g
Diffeomorphism of the Lie group G of Heisenberg algebra of rank 1 over \mathbb{Q} → \mathbb{R}ational Field

sage: L_g.display(chart1=G.chart_exp1(), chart2=G.chart_exp1())
G --> G
(x_0, x_1, x_2) |--> (x_0 + 1, x_1, 1/2*x_1 + x_2)

Left translation by a generic element:

sage: h = G.point([var('a'), var('b'), var('c')])
sage: L_h = G.left_translation(h)
sage: L_h.display(chart1=G.chart_exp1(), chart2=G.chart_exp1())
G --> G
(x_0, x_1, x_2) |--> (a + x_0, b + x_1, -1/2*b*x_0 + 1/2*a*x_1 + c + x_2)

lie_algebra()

Return the Lie algebra of self.

EXAMPLES:

sage: L = LieAlgebra(QQ, 2, step=2)
sage: G = L.lie_group()
sage: G.lie_algebra() == L
True

livf(**kwds)

Return the frame of left-invariant vector fields of self.

The labeling of the frame and the dual frame can be customized using keyword parameters as described in `sage.manifolds.differentiable.manifold.DifferentiableManifold.vector_frame()`.

EXAMPLES:

The default left-invariant frame:

sage: L = LieAlgebra(QQ, 2, step=2)
sage: G = L.lie_group()
sage: livf = G.left_invariant_frame(); livf
Vector frame (G, (X_1,X_2,X_12))
sage: coord_frame = G.chart_exp1().frame()
sage: livf[0].display(coord_frame)
X_1 = d/dx_1 - 1/2*x_2 d/dx_12
sage: livf[1].display(coord_frame)
X_2 = d/dx_2 + 1/2*x_1 d/dx_12
sage: livf[2].display(coord_frame)
X_12 = d/dx_12

Examples of custom labeling for the frame:

sage: G.left_invariant_frame(symbol='Y')
Vector frame (G, (Y_1,Y_2,Y_12))
sage: G.left_invariant_frame(symbol='Z', indices=None)
Vector frame (G, (Z_0,Z_1,Z_2))
sage: G.left_invariant_frame(symbol='W', indices=(a',b',c'))
Vector frame (G, (W_a,W_b,W_c))

log(x)

Return the logarithm of the element x of self.

INPUT:

- x -- an element of self
The logarithm is by definition the inverse of \( \exp() \).

If the Lie algebra of \( \text{self} \) does not admit symbolic coefficients, the logarithm is not defined for abstract, i.e. symbolic, points.

**EXAMPLES:**

The logarithm is the inverse of the exponential:

```
sage: L.<X,Y,Z> = LieAlgebra(QQ, 2, step=2)
sage: G = L.lie_group()
sage: G.log(G.exp(X)) == X
True
sage: G.log(G.exp(X)*G.exp(Y))
X + Y + 1/2*Z
```

The logarithm is not defined for abstract (symbolic) points:

```
sage: g = G.point([var('a'), 1, 2]); g
exp(a*X + Y + 2*Z)
sage: G.log(g)
Traceback (most recent call last):
  ...TypeError: unable to convert a to a rational
```

**one()**

Return the identity element of \( \text{self} \).

**EXAMPLES:**

```
sage: L = LieAlgebra(QQ, 2, step=4)
sage: G = L.lie_group()
sage: G.one()
exp(0)
```

**right_invariant_extension(\(X, \text{name} = \text{None}\))**

Return the right-invariant vector field that has the value \(X\) at the identity.

**INPUT:**

- \(X\) – an element of the Lie algebra of \(\text{self}\)
- \(\text{name}\) – (optional) a string to use as a name for the vector field; if nothing is given, the name of the vector \(X\) is used

**EXAMPLES:**

A right-invariant extension in the Heisenberg group:

```
sage: L = lie_algebras.Heisenberg(QQ, 1)
sage: p, q, z = L.basis()
sage: H = L.lie_group('H')
sage: X = H.right_invariant_extension(p); X
Vector field p1 on the Lie group H of Heisenberg algebra of rank 1 over '\Rational Field'
sage: X.display(H.chart_exp1().frame())
   \(p1 = \frac{1}{2}x_1\frac{\partial}{\partial x_0} + \frac{1}{2}x_2\frac{\partial}{\partial x_2}\)
```

Default vs. custom naming for the invariant vector field:
**sage:** Y = H.right_invariant_extension(p + q); Y
Vector field p1 + q1 on the Lie group H of Heisenberg algebra of rank 1 over Rational Field

**sage:** Z = H.right_invariant_extension(p + q, 'Z'); Z
Vector field Z on the Lie group H of Heisenberg algebra of rank 1 over Rational Field

### right_invariant_frame(**kwds**)

Return the frame of right-invariant vector fields of self.

The labeling of the frame and the dual frame can be customized using keyword parameters as described in `sage.manifolds.differentiable.manifold.DifferentiableManifold.vector_frame()`.

**EXAMPLES:**

The default right-invariant frame:

```python
**sage:** L = LieAlgebra(QQ, 2, step=2)
**sage:** G = L.lie_group()
**sage:** rivf = G.right_invariant_frame(); rivf
Vector frame (G, (XR_1,XR_2,XR_12))
**sage:** coord_frame = G.chart_exp1().frame()
**sage:** rivf[0].display(coord_frame)
XR_1 = d/dx_1 + 1/2*x_2 d/dx_12
**sage:** rivf[1].display(coord_frame)
XR_2 = d/dx_2 - 1/2*x_1 d/dx_12
**sage:** rivf[2].display(coord_frame)
XR_12 = d/dx_12
```

Examples of custom labeling for the frame:

```python
**sage:** G.right_invariant_frame(symbol='Y')
Vector frame (G, (Y_1,Y_2,Y_12))
**sage:** G.right_invariant_frame(symbol='Z', indices=None)
Vector frame (G, (Z_0,Z_1,Z_2))
**sage:** G.right_invariant_frame(symbol='W', indices=('a','b','c'))
Vector frame (G, (W_a,W_b,W_c))
```

### right_translation(g)

Return the right translation by g as an automorphism of self.

The right translation by g on a Lie group G is the map

\[ G \to G, \quad h \mapsto hg. \]

**INPUT:**

- g – an element of self

**EXAMPLES:**

A right translation in the Heisenberg group:

```python
**sage:** H = lie_algebras.Heisenberg(QQ, 1)
**sage:** p, q, z = H.basis()
**sage:** G = H.lie_group()
**sage:** g = G.exp(p)
**sage:** R_g = G.right_translation(g); R_g
```

(continues on next page)
Diffeomorphism of the Lie group $G$ of Heisenberg algebra of rank 1 over $\mathbb{R}$.

```python
sage: R_g.display(chart1=G.chart_exp1(), chart2=G.chart_exp1())
G --> G
  \( (x_0, x_1, x_2) \mapsto (x_0 + 1, x_1, -1/2 \cdot x_1 + x_2) \)
```

Right translation by a generic element:

```python
sage: h = G.point([var('a'), var('b'), var('c')])
sage: R_h = G.right_translation(h)
sage: R_h.display(chart1=G.chart_exp1(), chart2=G.chart_exp1())
G --> G
  \( (x_0, x_1, x_2) \mapsto (a + x_0, b + x_1, 1/2 \cdot b \cdot x_0 - 1/2 \cdot a \cdot x_1 + c + x_2) \)
```

```python
rivf(**kwds)
```

Return the frame of right-invariant vector fields of `self`.

The labeling of the frame and the dual frame can be customized using keyword parameters as described in `sage.manifolds.differentiable.manifold.DifferentiableManifold.vector_frame()`.

**EXAMPLES:**

The default right-invariant frame:

```python
sage: L = LieAlgebra(QQ, 2, step=2)
sage: G = L.lie_group()
sage: rivf = G.right_invariant_frame(); rivf
Vector frame (G, (XR_1,XR_2,XR_12))
sage: coord_frame = G.chart_exp1().frame()
sage: rivf[0].display(coord_frame)
XR_1 = d/dx_1 + 1/2 \cdot x_2 d/dx_12
sage: rivf[1].display(coord_frame)
XR_2 = d/dx_2 - 1/2 \cdot x_1 d/dx_12
sage: rivf[2].display(coord_frame)
XR_12 = d/dx_12
```

Examples of custom labeling for the frame:

```python
sage: G.right_invariant_frame(symbol='Y')
Vector frame (G, (Y_1,Y_2,Y_12))
sage: G.right_invariant_frame(symbol='Z', indices=None)
Vector frame (G, (Z_0,Z_1,Z_2))
sage: G.right_invariant_frame(symbol='W', indices=('a','b','c'))
Vector frame (G, (W_a,W_b,W_c))
```

**step()**

Return the nilpotency step of `self`.

**EXAMPLES:**

```python
sage: L = LieAlgebra(QQ, 2, step=4)
sage: G = L.lie_group()
sage: G.step()
4
```
27.1 Canonical augmentation

This module implements a general algorithm for generating isomorphism classes of objects. The class of objects in question must be some kind of structure which can be built up out of smaller objects by a process of augmentation, and for which an automorphism is a permutation in $S_n$ for some $n$. This process consists of starting with a finite number of “seed objects” and building up to more complicated objects by a sequence of “augmentations.” It should be noted that the word “canonical” in the term canonical augmentation is used loosely. Given an object $X$, one must define a canonical parent $M(X)$, which is essentially an arbitrary choice.

The class of objects in question must satisfy the assumptions made in the module `automorphism_group_canonical_label`, in particular the three custom functions mentioned there must be implemented:

1. `refine_and_return_invariant`:
   Signature:
   
   ```c
   int refine_and_return_invariant(PartitionStack *PS, void *S, int *cells_to_refine_by, int ctrb_len)
   ```

2. `compare_structures`:
   Signature:
   
   ```c
   int compare_structures(int *gamma_1, int *gamma_2, void *S1, void *S2, int degree)
   ```

3. `all_children_are_equivalent`:
   Signature:
   
   ```c
   bint all_children_are_equivalent(PartitionStack *PS, void *S)
   ```

In the following functions there is frequently a `mem_err` input. This is a pointer to an integer which must be set to a nonzero value in case of an allocation failure. Other functions have an int return value which serves the same purpose. The idea is that if a memory error occurs, the canonical generator should still be able to iterate over the objects already generated before it terminates.

More details about these functions can be found in that module. In addition, several other functions must be implemented, which will make use of the following:

```c
ctype struct iterator:
   void *data
   void *(*next)(void *data, int *degree, int *mem_err)
```

The following functions must be implemented for each specific type of object to be generated. Each function following which takes a `mem_err` variable as input should make use of this variable.
4. generate_children:
Signature:

    int generate_children(void *S, aut_gp_and_can_lab *group, iterator *it)

This function receives a pointer to an iterator \textit{it}. The iterator has two fields: data and next. The function \textit{generate_children} should set these two fields, returning 1 to indicate a memory error, or 0 for no error.

The function that \texttt{next} points to takes data as an argument, and should return a (void *) pointer to the next object to be iterated. It also takes a pointer to an int, and must update that int to reflect the degree of each generated object. The objects to be iterated over should satisfy the property that if $\gamma$ is an automorphism of the parent object $S$, then for any two child objects $C_1, C_2$ given by the iterator, it is not the case that $\gamma(C_1) = C_2$, where in the latter $\gamma$ is appropriately extended if necessary to operate on $C_1$ and $C_2$. It is essential for this iterator to handle its own data. If the \texttt{next} function is called and no suitable object is yielded, a NULL pointer indicates a termination of the iteration. At this point, the data pointed to by the data variable should be cleared by the \texttt{next} function, because the iterator struct itself will be deallocated.

The \texttt{next} function must check mem_err[0] before proceeding. If it is nonzero then the function should deallocate the iterator right away and return NULL to end the iteration. This ensures that the canonical augmentation software will finish iterating over the objects found before finishing, and the mem_err attribute of the canonical_generator_data will reflect this.

The objects which the iterator generates can be thought of as augmentations, which the following function must turn into objects.

5. apply_augmentation:
Signature:

    void *apply_augmentation(void *parent, void *aug, void *child, int *degree, bint *mem_err)

This function takes the parent, applies the augmentation \texttt{aug} and returns a pointer to the corresponding child object (freeing \texttt{aug} if necessary). Should also update degree[0] to be the degree of the new child.

6. free_object:
Signature:

    void free_object(void *child)

This function is a simple deallocation function for children which are not canonically generated, and therefore rejected in the canonical augmentation process. They should deallocate the contents of child.

7. free_iter_data:
Signature:

    void free_iter_data(void *data)

This function deallocates the data part of the iterator which is set up by \textit{generate_children}.

8. free_aug:
Signature:

    void free_aug(void *aug)
This function frees an augmentation as generated by the iterator returned by generate_children.

9. canonical_parent:

Signature:

void *canonical_parent(void *child, void *parent, int *permutation, int *degree, bint *mem_err)

Apply the permutation to the child, determine an arbitrary but fixed parent, apply the inverse of permutation to that parent, and return the resulting object. Must also set the integer degree points to the degree of the returned object.

Note: It is a good idea to try to implement an augmentation scheme where the degree of objects on each level of the augmentation tree is constant. The iteration will be more efficient in this case, as the relevant work spaces will never need to be reallocated. Otherwise, one should at least strive to iterate over augmentations in such a way that all children of the same degree are given in the same segment of iteration.

EXAMPLES:

```
sage: import sage.groups.perm_gps.partn_ref.canonical_augmentation
```

REFERENCE:


27.2 Data structures

This module implements basic data structures essential to the rest of the partn_ref module.

REFERENCES:


```
sage.groups.perm_gps.partn_ref.data_structures.OP_represent (n, merges, perm)
```

Demonstration and testing.

```
sage.groups.perm_gps.partn_ref.data_structures.PS_represent (partition, splits)
```

Demonstration and testing.

```
sage.groups.perm_gps.partn_ref.data_structures.SC_test_list_perms (L, n, limit, gap, limit_complain, test_contains)
```

Test that the permutation group generated by list perms in L of degree n is of the correct order, by comparing with GAP. Don’t test if the group is of size greater than limit.
27.3 Graph-theoretic partition backtrack functions

EXAMPLES:

```python
sage: import sage.groups.perm_gps.partn_ref.refinement_graphs
```

REFERENCE:


```python
class sage.groups.perm_gps.partn_ref.refinement_graphs.GraphStruct
    Bases: object
sage.groups.perm_gps.partn_ref.refinement_graphs.all_labeled_graphs(n)
    Return all labeled graphs on n vertices {0,1,...,n-1}.
    Used in classifying isomorphism types (naive approach), and more importantly in benchmarking the search algorithm.
    EXAMPLES:

sage: from sage.groups.perm_gps.partn_ref.refinement_graphs import all_labeled_graphs
sage: st = sage.groups.perm_gps.partn_ref.refinement_graphs.search_tree
sage: Glist = {}
sage: Giso = {}
sage: for n in [1..5]:  # long time (4s on sage.math, 2011)
    ....:     Glist[n] = all_labeled_graphs(n)
    ....:     Giso[n] = []
    ....:     for g in Glist[n]:
    ....:         a, b = st(g, [range(n)])
    ....:         inn = False
    ....:         for gi in Giso[n]:
    ....:             if b == gi:
    ....:                 inn = True
    ....:         if not inn:
    ....:             Giso[n].append(b)
sage: for n in Giso:  # long time
    ....:     print('{} {}'.format(n, len(Giso[n])))
    1 1
    2 2
    3 4
    4 11
    5 34
```

```python
sage.groups.perm_gps.partn_ref.refinement_graphs.coarsest_equitable_refinement(G, partition, directed)
    Return the coarsest equitable refinement of partition for G.
    This is a helper function for the graph function of the same name.
    DOCTEST (More thorough testing in sage/graphs/graph.py):
```

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sage: from sage.groups.perm_gps.partn_ref.refinement_graphs import coarsest_equitable_refinement
sage: from sage.graphs.base.sparse_graph import SparseGraph
sage: coarsest_equitable_refinement(SparseGraph(7), [[0], [1, 2, 3, 4], [5, 6]], 0)
[[0], [1, 2, 3, 4], [5, 6]]

EXAMPLES:

sage: from sage.groups.perm_gps.partn_ref.refinement_graphs import generate_dense_graphs_edge_addition

sage: for n in [0..6]:
....:     print(generate_dense_graphs_edge_addition(n, 1))
1
2
6
20
90
544
5096

sage: for n in [0..7]:
....:     print(generate_dense_graphs_edge_addition(n, 0))
1
1
2
4
11
34
156
1044
sage: generate_dense_graphs_edge_addition(8, 0) # long time - about 14 seconds at 2.4 GHz
12346

sage: from sage.groups.perm_gps.partn_ref.refinement_graphs import generate_dense_graphs_vert_addition

EXAMPLES:

sage: from sage.groups.perm_gps.partn_ref.refinement_graphs import generate_dense_graphs_vert_addition

27.3. Graph-theoretic partition backtrack functions
sage: for n in [0..7]:
...
... generate_dense_graphs_vert_addition(n)
1
2
4
8
19
53
209
1253
sage: generate_dense_graphs_vert_addition(8)  # long time
13599

sage.groups.perm_gps.partn_ref.refinement_graphs.get_orbits((gens, n))
Compute orbits given a list of generators of a permutation group, in list format.

DOCTEST (More thorough testing in sage/graphs/graph.py):

```python
sage: from sage.groups.perm_gps.partn_ref.refinement_graphs import get_orbits
sage: get_orbits([[1,2,3,0,4,5], [0,1,2,3,5,4]], 6)
[[0, 1, 2, 3], [4, 5]]
```

sage.groups.perm_gps.partn_ref.refinement_graphs.isomorphic(G1, G2, partn, ordering2, dig, use_indicator_function, sparse=False)
Test whether two graphs are isomorphic.

EXAMPLES:

```python
sage: from sage.groups.perm_gps.partn_ref.refinement_graphs import isomorphic
sage: G = Graph(2)
sage: H = Graph(2)
sage: isomorphic(G, H, [[0,1]], [0,1], 0, 1)
{0: 0, 1: 1}
sage: isomorphic(G, H, [[0,1]], [0,1], 0, 1)
{0: 0, 1: 1}
sage: isomorphic(G, H, [[0],[1]], [0,1], 0, 1)
{0: 0, 1: 1}
sage: isomorphic(G, H, [[0],[1]], [1,0], 0, 1)
{0: 1, 1: 0}
sage: G = Graph(3)
sage: H = Graph(3)
sage: isomorphic(G, H, [[0,1,2]], [0,1,2], 0, 1)
{0: 0, 1: 1, 2: 2}
sage: G.add_edge(0,1)
sage: isomorphic(G, H, [[0,1,2]], [0,1,2], 0, 1)
False
sage: H.add_edge(1,2)
sage: isomorphic(G, H, [[0,1,2]], [0,1,2], 0, 1)
{0: 1, 1: 2, 2: 0}
```

sage.groups.perm_gps.partn_ref.refinement_graphs.orbit_partition(gamma,
list_perm=False)
Assuming that G is a graph on vertices 0,1,\ldots,n-1, and gamma is an element of SymmetricGroup(n), returns the
partition of the vertex set determined by the orbits of gamma, considered as action on the set 1,2,..,n where we take 0 = n. In other words, returns the partition determined by a cyclic representation of gamma.

INPUT:

• list_perm - if True, assumes gamma is a list representing the map \( i \mapsto \text{"gamma"}[i] \)

EXAMPLES:

```python
sage: from sage.groups.perm_gps.partn_ref.refinement_graphs import orbit_partition
sage: G = graphs.PetersenGraph()
sage: S = SymmetricGroup(10)
sage: gamma = S('(10,1,2,3,4)(5,6,7)(8,9)')
sage: orbit_partition(gamma)
[[1, 2, 3, 4, 0], [5, 6, 7], [8, 9]]
sage: gamma = S('(10,5)(1,6)(2,7)(3,8)(4,9)')
sage: orbit_partition(gamma)
[[1, 6], [2, 7], [3, 8], [4, 9], [5, 0]]
```

`sage.groups.perm_gps.partn_ref.refinement_graphs.random_tests(num=10,
 n_max=60,
 perms_per_graph=5)`

Tests to make sure that \( C(\text{gamma}(G)) = C(G) \) for random permutations gamma and random graphs G, and that isomorphic returns an isomorphism.

INPUT:

• num – run tests for this many graphs
• n_max – test graphs with at most this many vertices
• perms_per_graph – test each graph with this many random permutations

DISCUSSION:

This code generates num random graphs G on at most n_max vertices. The density of edges is chosen randomly between 0 and 1.

For each graph G generated, we uniformly generate perms_per_graph random permutations and verify that the canonical labels of G and the image of G under the generated permutation are equal, and that the isomorphic function returns an isomorphism.

```python
sage.groups.perm_gps.partn_ref.refinement_graphs.search_tree(G_in, partition, lab=True, dig=False,
 dict_rep=False, certificate=False, verbosity=0, use_indicator_function=True, sparse=True,
 base=False, order=False)
```

Compute canonical labels and automorphism groups of graphs.

INPUT:

• G_in – a Sage graph
• partition – a list of lists representing a partition of the vertices
• lab – if True, compute and return the canonical label in addition to the automorphism group
• dig – set to True for digraphs and graphs with loops. If True, does not use optimizations based on Lemma 2.25 in [1] that are valid only for simple graphs.
• dict_rep – if True, return a dictionary with keys the vertices of the input graph G_in and values elements of the set the permutation group acts on. (The point is that graphs are arbitrarily labelled, often 0..n-1, and permutation groups always act on 1..n. This dictionary maps vertex labels (such as 0..n-1) to the domain of the permutations.)
• certificate – if True, return the permutation from G to its canonical label.
• verbosity – currently ignored
• use_indicator_function – option to turn off indicator function (True is generally faster)
• sparse – whether to use sparse or dense representation of the graph (ignored if G is already a CGraph - see sage.graphs.base)
• base – whether to return the first sequence of split vertices (used in computing the order of the group)
• order – whether to return the order of the automorphism group

OUTPUT:

Depends on the options. If more than one thing is returned, they are in a tuple in the following order:
• list of generators in list-permutation format – always
• dict – if dict_rep
• graph – if lab
• dict – if certificate
• list – if base
• integer – if order

EXAMPLES:

```python
sage: st = sage.groups.perm_gps.partn_ref.refinement_graphs.search_tree
sage: from sage.graphs.base.dense_graph import DenseGraph
sage: from sage.graphs.base.sparse_graph import SparseGraph

Graphs on zero vertices:
```
sage: G = Graph()
sage: st(G, [[]], order=True)
([], Graph on 0 vertices, 1)
```

Graphs on one vertex:
```
sage: G = Graph(1)
sage: st(G, [[0]], order=True)
([], Graph on 1 vertex, 1)
```

Graphs on two vertices:
```
sage: G = Graph(2)
sage: st(G, [[0,1]], order=True)
([[1, 0]], Graph on 2 vertices, 2)
sage: st(G, [[0],[1]], order=True)
([], Graph on 2 vertices, 1)
sage: G.add_edge(0,1)
```

(continues on next page)
Graphs on three vertices:

```
sage: G = Graph(3)
sage: st(G, [0, 1, 2], order=True)
([], Graph on 3 vertices, 1)
```

The Dodecahedron has automorphism group of size 120:

```
sage: G = graphs.DodecahedralGraph()
sage: Pi = [range(20)]
sage: st(G, Pi, order=True)[2]
120
```

The three-cube has automorphism group of size 48:

```
sage: G = graphs.CubeGraph(3)
sage: G.relabel()
```

We obtain the same output using different types of Sage graphs:

```
sage: G = graphs.DodecahedralGraph()
sage: GD = DenseGraph(20)
sage: GS = SparseGraph(20)
sage: for i,j,_ in G.edge_iterator():
    ....: GD.add_arc(i,j)
    ....: GS.add_arc(i,j)
sage: Pi=[range(20)]
sage: a,b = st(G, Pi)
sage: asp,bsp = st(GS, Pi)
sage: ade,bde = st(GD, Pi)
sage: bsg = Graph()
sage: bdg = Graph()
sage: for i in range(20):
    ....:     for j in range(20):
    ....:         if bsp.has_arc(i,j):
    ....:             bsg.add_edge(i,j)
    ....:         if bde.has_arc(i,j):
```

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....:
    bdg.add_edge(i,j)
sage: a, b.graph6_string()  
(([0, 19, 3, 2, 6, 5, 4, 17, 18, 11, 10, 9, 13, 12, 16, 15, 14, 7, 8, 1], [0, 1, 8, 9, 13, 14, 7, 6, 2, 3, 19, 18, 17, 4, 5, 15, 16, 12, 11, 10], [1, 8, 9, 10, 11, 12, 13, 14, 7, 6, 2, 3, 4, 5, 15, 16, 17, 18, 19, 0]), 'S?_[PG__EO?_?_?P?CO?_AE?EC?Ac?@O')
sage: a == asp
True
sage: a == ade
True
sage: b == bsg
True
sage: b == bdg
True

Cubes!:

sage: C = graphs.CubeGraph(1)
sage: gens, order = st(C, [C.vertices()], lab=False, order=True); order
2
sage: C = graphs.CubeGraph(2)
sage: gens, order = st(C, [C.vertices()], lab=False, order=True); order
8
sage: C = graphs.CubeGraph(3)
sage: gens, order = st(C, [C.vertices()], lab=False, order=True); order
48
sage: C = graphs.CubeGraph(4)
sage: gens, order = st(C, [C.vertices()], lab=False, order=True); order
384
sage: C = graphs.CubeGraph(5)
sage: gens, order = st(C, [C.vertices()], lab=False, order=True); order
3840
sage: C = graphs.CubeGraph(6)
sage: gens, order = st(C, [C.vertices()], lab=False, order=True); order
46080

One can also turn off the indicator function (note: this will take longer):

sage: D1 = DiGraph({0:[2],2:[0],1:[1]}, loops=True)
sage: D2 = DiGraph({1:[2],2:[1],0:[0]}, loops=True)
sage: a,b = st(D1, [D1.vertices()], dig=True, use_indicator_function=False)
sage: c,d = st(D2, [D2.vertices()], dig=True, use_indicator_function=False)
sage: b==d
True

This example is due to Chris Godsil:

sage: HS = graphs.HoffmanSingletonGraph()
sage: alqs = [Set(c) for c in (HS.complement()).cliques_maximum()]
sage: Y = Graph([alqs, lambda s,t: len(s.intersection(t))==0])
sage: Y0,Y1 = Y.connected_components_subgraphs()
sage: st(Y0, [Y0.vertices()])[1] == st(Y1, [Y1.vertices()])[1]
True
sage: st(Y0, [Y0.vertices()])[1] == st(HS, [HS.vertices()])[1]
True
sage: st(HS, [HS.vertices()])[1] == st(Y1, [Y1.vertices()])[1]
True
Certain border cases need to be tested as well:

```python
sage: G = Graph('Fll^G')
sage: a,b,c = st(G, [range(G.num_verts())], order=True); b
Graph on 7 vertices
sage: c
48
sage: G = Graph(21)
sage: st(G, [range(G.num_verts())], order=True)[2] == factorial(21)
True
sage: G = Graph('^????????????????????{??N??@w??FaGa?PCO@CP?AGa?_QO?Q@G?CcA??cc???
˓->?Bo????{????F_')
sage: perm = {3:15, 15:3}
sage: H = G.relabel(perm, inplace=False)
sage: st(G, [range(G.num_verts())])[1] == st(H, [range(H.num_verts())])[1]
True
sage: st(Graph(':Dkw'), [range(5)], lab=False, dig=True)
[[4, 1, 2, 3, 0], [0, 2, 1, 3, 4]]
```

### 27.4 Partition backtrack functions for lists – a simple example of using partn_ref.

**EXAMPLES:**

```python
sage: import sage.groups.perm_gps.partn_ref.refinement_lists

sage.groups.perm_gps.partn_ref.refinement_lists.is_isomorphic(self, other)
Return the bijection as a permutation if two lists are isomorphic, return False otherwise.

**EXAMPLES:**

```python
sage: from sage.groups.perm_gps.partn_ref.refinement_lists import is_isomorphic
sage: is_isomorphic([0,0,1],[1,0,0])
[1, 2, 0]
```

### 27.5 Partition backtrack functions for matrices

**EXAMPLES:**

```python
sage: import sage.groups.perm_gps.partn_ref.refinement_matrices

class sage.groups.perm_gps.partn_ref.refinement_matrices.MatrixStruct
Bases: object
```

**REFERENCE:**

automorphism_group()

Returns a list of generators of the automorphism group, along with its order and a base for which the list of generators is a strong generating set.

For more examples, see self.run().

EXAMPLES:

```
sage: from sage.groups.perm_gps.partn_ref.refinement_matrices import MatrixStruct

sage: M = MatrixStruct(matrix(GF(3), [[0,1,2],[0,2,1]]))
sage: M.automorphism_group()
([[0, 2, 1]], 2, [1])
```
run (partition=None)
Perform the canonical labeling and automorphism group computation, storing results to self.

INPUT:

partition – an optional list of lists partition of the columns.
Default is the unit partition.

EXAMPLES:

```
sage: from sage.groups.perm_gps.partn_ref.refinement_matrices import MatrixStruct
sage: M = MatrixStruct(matrix(GF(3),[[0,1,2],[0,2,1]]))
sage: M.run()
sage: M.automorphism_group()
([[0, 2, 1]], 2, [1])
sage: M.canonical_relabeling()
[0, 1, 2]
sage: M = MatrixStruct(matrix(GF(3),[[0,1,2],[0,2,1],[1,0,2],[1,2,0],[2,0,1],
   \[2,1,0]])
sage: M.automorphism_group()[1] == 6
True
sage: M = MatrixStruct(matrix(GF(3),[[0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,2]]))
sage: M.automorphism_group()[1] == factorial(14)
True
```

sage.groups.perm_gps.partn_ref.refinement_matrices.random_tests (n=10,
nrows_max=50,
ncols_max=50,
nsymbols_max=10,
perms_per_matrix=5,
density_range=(0.1, 0.9))
Tests to make sure that C(gamma(M)) == C(M) for random permutations gamma and random matrices M, and that M.is_isomorphic(gamma(M)) returns an isomorphism.

INPUT:

• n – run tests on this many matrices
• nrows_max – test matrices with at most this many rows
• ncols_max – test matrices with at most this many columns
• perms_per_matrix – test each matrix with this many random permutations
• nsymbols_max – maximum number of distinct symbols in the matrix

This code generates n random matrices M on at most ncols_max columns and at most nrows_max rows. The density of entries in the basis is chosen randomly between 0 and 1.

For each matrix M generated, we uniformly generate perms_per_matrix random permutations and verify that the canonical labels of M and the image of M under the generated permutation are equal, and that the isomorphism is discovered by the double coset function.
28.1 Base for Classical Matrix Groups

This module implements the base class for matrix groups that have various famous names, like the general linear group.

EXAMPLES:

```
sage: SL(2, ZZ)
Special Linear Group of degree 2 over Integer Ring
sage: G = SL(2,GF(3)); G
Special Linear Group of degree 2 over Finite Field of size 3
sage: G.is_finite()
True
sage: G.conjugacy_classes_representatives()
([1 0], [0 2], [0 1], [2 0], [0 1], [0 2], [0 1], [0 2], [2 1], [1 2], [0 2], [1 0])
sage: G = SL(6,GF(5))
sage: G.gens()
([2 0 0 0 0 0], [0 3 0 0 0 0], [0 0 3 0 0 0], [0 0 0 4 0 0], [0 0 0 0 1 0], [0 0 0 0 0 1])
```

```
class sage.groups.matrix_gps.named_group.NamedMatrixGroup_gap(degree, base_ring, special, sage_name, latex_string, gap_command_string, category=None)

Bases: sage.groups.matrix_gps.named_group.NamedMatrixGroup_generic, sage.groups.matrix_gps.matrix_group.MatrixGroup_gap

Base class for “named” matrix groups using LibGAP

INPUT:

- degree – integer. The degree (number of rows/columns of matrices).
- base_ring – ring. The base ring of the matrices.
```
• special – boolean. Whether the matrix group is special, that is, elements have determinant one.
• latex_string – string. The latex representation.
• gap_command_string – string. The GAP command to construct the matrix group.

EXAMPLES:

```python
sage: G = GL(2, GF(3))
sage: from sage.groups.matrix_gps.named_group import NamedMatrixGroup_gap
sage: isinstance(G, NamedMatrixGroup_gap)
True
```

```python
class sage.groups.matrix_gps.named_group.NamedMatrixGroup_generic(degree, base_ring, special, sage_name, latex_string, category=None, invariant_form=None)
```

Base class for “named” matrix groups

INPUT:

• degree – integer; the degree (number of rows/columns of matrices)
• base_ring – ring; the base ring of the matrices
• special – boolean; whether the matrix group is special, that is, elements have determinant one
• sage_name – string; the name of the group
• latex_string – string; the latex representation
• category – (optional) a subcategory of sage.categories.groups.Groups passed to the constructor of sage.groups.matrix_gps.matrix_group.MatrixGroup_generic
• invariant_form – (optional) square-matrix of the given degree over the given base_ring describing a bilinear form to be kept invariant by the group

EXAMPLES:

```python
sage: G = GL(2, QQ)
sage: from sage.groups.matrix_gps.named_group import NamedMatrixGroup_generic
sage: isinstance(G, NamedMatrixGroup_generic)
True
```

See also:

See the examples for GU(), SU(), Sp(), etc. as well.

```python
sage.groups.matrix_gps.named_group.normalize_args_invariant_form(R, d, invariant_form)
```

Normalize the input of a user defined invariant bilinear form for orthogonal, unitary and symplectic groups.

Further informations and examples can be found in the defining functions (GU(), SU(), Sp(), etc.) for unitary, symplectic groups, etc.
INPUT:
- \( R \) – instance of the integral domain which should become the \texttt{base\_ring} of the classical group
- \( d \) – integer giving the dimension of the module the classical group is operating on
- \texttt{invariant\_form} – (optional) instances being accepted by the matrix-constructor that define a \( d \times d \)
  square matrix over \( R \) describing the bilinear form to be kept invariant by the classical group

OUTPUT:
None if \texttt{invariant\_form} was not specified (or \texttt{None}). A matrix if the normalization was possible; otherwise an error is raised.

AUTHORS:
- Sebastian Oehms (2018-8) (see trac ticket \#26028)

\texttt{sage.groups.matrix_gps.named_group.normalize\_args\_vectorspace}(\ast\texttt{args}, \ast\ast\texttt{kwds})
Normalize the arguments that relate to a vector space.

INPUT:
Something that defines an affine space. For example
- An affine space itself:
  - \( A \) – affine space
- A vector space:
  - \( V \) – a vector space
- Degree and base ring:
  - \texttt{degree} – integer. The degree of the affine group, that is, the dimension of the affine space the group
    is acting on.
  - \texttt{ring} – a ring or an integer. The base ring of the affine space. If an integer is given, it must be a prime
    power and the corresponding finite field is constructed.
  - \texttt{var}='a' – optional keyword argument to specify the finite field generator name in the case where
    \texttt{ring} is a prime power.

OUTPUT:
A pair \texttt{(degree, ring)}. 

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