# **Combinatorial and Discrete Geometry**

Release 9.7

**The Sage Development Team** 

# **CONTENTS**

1	Hyperplane arrangements	3
2	Polyhedral computations	61
3	Triangulations	665
4	Miscellaneous	701
5	Helper functions	749
6	Indices and Tables	767
Python Module Index		769
Index		771

Sage includes classes for hyperplane arrangements, polyhedra, toric varieties (including polyhedral cones and fans), triangulations and some other helper classes and functions.

CONTENTS 1

2 CONTENTS

**CHAPTER** 

ONE

# HYPERPLANE ARRANGEMENTS

# 1.1 Hyperplane Arrangements

Before talking about hyperplane arrangements, let us start with individual hyperplanes. This package uses certain linear expressions to represent hyperplanes, that is, a linear expression 3x + 3y - 5z - 7 stands for the hyperplane with the equation 3x + 3y - 5z = 7. To create it in Sage, you first have to create a *HyperplaneArrangements* object to define the variables x, y, z:

```
sage: H.<x,y,z> = HyperplaneArrangements(QQ)
sage: h = 3*x + 2*y - 5*z - 7; h
Hyperplane 3*x + 2*y - 5*z - 7
sage: h.normal()
(3, 2, -5)
sage: h.constant_term()
-7
```

The individual hyperplanes behave like the linear expression with regard to addition and scalar multiplication, which is why you can do linear combinations of the coordinates:

```
sage: -2*h
Hyperplane -6*x - 4*y + 10*z + 14
sage: x, y, z
(Hyperplane x + 0*y + 0*z + 0,
Hyperplane 0*x + y + 0*z + 0,
Hyperplane 0*x + z + 0
```

See sage.geometry.hyperplane\_arrangement.hyperplane for more functionality of the individual hyperplanes.

# 1.1.1 Arrangements

There are several ways to create hyperplane arrangements:

Notation (i): by passing individual hyperplanes to the HyperplaneArrangements object:

```
sage: H.<x,y> = HyperplaneArrangements(QQ)
sage: box = x | y | x-1 | y-1; box
Arrangement <y - 1 | y | x - 1 | x>
sage: box == H(x, y, x-1, y-1) # alternative syntax
True
```

Notation (ii): by passing anything that defines a hyperplane, for example a coefficient vector and constant term:

```
sage: H = HyperplaneArrangements(QQ, ('x', 'y'))
sage: triangle = H([(1, 0), 0], [(0, 1), 0], [(1,1), -1]); triangle
Arrangement <y | x | x + y - 1>

sage: H.inject_variables()
Defining x, y
sage: triangle == x | y | x+y-1
True
```

The default base field is **Q**, the rational numbers. Finite fields are also supported:

```
sage: H.<x,y,z> = HyperplaneArrangements(GF(5))
sage: a = H([(1,2,3), 4], [(5,6,7), 8]); a
Arrangement <y + 2*z + 3 \mid x + 2*y + 3*z + 4>
```

Number fields are also possible:

Notation (iii): a list or tuple of hyperplanes:

```
sage: H.<x,y,z> = HyperplaneArrangements(GF(5))
sage: k = [x+i for i in range(4)]; k
[Hyperplane x + 0*y + 0*z + 0, Hyperplane x + 0*y + 0*z + 1,
Hyperplane x + 0*y + 0*z + 2, Hyperplane x + 0*y + 0*z + 3]
sage: H(k)
Arrangement <x | x + 1 | x + 2 | x + 3>
```

Notation (iv): using the library of arrangements:

```
sage: hyperplane_arrangements.braid(4)
Arrangement of 6 hyperplanes of dimension 4 and rank 3
sage: hyperplane_arrangements.semiorder(3)
Arrangement of 6 hyperplanes of dimension 3 and rank 2
sage: hyperplane_arrangements.graphical(graphs.PetersenGraph())
Arrangement of 15 hyperplanes of dimension 10 and rank 9
sage: hyperplane_arrangements.Ish(5)
Arrangement of 20 hyperplanes of dimension 5 and rank 4
```

Notation (v): from the bounding hyperplanes of a polyhedron:

```
sage: a = polytopes.cube().hyperplane_arrangement(); a
Arrangement of 6 hyperplanes of dimension 3 and rank 3
sage: a.n_regions()
27
```

New arrangements from old:

```
sage: a = hyperplane_arrangements.braid(3)
sage: b = a.add_hyperplane([4, 1, 2, 3])
Arrangement <t1 - t2 | t0 - t1 | t0 - t2 | t0 + 2*t1 + 3*t2 + 4>
sage: c = b.deletion([4, 1, 2, 3])
sage: a == c
True
sage: a = hyperplane_arrangements.braid(3)
sage: b = a.union(hyperplane_arrangements.semiorder(3))
sage: b == a | hyperplane_arrangements.semiorder(3)
                                                      # alternate syntax
sage: b == hyperplane_arrangements.Catalan(3)
True
sage: a
Arrangement <t1 - t2 | t0 - t1 | t0 - t2>
sage: a = hyperplane_arrangements.coordinate(4)
sage: h = a.hyperplanes()[0]
sage: b = a.restriction(h)
sage: b == hyperplane_arrangements.coordinate(3)
```

# 1.1.2 Properties of Arrangements

A hyperplane arrangement is *essential* if the normals to its hyperplanes span the ambient space. Otherwise, it is *inessential*. The essentialization is formed by intersecting the hyperplanes by this normal space (actually, it is a bit more complicated over finite fields):

```
sage: a = hyperplane_arrangements.braid(4); a
Arrangement of 6 hyperplanes of dimension 4 and rank 3
sage: a.is_essential()
False
sage: a.rank() < a.dimension() # double-check
True
sage: a.essentialization()
Arrangement of 6 hyperplanes of dimension 3 and rank 3</pre>
```

The connected components of the complement of the hyperplanes of an arrangement in  $\mathbb{R}^n$  are called the *regions* of the arrangement:

```
sage: a = hyperplane_arrangements.semiorder(3)
sage: b = a.essentialization(); b
Arrangement of 6 hyperplanes of dimension 2 and rank 2
sage: b.n_regions()
19
sage: b.regions()
(A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 6 vertices,
    A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 3 vertices,
    A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 3 vertices,
```

```
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 3 vertices and 1 ray,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 3 vertices,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 3 vertices and 1 ray,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and 2 rays,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 3 vertices,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 3 vertices and 1 ray,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and 2 rays,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 3 vertices,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 3 vertices and 1 ray,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and 2 rays,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 3 vertices,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 3 vertices and 1 ray,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and 2 rays,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 3 vertices and 1 ray,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and 2 rays,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and 2 rays)
sage: b.bounded_regions()
(A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 6 vertices,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 3 vertices,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 3 vertices,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 3 vertices,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 3 vertices,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 3 vertices,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 3 vertices)
sage: b.n_bounded_regions()
sage: a.unbounded_regions()
(A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 1 vertex, 2 rays, 1.
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 3 vertices, 1 ray, 1.
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 1 vertex, 2 rays, 1
→line.
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 3 vertices, 1 ray, 1.
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 1 vertex, 2 rays, 1...
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 3 vertices, 1 ray, 1.
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 3 vertices, 1 ray, 1.
→line.
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 1 vertex, 2 rays, 1
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 3 vertices, 1 ray, 1
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 1 vertex, 2 rays, 1
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 3 vertices, 1 ray, 1.
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 1 vertex, 2 rays, 1
→line)
```

The distance between regions is defined as the number of hyperplanes separating them. For example:

```
sage: r1 = b.regions()[0]
sage: r2 = b.regions()[1]
sage: b.distance_between_regions(r1, r2)
1
sage: [hyp for hyp in b if b.is_separating_hyperplane(r1, r2, hyp)]
[Hyperplane 2*t1 + t2 + 1]
sage: b.distance_enumerator(r1) # generating function for distances from r1
6*x^3 + 6*x^2 + 6*x + 1
```

**Note:** *bounded region* really mean *relatively bounded* here. A region is relatively bounded if its intersection with space spanned by the normals of the hyperplanes in the arrangement is bounded.

The intersection poset of a hyperplane arrangement is the collection of all nonempty intersections of hyperplanes in the arrangement, ordered by reverse inclusion. It includes the ambient space of the arrangement (as the intersection over the empty set):

```
sage: a = hyperplane_arrangements.braid(3)
sage: p = a.intersection_poset()
sage: p.is_ranked()
True
sage: p.order_polytope()
A 5-dimensional polyhedron in ZZ^5 defined as the convex hull of 10 vertices
```

The characteristic polynomial is a basic invariant of a hyperplane arrangement. It is defined as

$$\chi(x) := \sum_{w \in P} \mu(w) x^{dim(w)}$$

where the sum is P is the intersection\_poset() of the arrangement and  $\mu$  is the Möbius function of P:

```
sage: a = hyperplane_arrangements.semiorder(5)
sage: a.characteristic_polynomial()
                                                   # long time (about a second on Core i7)
x^5 - 20*x^4 + 180*x^3 - 790*x^2 + 1380*x
                                                   # long time
sage: a.poincare_polynomial()
1380*x^4 + 790*x^3 + 180*x^2 + 20*x + 1
sage: a.n_regions()
                                                   # long time
sage: charpoly = a.characteristic_polynomial()
                                                   # long time
sage: charpoly(-1)
                                                   # long time
-2371
sage: a.n_bounded_regions()
                                                   # long time
751
sage: charpoly(1)
                                                   # long time
751
```

For finer invariants derived from the intersection poset, see <a href="whitney\_number">whitney\_number</a>() and <a href="mailto:doubly\_indexed\_whitney\_number">doubly\_indexed\_whitney\_number</a>().

Miscellaneous methods (see documentation for an explanation):

```
sage: a = hyperplane_arrangements.semiorder(3)
sage: a.has_good_reduction(5)
True
```

```
sage: b = a.change_ring(GF(5))
sage: pa = a.intersection_poset()
sage: pb = b.intersection_poset()
sage: pa.is_isomorphic(pb)
sage: a.face_vector()
(0, 12, 30, 19)
sage: a.face_vector()
(0, 12, 30, 19)
sage: a.is_central()
False
sage: a.is_linear()
False
sage: a.sign_vector((1,1,1))
(-1, 1, -1, 1, -1, 1)
sage: a.varchenko_matrix()
                               h2*h4
           1
                      h2
                                            h2*h3
                                                     h2*h3*h4 h2*h3*h4*h5]
h2
                       1
                                  h4
                                               h3
                                                        h3*h4
                                                                 h3*h4*h5]
       h2*h4
                                            h3*h4
                                                           h3
h4
                                                                     h3*h5]
                                   1
       h2*h3
                                h3*h4
                                                           h4
                                                                     h4*h5]
Γ
                      h3
                                                1
                   h3*h4
    h2*h3*h4
                                               h4
                                                                        h5]
                                   h3
                                                            1
[h2*h3*h4*h5
                h3*h4*h5
                               h3*h5
                                            h4*h5
                                                            h5
                                                                         17
```

There are extensive methods for visualizing hyperplane arrangements in low dimensions. See plot() for details.

# **AUTHORS:**

- David Perkinson (2013-06): initial version
- Qiaoyu Yang (2013-07)
- Kuai Yu (2013-07)
- Volker Braun (2013-10): Better Sage integration, major code refactoring.

This module implements hyperplane arrangements defined over the rationals or over finite fields. The original motivation was to make a companion to Richard Stanley's notes [Sta2007] on hyperplane arrangements.

class sage.geometry.hyperplane\_arrangement.arrangement.HyperplaneArrangementElement(parent,

hyperplanes,
check=True,
backend=None)

Bases: sage.structure.element.Element

A hyperplane arrangement.

**Warning:** You should never create *HyperplaneArrangementElement* instances directly, always use the parent.

# add\_hyperplane(other)

The union of self with other.

INPUT:

• other – a hyperplane arrangement or something that can be converted into a hyperplane arrangement OUTPUT:

A new hyperplane arrangement.

#### **EXAMPLES:**

```
sage: H.<x,y> = HyperplaneArrangements(QQ)
sage: A = H([1,2,3], [0,1,1], [0,1,-1], [1,-1,0], [1,1,0])
sage: B = H([1,1,1], [1,-1,1], [1,0,-1])
sage: A.union(B)
Arrangement of 8 hyperplanes of dimension 2 and rank 2
sage: A | B # syntactic sugar
Arrangement of 8 hyperplanes of dimension 2 and rank 2
```

A single hyperplane is coerced into a hyperplane arrangement if necessary:

```
sage: A.union(x+y-1)
Arrangement of 6 hyperplanes of dimension 2 and rank 2
sage: A.add_hyperplane(x+y-1) # alias
Arrangement of 6 hyperplanes of dimension 2 and rank 2

sage: P.<x,y> = HyperplaneArrangements(RR)
sage: C = P(2*x + 4*y + 5)
sage: C.union(A)
Arrangement of 6 hyperplanes of dimension 2 and rank 2
```

# backend()

Return the backend used for polyhedral objects

**OUTPUT**:

A string giving the backend or None if none is specified.

**EXAMPLES:** 

By default, no backend is specified:

```
sage: H = HyperplaneArrangements(QQ)
sage: A = H()
sage: A.backend()
```

Otherwise, one may specify a polyhedral backend:

```
sage: A = H(backend='ppl')
sage: A.backend()
'ppl'
sage: A = H(backend='normaliz')
sage: A.backend()
'normaliz'
```

# bounded\_regions()

Return the relatively bounded regions of the arrangement.

A region is relatively bounded if its intersection with the space spanned by the normals to the hyperplanes is bounded. This is the same as being bounded in the case that the hyperplane arrangement is essential. It is assumed that the arrangement is defined over the rationals.

#### **OUTPUT**:

Tuple of polyhedra. The relatively bounded regions of the arrangement.

#### See also:

unbounded\_regions()

#### **EXAMPLES:**

```
sage: A = hyperplane_arrangements.semiorder(3)
sage: A.bounded_regions()
(A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 3 vertices.
→and 1 line,
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 3 vertices.
→and 1 line,
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 3 vertices.
→and 1 line,
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 6 vertices
→and 1 line,
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 3 vertices.
→and 1 line,
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 3 vertices.
→and 1 line.
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 3 vertices_
→and 1 line)
sage: A.bounded_regions()[0].is_compact()
                                             # the regions are only_
→*relatively* bounded
False
sage: A.is_essential()
False
```

# center()

Return the center of the hyperplane arrangement.

The polyhedron defined to be the set of all points in the ambient space of the arrangement that lie on all of the hyperplanes.

# **OUTPUT**:

A polyhedron.

#### **EXAMPLES:**

The empty hyperplane arrangement has the entire ambient space as its center:

```
sage: H.<x,y> = HyperplaneArrangements(QQ)
sage: A = H()
sage: A.center()
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and 2

→lines
```

The Shi arrangement in dimension 3 has an empty center:

```
sage: A = hyperplane_arrangements.Shi(3)
sage: A.center()
The empty polyhedron in QQ^3
```

The Braid arrangement in dimension 3 has a center that is neither empty nor full-dimensional:

# change\_ring(base\_ring)

Return hyperplane arrangement over the new base ring.

#### INPUT:

• base\_ring - the new base ring; must be a field for hyperplane arrangements

#### **OUTPUT**:

The hyperplane arrangement obtained by changing the base field, as a new hyperplane arrangement.

**Warning:** While there is often a one-to-one correspondence between the hyperplanes of self and those of self.change\_ring(base\_ring), there is no guarantee that the order in which they appear in self.hyperplanes() will match the order in which their counterparts in self.cone() will appear in self.change\_ring(base\_ring).hyperplanes()!

#### **EXAMPLES:**

```
sage: H.<x,y> = HyperplaneArrangements(QQ)
sage: A = H([(1,1), 0], [(2,3), -1])
sage: A.change_ring(FiniteField(2))
Arrangement <y + 1 | x + y>
```

# characteristic\_polynomial()

Return the characteristic polynomial of the hyperplane arrangement.

# **OUTPUT**:

The characteristic polynomial in  $\mathbf{Q}[x]$ .

# **EXAMPLES:**

```
sage: a = hyperplane_arrangements.coordinate(2)
sage: a.characteristic_polynomial()
x^2 - 2*x + 1
```

# closed\_faces(labelled=True)

Return the closed faces of the hyperplane arrangement self (provided that self is defined over a totally ordered field).

Let  $\mathcal{A}$  be a hyperplane arrangement in the vector space  $K^n$ , whose hyperplanes are the zero sets of the affine-linear functions  $u_1, u_2, \ldots, u_N$ . (We consider these functions  $u_1, u_2, \ldots, u_N$ , and not just the hyperplanes, as given. We also assume the field K to be totally ordered.) For any point  $x \in K^n$ , we define the sign vector of x to be the vector  $(v_1, v_2, \ldots, v_N) \in \{-1, 0, 1\}^N$  such that (for each i) the number  $v_i$  is the sign of  $u_i(x)$ . For any  $v \in \{-1, 0, 1\}^N$ , we let  $F_v$  be the set of all  $x \in K^n$  which have sign vector v. The nonempty ones among all these subsets  $F_v$  are called the *open faces* of  $\mathcal{A}$ . They form a partition of the set  $K^n$ .

Furthermore, for any  $v = (v_1, v_2, \dots, v_N) \in \{-1, 0, 1\}^N$ , we let  $G_v$  be the set of all  $x \in K^n$  such that, for every i, the sign of  $u_i(x)$  is either 0 or  $v_i$ . Then,  $G_v$  is a polyhedron. The nonempty ones among all these polyhedra  $G_v$  are called the *closed faces* of A. While several sign vectors v can lead to one and the same closed face  $G_v$ , we can assign to every closed face a canonical choice of a sign vector: Namely, if G

is a closed face of A, then the *sign vector* of G is defined to be the vector  $(v_1, v_2, \ldots, v_N) \in \{-1, 0, 1\}^N$  where x is any point in the relative interior of G and where, for each i, the number  $v_i$  is the sign of  $u_i(x)$ . (This does not depend on the choice of x.)

There is a one-to-one correspondence between the closed faces and the open faces of A. It sends a closed face G to the open face  $F_v$ , where v is the sign vector of G; this  $F_v$  is also the relative interior of  $G_v$ . The inverse map sends any open face O to the closure of O.

#### INPUT:

• labelled – boolean (default: True); if True, then this method returns not the faces itself but rather pairs (v, F) where F is a closed face and v is its sign vector (here, the order and the orientation of the  $u_1, u_2, \ldots, u_N$  is as given by self.hyperplanes()).

#### **OUTPUT:**

A tuple containing the closed faces as polyhedra, or (if labelled is set to True) the pairs of sign vectors and corresponding closed faces.

**Todo:** Should the output rather be a dictionary where the keys are the sign vectors and the values are the faces?

#### **EXAMPLES:**

```
sage: a = hyperplane_arrangements.braid(2)
sage: a.hyperplanes()
(Hyperplane t0 - t1 + 0,)
sage: a.closed_faces()
(((0,),
 A 1-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and
\rightarrow 1 line),
 ((1,),
 A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex, 1
\rightarrowray, 1 line),
((-1,),
 A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex, 1
\rightarrowray, 1 line))
sage: a.closed_faces(labelled=False)
(A 1-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and.
\rightarrow 1 line.
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex, 1
⇒ray, 1 line,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex, 1.
→ray, 1 line)
sage: [(v, F, F.representative_point()) for v, F in a.closed_faces()]
[((0,),
 A 1-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and.
\hookrightarrow1 line,
 (0, 0)),
 ((1,),
 A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex, 1
→ray, 1 line,
 (0, -1)),
 ((-1,),
 A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex, 1
⊶ray, 1 line,
                                                                     (continues on next page)
```

```
(-1, 0))
sage: H.<x,y> = HyperplaneArrangements(QQ)
sage: a = H(x, y+1)
sage: a.hyperplanes()
(Hyperplane 0*x + y + 1, Hyperplane x + 0*y + 0)
sage: [(v, F, F.representative_point()) for v, F in a.closed_faces()]
[((0, 0),
  A 0-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex,
  (0, -1)),
 ((0, 1),
 A 1-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and
\hookrightarrow1 ray,
  (1, -1)),
((0, -1),
 A 1-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and
 (-1, -1)),
 ((1, 0),
 A 1-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and.
\hookrightarrow 1 ray,
  (0, 0)),
 ((1, 1),
 A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and.
\rightarrow2 rays,
  (1, 0)),
 ((1, -1),
 A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and
\rightarrow2 rays,
 (-1, 0)),
 ((-1, 0),
 A 1-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and
\hookrightarrow1 ray,
 (0, -2)),
 ((-1, 1),
 A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and.
\rightarrow2 rays,
 (1, -2)),
((-1, -1),
 A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and.
\rightarrow2 rays,
 (-1, -2))
sage: a = hyperplane_arrangements.braid(3)
sage: a.hyperplanes()
(Hyperplane 0*t0 + t1 - t2 + 0,
Hyperplane t0 - t1 + 0*t2 + 0,
Hyperplane t0 + 0*t1 - t2 + 0)
sage: [(v, F, F.representative_point()) for v, F in a.closed_faces()]
[((0, 0, 0),
 A 1-dimensional polyhedron in QQ^3 defined as the convex hull of 1 vertex and
\rightarrow 1 line.
```

```
(0, 0, 0)),
((0, 1, 1),
 A 2-dimensional polyhedron in QQ^3 defined as the convex hull of 1 vertex, 1
⇒ray, 1 line,
 (0, -1, -1)),
((0, -1, -1),
 A 2-dimensional polyhedron in QQ^3 defined as the convex hull of 1 vertex, 1.
⇒ray, 1 line,
 (-1, 0, 0)),
((1, 0, 1),
 A 2-dimensional polyhedron in QQ^3 defined as the convex hull of 1 vertex, 1
⇒ray, 1 line,
 (1, 1, 0)),
((1, 1, 1),
 A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 1 vertex, 2
⇒rays, 1 line,
 (0, -1, -2)),
((1, -1, 0),
 A 2-dimensional polyhedron in QQ^3 defined as the convex hull of 1 vertex, 1_{\square}
⇒ray, 1 line,
 (-1, 0, -1)),
((1, -1, 1),
 A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 1 vertex, 2.
⇒rays, 1 line,
 (1, 2, 0)),
((1, -1, -1),
 A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 1 vertex, 2.
⇒rays, 1 line,
 (-2, 0, -1)),
((-1, 0, -1),
 A 2-dimensional polyhedron in QQ^3 defined as the convex hull of 1 vertex, 1
→ray, 1 line,
 (0, 0, 1)),
((-1, 1, 0),
 A 2-dimensional polyhedron in QQ^3 defined as the convex hull of 1 vertex, 1
⊸ray, 1 line,
 (1, 0, 1)),
((-1, 1, 1),
 A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 1 vertex, 2
⇒rays, 1 line,
 (0, -2, -1)),
((-1, 1, -1),
 A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 1 vertex, 2.
⇒rays, 1 line,
 (1, 0, 2)),
((-1, -1, -1),
 A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 1 vertex, 2
⊸rays, 1 line,
 (-1, 0, 1))]
```

Let us check that the number of closed faces with a given dimension computed using self. closed\_faces() equals the one computed using face\_vector():

#### cone(variable='t')

Return the cone over the hyperplane arrangement.

# INPUT:

• variable – string; the name of the additional variable

#### **OUTPUT**:

A new hyperplane arrangement. Its equations consist of  $[0, -d, a_1, \dots, a_n]$  for each  $[d, a_1, \dots, a_n]$  in the original arrangement and the equation  $[0, 1, 0, \dots, 0]$ .

**Warning:** While there is an almost-one-to-one correspondence between the hyperplanes of self and those of self.cone(), there is no guarantee that the order in which they appear in self. hyperplanes() will match the order in which their counterparts in self.cone() will appear in self.cone().hyperplanes()!

# **EXAMPLES:**

```
sage: a.<x,y,z> = hyperplane_arrangements.semiorder(3)
sage: b = a.cone()
sage: a.characteristic_polynomial().factor()
x * (x^2 - 6*x + 12)
sage: b.characteristic_polynomial().factor()
(x - 1) * x * (x^2 - 6*x + 12)
sage: a.hyperplanes()
(Hyperplane 0*x + y - z - 1,
Hyperplane 0*x + y - z + 1,
Hyperplane x - y + 0*z - 1,
Hyperplane x - y + 0*z + 1,
Hyperplane x + 0*y - z - 1,
Hyperplane x + 0*y - z + 1
sage: b.hyperplanes()
(Hyperplane -t + 0*x + y - z + 0,
Hyperplane -t + x - y + 0*z + 0,
Hyperplane -t + x + 0*y - z + 0,
Hyperplane t + 0*x + 0*y + 0*z + 0,
Hyperplane t + 0*x + y - z + 0,
Hyperplane t + x - y + 0*z + 0,
Hyperplane t + x + 0*y - z + 0
```

# defining\_polynomial()

Return the defining polynomial of A.

Let  $A = (H_i)_i$  be a hyperplane arrangement in a vector space V corresponding to the null spaces of  $\alpha_{H_i} \in V^*$ . Then the *defining polynomial* of A is given by

$$Q(A) = \prod_{i} \alpha_{H_i} \in S(V^*).$$

#### **EXAMPLES:**

```
sage: H.<x,y,z> = HyperplaneArrangements(QQ)
sage: A = H([2*x + y - z, -x - 2*y + z])
sage: p = A.defining_polynomial(); p
-2*x^2 - 5*x*y - 2*y^2 + 3*x*z + 3*y*z - z^2
sage: p.factor()
(-1) * (x + 2*y - z) * (2*x + y - z)
```

# deletion(hyperplanes)

Return the hyperplane arrangement obtained by removing h.

#### INPUT:

• h – a hyperplane or hyperplane arrangement

#### **OUTPUT:**

A new hyperplane arrangement with the given hyperplane(s) h removed.

#### See also:

restriction()

# **EXAMPLES:**

```
sage: H.<x,y> = HyperplaneArrangements(QQ)
sage: A = H([0,1,0], [1,0,1], [-1,0,1], [0,1,-1], [0,1,1]); A
Arrangement of 5 hyperplanes of dimension 2 and rank 2
sage: A.deletion(x)
Arrangement <y - 1 | y + 1 | x - y | x + y>
sage: h = H([0,1,0], [0,1,1])
sage: A.deletion(h)
Arrangement <y - 1 | y + 1 | x - y>
```

# derivation\_module\_basis(algorithm='singular')

Return a basis for the derivation module of self if one exists, otherwise return None.

# See also:

```
derivation_module_free_chain(), is_free()
```

# INPUT:

- algorithm (default: "singular") can be one of the following:
  - "singular" use Singular's minimal free resolution
  - "BC" use the algorithm given by Barakat and Cuntz in [BC2012] (much slower than using Singular)

#### **OUTPUT**:

A basis for the derivation module (over S, the symmetric space) as vectors of a free module over S.

#### ALGORITHM:

# **Singular**

This gets the reduced syzygy module of the Jacobian ideal of the defining polynomial f of self. It then checks Saito's criterion that the determinant of the basis matrix is a scalar multiple of f. If the basis matrix is not square or it fails Saito's criterion, then we check if the arrangement is free. If it is free, then we fall back to the Barakat-Cuntz algorithm.

# BC

Return the product of the derivation module free chain matrices. See Section 6 of [BC2012].

# **EXAMPLES:**

```
sage: W = WeylGroup(['A',2], prefix='s')
sage: A = W.long_element().inversion_arrangement()
sage: A.derivation_module_basis()
[(a1, a2), (0, a1*a2 + a2^2)]
```

# derivation\_module\_free\_chain()

Return a free chain for the derivation module if one exists, otherwise return None.

## See also:

```
is_free()
```

# **EXAMPLES:**

```
sage: W = WeylGroup(['A',3], prefix='s')
sage: A = W.long_element().inversion_arrangement()
sage: for M in A.derivation_module_free_chain(): print("%s\n"%M)
[1 \quad 0 \quad 0]
[0 1 0]
[ 0 0 a3]
[ 1 0 0]
[ 0 0
       1]
[ 0 a2 0]
  1
      0
          0]
     -1 -1]
  0 a2 -a3]
[0 1 0]
[ 0 0
       1]
[a1 0 0]
[1 \ 0 \ -1]
[a3 -1 0]
[a1 0 a2]
1
                0
                          0]
      a3
                -1
                         -1]
a1 - a2 - a3
```

# dimension()

Return the ambient space dimension of the arrangement.

#### **OUTPUT:**

An integer.

#### **EXAMPLES:**

```
sage: H.<x,y> = HyperplaneArrangements(QQ)
sage: (x | x-1 | x+1).dimension()
2
sage: H(x).dimension()
2
```

# distance\_between\_regions(region1, region2)

Return the number of hyperplanes separating the two regions.

## INPUT:

• region1, region2 – regions of the arrangement or representative points of regions

# **OUTPUT**:

An integer. The number of hyperplanes separating the two regions.

#### **EXAMPLES:**

```
sage: c = hyperplane_arrangements.coordinate(2)
sage: r = c.region_containing_point([-1, -1])
sage: s = c.region_containing_point([1, 1])
sage: c.distance_between_regions(r, s)
2
sage: c.distance_between_regions(s, s)
0
```

# distance\_enumerator(base\_region)

Return the generating function for the number of hyperplanes at given distance.

#### INPUT:

• base\_region – region of arrangement or point in region

# **OUTPUT**:

A polynomial f(x) for which the coefficient of  $x^i$  is the number of hyperplanes of distance i from base\_region, i.e., the number of hyperplanes separated by i hyperplanes from base\_region.

#### **EXAMPLES:**

```
sage: c = hyperplane_arrangements.coordinate(3)
sage: c.distance_enumerator(c.region_containing_point([1,1,1]))
x^3 + 3*x^2 + 3*x + 1
```

# doubly\_indexed\_whitney\_number(i, j, kind=1)

Return the i, j-th doubly-indexed Whitney number.

If kind=1, this number is obtained by adding the Möbius function values mu(x,y) over all x,y in the intersection poset with rank(x) = i and rank(y) = j.

If kind = 2, this number is the number of elements x, y in the intersection poset such that  $x \le y$  with ranks i and j, respectively.

# INPUT:

- i, j integers
- kind (default: 1) 1 or 2

#### **OUTPUT:**

Integer. The (i, j)-th entry of the kind Whitney number.

#### See also:

```
whitney_number(), whitney_data()
```

#### **EXAMPLES:**

```
sage: A = hyperplane_arrangements.Shi(3)
sage: A.doubly_indexed_whitney_number(0, 2)
9
sage: A.whitney_number(2)
9
sage: A.doubly_indexed_whitney_number(1, 2)
-15
```

#### REFERENCES:

• [GZ1983]

#### essentialization()

Return the essentialization of the hyperplane arrangement.

The essentialization of a hyperplane arrangement whose base field has characteristic 0 is obtained by intersecting the hyperplanes by the space spanned by their normal vectors.

# **OUTPUT**:

The essentialization as a new hyperplane arrangement.

# **EXAMPLES:**

```
sage: a = hyperplane_arrangements.braid(3)
sage: a.is_essential()
False
sage: a.essentialization()
Arrangement <t1 - t2 | t1 + 2*t2 | 2*t1 + t2>
sage: H.<x,y> = HyperplaneArrangements(QQ)
sage: B = H([(1,0),1], [(1,0),-1])
sage: B.is_essential()
False
sage: B.essentialization()
Arrangement \langle -x + 1 \mid x + 1 \rangle
sage: B.essentialization().parent()
Hyperplane arrangements in 1-dimensional linear space over
Rational Field with coordinate x
sage: H.<x,y> = HyperplaneArrangements(GF(2))
sage: C = H([(1,1),1], [(1,1),0])
sage: C.essentialization()
Arrangement <y | y + 1>
```

```
sage: h = hyperplane_arrangements.semiorder(4)
sage: h.essentialization()
Arrangement of 12 hyperplanes of dimension 3 and rank 3
```

#### face\_product(F, G, normalize=True)

Return the product FG in the face semigroup of self, where F and G are two closed faces of self.

The face semigroup of a hyperplane arrangement  $\mathcal{A}$  is defined as follows: As a set, it is the set of all open faces of self (see closed\_faces()). Its product is defined by the following rule: If F and G are two open faces of  $\mathcal{A}$ , then FG is an open face of  $\mathcal{A}$ , and for every hyperplane  $H \in \mathcal{A}$ , the open face FG lies on the same side of H as F unless  $F \subseteq H$ , in which case FG lies on the same side of H as G. Alternatively, FG can be defined as follows: If f and g are two points in F and G, respectively, then FG is the face that contains the point  $(f + \varepsilon g)/(1 + \varepsilon)$  for any sufficiently small positive  $\varepsilon$ .

In our implementation, the face semigroup consists of closed faces rather than open faces (thanks to the 1-to-1 correspondence between open faces and closed faces, this is not really a different semigroup); these closed faces are given as polyhedra.

The face semigroup of a hyperplane arrangement is always a left-regular band (i.e., a semigroup satisfying the identities  $x^2 = x$  and xyx = xy). When the arrangement is central, then this semigroup is a monoid. See [Br2000] (Appendix A in particular) for further properties.

#### INPUT:

- F, G two faces of self (as polyhedra)
- normalize Boolean (default: True); if True, then this method returns the precise instance of FG in the list returned by self.closed\_faces(), rather than creating a new instance

# **EXAMPLES:**

```
sage: a = hyperplane_arrangements.braid(3)
sage: a.hyperplanes()
(Hyperplane 0*t0 + t1 - t2 + 0,
Hyperplane t0 - t1 + 0*t2 + 0,
Hyperplane t0 + 0*t1 - t2 + 0)
sage: faces = {F0: F1 for F0, F1 in a.closed_faces()}
sage: xGyEz = faces[(0, 1, 1)] # closed face x >= y = z
sage: xGyEz.representative_point()
(0, -1, -1)
sage: xGyEz = faces[(0, 1, 1)] # closed face x >= y = z
sage: xGyEz.representative_point()
(0, -1, -1)
sage: yGxGz = faces[(1, -1, 1)] \# closed face y >= x >= z
sage: xGyGz = faces[(1, 1, 1)] \# closed face x >= y >= z
sage: a.face_product(xGyEz, yGxGz) == xGyGz
True
sage: a.face_product(yGxGz, xGyEz) == yGxGz
True
sage: xEzGy = faces[(-1, 1, 0)] \# closed face x = z >= y
sage: xGzGy = faces[(-1, 1, 1)] \# closed face x >= z >= y
sage: a.face_product(xEzGy, yGxGz) == xGzGy
True
```

## face\_semigroup\_algebra(field=None, names='e')

Return the face semigroup algebra of self.

This is the semigroup algebra of the face semigroup of self (see face\_product() for the definition of the semigroup).

Due to limitations of the current Sage codebase (e.g., semigroup algebras do not profit from the functionality of the FiniteDimensionalAlgebra class), this is implemented not as a semigroup algebra, but as a FiniteDimensionalAlgebra. The closed faces of self (in the order in which the  $closed\_faces()$  method outputs them) are identified with the vectors  $(0,0,\ldots,0,1,0,0,\ldots,0)$  (with the 1 moving from left to right).

# INPUT:

- field a field (default: **Q**), to be used as the base ring for the algebra (can also be a commutative ring, but then certain representation-theoretical methods might misbehave)
- names (default: 'e') string; names for the basis elements of the algebra

**Todo:** Also implement it as an actual semigroup algebra?

#### **EXAMPLES:**

```
sage: a = hyperplane_arrangements.braid(3)
sage: [(i, F[0]) for i, F in enumerate(a.closed_faces())]
[(0, (0, 0, 0)),
 (1, (0, 1, 1)),
 (2, (0, -1, -1)),
 (3, (1, 0, 1)),
 (4, (1, 1, 1)),
 (5, (1, -1, 0)),
 (6, (1, -1, 1)),
 (7, (1, -1, -1)),
 (8, (-1, 0, -1)),
 (9, (-1, 1, 0)),
 (10, (-1, 1, 1)),
(11, (-1, 1, -1)),
(12, (-1, -1, -1))]
sage: U = a.face_semigroup_algebra(); U
Finite-dimensional algebra of degree 13 over Rational Field
sage: e0, e1, e2, e3, e4, e5, e6, e7, e8, e9, e10, e11, e12 = U.basis()
sage: e0 * e1
e1
sage: e0 * e5
sage: e5 * e0
sage: e3 * e2
sage: e7 * e12
e7
sage: e3 * e12
e6
sage: e4 * e8
e4
```

```
sage: e8 * e4
e11
sage: e8 * e1
e11
sage: e5 * e12
e7
sage: (e3 + 2*e4) * (e1 - e7)
e4 - e6

sage: U3 = a.face_semigroup_algebra(field=GF(3)); U3
Finite-dimensional algebra of degree 13 over Finite Field of size 3
```

#### face\_vector()

Return the face vector.

**OUTPUT:** 

A vector of integers.

The d-th entry is the number of faces of dimension d. A face is the intersection of a region with a hyperplane of the arrangement.

**EXAMPLES:** 

```
sage: A = hyperplane_arrangements.Shi(3)
sage: A.face_vector()
(0, 6, 21, 16)
```

# has\_good\_reduction(p)

Return whether the hyperplane arrangement has good reduction mod p.

Let A be a hyperplane arrangement with equations defined over the integers, and let B be the hyperplane arrangement defined by reducing these equations modulo a prime p. Then A has good reduction modulo p if the intersection posets of A and B are isomorphic.

# INPUT:

• p – prime number

# **OUTPUT**:

A boolean.

# **EXAMPLES:**

```
sage: a = hyperplane_arrangements.semiorder(3)
sage: a.has_good_reduction(5)
True
sage: a.has_good_reduction(3)
False
sage: b = a.change_ring(GF(3))
sage: a.characteristic_polynomial()
x^3 - 6*x^2 + 12*x
sage: b.characteristic_polynomial() # not equal to that for a
x^3 - 6*x^2 + 10*x
```

# hyperplanes()

Return the hyperplanes in the arrangement as a tuple.

#### **OUTPUT**:

An integer.

# **EXAMPLES:**

```
sage: H.<x,y> = HyperplaneArrangements(QQ)
sage: A = H([1,1,0], [2,3,-1], [4,5,3])
sage: A.hyperplanes()
(Hyperplane x + 0*y + 1, Hyperplane 3*x - y + 2, Hyperplane 5*x + 3*y + 4)
```

Note that the hyperplanes can be indexed as if they were a list:

```
sage: A[0]
Hyperplane x + 0*y + 1
```

# intersection\_poset(element\_label='int')

Return the intersection poset of the hyperplane arrangement.

#### INPUT:

- element\_label (default: "int") specify how an intersection should be represented; must be one of the following:
  - "subspace" as a subspace
  - "subset" as a subset of the defining hyperplanes
  - "int" as an integer

# **OUTPUT**:

The poset of non-empty intersections of hyperplanes, with intersections represented by integers, subsets of integers or subspaces (see the examples for more details).

# **EXAMPLES:**

By default, the elements of the poset are the integers from 0 through the cardinality of the poset *minus one*. The element labelled 0 always corresponds to the ambient vector space, and the hyperplanes themselves are labelled  $1, 2, \ldots, n$ , where n is the number of hyperplanes of the arrangement.

```
sage: A = hyperplane_arrangements.coordinate(2)
sage: L = A.intersection_poset(); L
Finite poset containing 4 elements
sage: sorted(L)
[0, 1, 2, 3]
sage: L.level_sets()
[[0], [1, 2], [3]]
```

```
sage: A = hyperplane_arrangements.semiorder(3)
sage: L = A.intersection_poset(); L
Finite poset containing 19 elements
sage: sorted(L)
[0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18]
sage: [sorted(level_set) for level_set in L.level_sets()]
[[0], [1, 2, 3, 4, 5, 6], [7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18]]
```

By passing the argument element\_label="subset", each element of the intesection poset is labelled by the set of indices of the hyperplanes whose intersection is said element. The index of a hyperplane is its index in self.hyperplanes().

```
sage: H.<x,y> = HyperplaneArrangements(QQ)
sage: A = H((y , (y-1) , (y+1) , (x - y) , (x + y)))
sage: L = A.intersection_poset(element_label='subset')
sage: sorted(L, key=sorted)
[{}, {0}, {0, 3}, {0, 4}, {1}, {1, 3, 4}, {2}, {2, 3}, {2, 4}, {3}, {4}]
```

One can instead use affine subspaces as elements, which is what is used to compute the poset in the first place:

```
sage: A = hyperplane_arrangements.coordinate(2)
sage: L = A.intersection_poset(element_label='subspace'); L
Finite poset containing 4 elements
sage: sorted(L, key=lambda S: (S.dimension(), S.linear_part().basis_matrix()))
[Affine space p + W where:
  p = (0, 0)
  W = Vector space of degree 2 and dimension 0 over Rational Field
Basis matrix:
 [], Affine space p + W where:
  p = (0, 0)
  W = Vector space of degree 2 and dimension 1 over Rational Field
Basis matrix:
 [0 1], Affine space p + W where:
  p = (0, 0)
  W = Vector space of degree 2 and dimension 1 over Rational Field
Basis matrix:
 [1 0], Affine space p + W where:
  p = (0, 0)
   W = Vector space of dimension 2 over Rational Field]
```

#### is\_central(certificate=False)

Test whether the intersection of all the hyperplanes is nonempty.

A hyperplane arrangement is central if the intersection of all the hyperplanes in the arrangement is nonempty.

#### INPUT:

• certificate – boolean (default: False); specifies whether to return the center as a polyhedron (possibly empty) as part of the output

# **OUTPUT**:

If certificate is True, returns a tuple containing:

- 1. A boolean
- 2. The polyhedron defined to be the intersection of all the hyperplanes

If certificate is False, returns a boolean.

#### **EXAMPLES:**

```
sage: a = hyperplane_arrangements.braid(2)
sage: a.is_central()
True
```

The Catalan arrangement in dimension 3 is not central:

```
sage: b = hyperplane_arrangements.Catalan(3)
sage: b.is_central(certificate=True)
(False, The empty polyhedron in QQ^3)
```

The empty arrangement in dimension 5 is central:

```
sage: H = HyperplaneArrangements(QQ,names=tuple(['x'+str(i) for i in range(7)]))
sage: c = H()
sage: c.is_central(certificate=True)
(True, A 7-dimensional polyhedron in QQ^7 defined as the convex
hull of 1 vertex and 7 lines)
```

#### is\_essential()

Test whether the hyperplane arrangement is essential.

A hyperplane arrangement is essential if the span of the normals of its hyperplanes spans the ambient space.

#### See also:

```
essentialization()
```

# **OUTPUT**:

A boolean indicating whether the hyperplane arrangement is essential.

#### **EXAMPLES:**

```
sage: H.<x,y> = HyperplaneArrangements(QQ)
sage: H(x, x+1).is_essential()
False
sage: H(x, y).is_essential()
True
```

# is\_formal()

Return if self is formal.

A hyperplane arrangement is *formal* if it is 3-generated [Yuz1993], where k-generated is defined in  $minimal\_generated\_number()$ .

# **EXAMPLES:**

# is\_free(algorithm='singular')

Return if self is free.

A hyperplane arrangement A is free if the module of derivations Der(A) is a free S-module, where S is the corresponding symmetric space.

# INPUT:

- algorithm (default: "singular") can be one of the following:
  - "singular" use Singular's minimal free resolution
  - "BC" use the algorithm given by Barakat and Cuntz in [BC2012] (much slower than using Singular)

#### ALGORITHM:

# singular

Check that the minimal free resolution has length at most 2 by using Singular.

#### BC

This implementation follows [BC2012] by constructing a chain of free modules

$$D(A) = D(A_n) < D(A_{n-1}) < \cdots < D(A_1) < D(A_0)$$

corresponding to some ordering of the arrangements  $A_0 \subset A_1 \subset \cdots \subset A_{n-1} \subset A_n = A$ . Such a chain is found by using a backtracking algorithm.

#### **EXAMPLES:**

For type A arrangements, chordality is equivalent to freeness. We verify that in type  $A_3$ :

```
sage: W = WeylGroup(['A',3], prefix='s')
sage: for x in W:
...: A = x.inversion_arrangement()
...: assert A.matroid().is_chordal() == A.is_free()
```

#### is\_linear()

Test whether all hyperplanes pass through the origin.

#### **OUTPUT:**

A boolean. Whether all the hyperplanes pass through the origin.

# **EXAMPLES:**

```
sage: a = hyperplane_arrangements.semiorder(3)
sage: a.is_linear()
False
sage: b = hyperplane_arrangements.braid(3)
sage: b.is_linear()
True

sage: H.<x,y> = HyperplaneArrangements(QQ)
sage: c = H(x+1, y+1)
sage: c.is_linear()
```

```
False
sage: c.is_central()
True
```

# is\_separating\_hyperplane(region1, region2, hyperplane)

Test whether the hyperplane separates the given regions.

# INPUT:

- region1, region2 polyhedra or list/tuple/iterable of coordinates which are regions of the arrangement or an interior point of a region
- hyperplane a hyperplane

# **OUTPUT**:

A boolean. Whether the hyperplane hyperplane separate the given regions.

#### **EXAMPLES:**

```
sage: A.<x,y> = hyperplane_arrangements.coordinate(2)
sage: A.is_separating_hyperplane([1,1], [2,1], y)
False
sage: A.is_separating_hyperplane([1,1], [-1,1], x)
True
sage: r = A.region_containing_point([1,1])
sage: s = A.region_containing_point([-1,1])
sage: A.is_separating_hyperplane(r, s, x)
True
```

# is\_simplicial()

Test whether the arrangement is simplicial.

A region is simplicial if the normal vectors of its bounding hyperplanes are linearly independent. A hyperplane arrangement is said to be simplicial if every region is simplicial.

# **OUTPUT**:

A boolean whether the hyperplane arrangement is simplicial.

# **EXAMPLES:**

```
sage: H.<x,y,z> = HyperplaneArrangements(QQ)
sage: A = H([[0,1,1,1],[0,1,2,3]])
sage: A.is_simplicial()
True
sage: A = H([[0,1,1,1],[0,1,2,3],[0,1,3,2]])
sage: A.is_simplicial()
True
sage: A = H([[0,1,1,1],[0,1,2,3],[0,1,3,2],[0,2,1,3]])
sage: A.is_simplicial()
False
sage: hyperplane_arrangements.braid(3).is_simplicial()
True
```

# matroid()

Return the matroid associated to self.

Let A denote a central hyperplane arrangement and  $n_H$  the normal vector of some hyperplane  $H \in A$ . We define a matroid  $M_A$  as the linear matroid spanned by  $\{n_H|H \in A\}$ . The matroid  $M_A$  is such that the lattice of flats of M is isomorphic to the intersection lattice of A (Proposition 3.6 in [Sta2007]).

# **EXAMPLES:**

```
sage: P.<x,y,z> = HyperplaneArrangements(QQ)
sage: A = P(x, y, z, x+y+z, 2*x+y+z, 2*x+3*y+z, 2*x+3*y+4*z)
sage: M = A.matroid(); M
Linear matroid of rank 3 on 7 elements represented over the Rational Field
```

We check the lattice of flats is isomorphic to the intersection lattice:

```
sage: f = sum([list(M.flats(i)) for i in range(M.rank()+1)], [])
sage: PF = Poset([f, lambda x,y: x < y])
sage: PF.is_isomorphic(A.intersection_poset())
True</pre>
```

# minimal\_generated\_number()

Return the minimum k such that self is k-generated.

Let A be a central hyperplane arrangement. Let  $W_k$  denote the solution space of the linear system corresponding to the linear dependencies among the hyperplanes of A of length at most k. We say A is k-generated if  $\dim W_k = \operatorname{rank} A$ .

Equivalently this says all dependencies forming the Orlik-Terao ideal are generated by at most k hyperplanes.

#### **EXAMPLES:**

We construct Example 2.2 from [Yuz1993]:

#### n\_bounded\_regions()

Return the number of (relatively) bounded regions.

#### OUTPUT

An integer. The number of relatively bounded regions of the hyperplane arrangement.

#### **EXAMPLES:**

```
sage: A = hyperplane_arrangements.semiorder(3)
sage: A.n_bounded_regions()
7
```

# n\_hyperplanes()

Return the number of hyperplanes in the arrangement.

# **OUTPUT**:

An integer.

# **EXAMPLES:**

```
sage: H.<x,y> = HyperplaneArrangements(QQ)
sage: A = H([1,1,0], [2,3,-1], [4,5,3])
sage: A.n_hyperplanes()
3
sage: len(A) # equivalent
3
```

#### n\_regions()

The number of regions of the hyperplane arrangement.

#### **OUTPUT**:

An integer.

# **EXAMPLES:**

```
sage: A = hyperplane_arrangements.semiorder(3)
sage: A.n_regions()
19
```

# orlik\_solomon\_algebra(base\_ring=None, ordering=None, \*\*kwds)

Return the Orlik-Solomon algebra of self.

#### INPUT:

- base\_ring (default: the base field of self) the ring over which the Orlik-Solomon algebra will be defined
- ordering (optional) an ordering of the ground set

# **EXAMPLES:**

```
sage: P.<x,y,z> = HyperplaneArrangements(QQ)
sage: A = P(x, y, z, x+y+z, 2*x+y+z, 2*x+3*y+z, 2*x+3*y+4*z)
sage: A.orlik_solomon_algebra()
Orlik-Solomon algebra of Linear matroid of rank 3 on 7 elements
represented over the Rational Field
sage: A.orlik_solomon_algebra(base_ring=ZZ)
Orlik-Solomon algebra of Linear matroid of rank 3 on 7 elements
represented over the Rational Field
```

# orlik\_terao\_algebra(base\_ring=None, ordering=None, \*\*kwds)

Return the Orlik-Terao algebra of self.

# INPUT:

- base\_ring (default: the base field of self) the ring over which the Orlik-Terao algebra will be defined
- ordering (optional) an ordering of the ground set

# **EXAMPLES:**

```
sage: P.<x,y,z> = HyperplaneArrangements(QQ)
sage: A = P(x, y, z, x+y+z, 2*x+y+z, 2*x+3*y+z, 2*x+3*y+4*z)
sage: A.orlik_terao_algebra()
Orlik-Terao algebra of Linear matroid of rank 3 on 7 elements
```

```
represented over the Rational Field over Rational Field

sage: A.orlik_terao_algebra(base_ring=QQ['t'])

Orlik-Terao algebra of Linear matroid of rank 3 on 7 elements

represented over the Rational Field

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

# plot(\*\*kwds)

Plot the hyperplane arrangement.

**OUTPUT:** 

A graphics object.

**EXAMPLES:** 

```
sage: L.<x, y> = HyperplaneArrangements(QQ)
sage: L(x, y, x+y-2).plot() # optional - sage.plot
Graphics object consisting of 3 graphics primitives
```

## poincare\_polynomial()

Return the Poincaré polynomial of the hyperplane arrangement.

OUTPUT:

The Poincaré polynomial in  $\mathbf{Q}[x]$ .

**EXAMPLES:** 

```
sage: a = hyperplane_arrangements.coordinate(2)
sage: a.poincare_polynomial()
x^2 + 2*x + 1
```

# poset\_of\_regions(B=None, numbered\_labels=True)

Return the poset of regions for a central hyperplane arrangement.

The poset of regions is a partial order on the set of regions where the regions are ordered by  $R \leq R'$  if and only if  $S(R) \subseteq S(R')$  where S(R) is the set of hyperplanes which separate the region R from the base region R.

# INPUT:

- B a region (optional; default: None); if None, then an arbitrary region is chosen as the base region.
- numbered\_labels bool (optional; default: True); if True, then the elements of the poset are numbered. Else they are labelled with the regions themselves.

#### **OUTPUT**:

A Poset object containing the poset of regions.

**EXAMPLES:** 

```
sage: H.<x,y,z> = HyperplaneArrangements(QQ)
sage: A = H([[0,1,1,1],[0,1,2,3]])
sage: A.poset_of_regions()
Finite poset containing 4 elements

sage: A = hyperplane_arrangements.braid(3)
sage: A.poset_of_regions()
```

```
Finite poset containing 6 elements
sage: A.poset_of_regions(numbered_labels=False)
Finite poset containing 6 elements
sage: A = hyperplane_arrangements.braid(4)
sage: A.poset_of_regions()
Finite poset containing 24 elements

sage: H.<x,y,z> = HyperplaneArrangements(QQ)
sage: A = H([[0,1,1,1],[0,1,2,3],[0,1,3,2],[0,2,1,3]])
sage: R = A.regions()
sage: base_region = R[3]
sage: A.poset_of_regions(B=base_region)
Finite poset containing 14 elements
```

#### rank()

Return the rank.

#### **OUTPUT**:

The dimension of the span of the normals to the hyperplanes in the arrangement.

## **EXAMPLES:**

```
sage: H.<x,y,z> = HyperplaneArrangements(QQ)
sage: A = H([[0, 1, 2, 3],[-3, 4, 5, 6]])
sage: A.dimension()
3
sage: A.rank()
2

sage: B = hyperplane_arrangements.braid(3)
sage: B.hyperplanes()
(Hyperplane 0*t0 + t1 - t2 + 0,
Hyperplane t0 - t1 + 0*t2 + 0,
Hyperplane t0 + 0*t1 - t2 + 0)
sage: B.dimension()
3
sage: B.rank()
2

sage: p = polytopes.simplex(5, project=True)
sage: H = p.hyperplane_arrangement()
sage: H.rank()
5
```

# region\_containing\_point(p)

The region in the hyperplane arrangement containing a given point.

The base field must have characteristic zero.

# INPUT:

• p - point

# **OUTPUT**:

A polyhedron. A ValueError is raised if the point is not interior to a region, that is, sits on a hyperplane.

#### **EXAMPLES:**

```
sage: H.<x,y> = HyperplaneArrangements(QQ)
sage: A = H([(1,0), 0], [(0,1), 1], [(0,1), -1], [(1,-1), 0], [(1,1), 0])
sage: A.region_containing_point([1,2])
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 2 vertices and_
\rightarrow2 rays
```

# regions()

Return the regions of the hyperplane arrangement.

The base field must have characteristic zero.

# **OUTPUT**:

A tuple containing the regions as polyhedra.

The regions are the connected components of the complement of the union of the hyperplanes as a subset of  $\mathbb{R}^n$ .

# **EXAMPLES:**

```
sage: a = hyperplane_arrangements.braid(2)
sage: a.regions()
(A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex, 1
→ray, 1 line,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex, 1
→ray, 1 line)
sage: H.<x,y> = HyperplaneArrangements(QQ)
sage: A = H(x, y+1)
sage: A.regions()
(A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and.
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and.
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and.
\rightarrow2 ravs.
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and
\rightarrow2 rays)
sage: chessboard = []
sage: N = 8
sage: for x0 in range(N+1):
. . . . :
          for y0 in range(N+1):
              chessboard.extend([x-x0, y-y0])
sage: chessboard = H(chessboard)
sage: len(chessboard.bounded_regions()) # long time, 359 ms on a Core i7
64
```

# Example 6 of [KP2020]:

```
sage: from itertools import product
sage: def zero_one(d):
....:    for x in product([0,1], repeat=d):
....:        if any(y for y in x):
```

```
. . . . :
                   yield [0] + list(x)
. . . . :
sage: K.<x,y> = HyperplaneArrangements(QQ)
sage: A = K(*zero_one(2))
sage: len(A.regions())
sage: K.<x,y,z> = HyperplaneArrangements(QQ)
sage: A = K(*zero_one(3))
sage: len(A.regions())
sage: K.<x,y,z,w> = HyperplaneArrangements(QQ)
sage: A = K(*zero\_one(4))
sage: len(A.regions())
370
sage: K.\langle x,y,z,w,r\rangle = HyperplaneArrangements(QQ)
sage: A = K(*zero_one(5))
sage: len(A.regions())
                                    # not tested (~25s)
11292
```

It is possible to specify the backend:

```
sage: K.<q> = CyclotomicField(9)
sage: L.\langle r9 \rangle = NumberField((q+q**(-1)).minpoly(),embedding = AA(q+q**-1))
sage: norms = [[1,1/3*(-2*r9**2-r9+1),0],
              [1, -r9**2-r9, 0],
....
               [1, -r9**2+1, 0],
                [1, -r9**2, 0],
. . . . . .
                [1,r9**2-4,-r9**2+3]]
sage: H.\langle x,y,z\rangle = HyperplaneArrangements(L)
sage: A = H(backend='normaliz')
sage: for v in norms:
. . . . . . .
          a,b,c = v
          A = A.add_hyperplane(a*x + b*y + c*z)
sage: R = A.regions()
                                       # optional - pynormaliz
sage: R[0].backend()
                                       # optional - pynormaliz
'normaliz'
```

#### restriction(hyperplane)

Return the restriction to a hyperplane.

## INPUT:

• hyperplane – a hyperplane of the hyperplane arrangement

# OUTPUT:

The restriction of the hyperplane arrangement to the given hyperplane.

## **EXAMPLES:**

```
sage: A.<u,x,y,z> = hyperplane_arrangements.braid(4); A
Arrangement of 6 hyperplanes of dimension 4 and rank 3
sage: H = A[0]; H
Hyperplane 0*u + 0*x + y - z + 0
sage: R = A.restriction(H); R
```

```
Arrangement <x - z | u - x | u - z>
sage: D = A.deletion(H); D
Arrangement of 5 hyperplanes of dimension 4 and rank 3
sage: ca = A.characteristic_polynomial()
sage: cr = R.characteristic_polynomial()
sage: cd = D.characteristic_polynomial()
sage: ca
x^4 - 6*x^3 + 11*x^2 - 6*x
sage: cd - cr
x^4 - 6*x^3 + 11*x^2 - 6*x
```

#### See also:

deletion()

## sign\_vector(p)

Indicates on which side of each hyperplane the given point p lies.

The base field must have characteristic zero.

#### INPUT:

• p – point as a list/tuple/iterable

#### **OUTPUT**:

A vector whose entries are in [-1, 0, +1].

#### **EXAMPLES:**

```
sage: H.<x,y> = HyperplaneArrangements(QQ)
sage: A = H([(1,0), 0], [(0,1), 1]); A
Arrangement <y + 1 | x>
sage: A.sign_vector([2, -2])
(-1, 1)
sage: A.sign_vector((-1, -1))
(0, -1)
```

## unbounded\_regions()

Return the relatively bounded regions of the arrangement.

## **OUTPUT**:

Tuple of polyhedra. The regions of the arrangement that are not relatively bounded. It is assumed that the arrangement is defined over the rationals.

## See also:

bounded\_regions()

#### **EXAMPLES:**

```
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 3 vertices and 1 ray,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and 2 rays,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 3 vertices and 1 ray,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and 2 rays,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 3 vertices and 1 ray,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and 2 rays,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 3 vertices and 1 ray,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 3 vertices and 1 ray,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and 2 rays,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 3 vertices and 1 ray,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and 2 rays,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and 2 rays,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and 2 rays,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and 2 rays,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and 2 rays,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and 2 rays,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and 2 rays,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and 2 rays,
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and 2 rays,
```

#### union(other)

The union of self with other.

## INPUT:

• other – a hyperplane arrangement or something that can be converted into a hyperplane arrangement OUTPUT:

A new hyperplane arrangement.

## **EXAMPLES:**

```
sage: H.<x,y> = HyperplaneArrangements(QQ)
sage: A = H([1,2,3], [0,1,1], [0,1,-1], [1,-1,0], [1,1,0])
sage: B = H([1,1,1], [1,-1,1], [1,0,-1])
sage: A.union(B)
Arrangement of 8 hyperplanes of dimension 2 and rank 2
sage: A | B # syntactic sugar
Arrangement of 8 hyperplanes of dimension 2 and rank 2
```

A single hyperplane is coerced into a hyperplane arrangement if necessary:

```
sage: A.union(x+y-1)
Arrangement of 6 hyperplanes of dimension 2 and rank 2
sage: A.add_hyperplane(x+y-1) # alias
Arrangement of 6 hyperplanes of dimension 2 and rank 2

sage: P.<x,y> = HyperplaneArrangements(RR)
sage: C = P(2*x + 4*y + 5)
sage: C.union(A)
Arrangement of 6 hyperplanes of dimension 2 and rank 2
```

#### varchenko\_matrix(names='h')

Return the Varchenko matrix of the arrangement.

Let  $H_1, \ldots, H_s$  and  $R_1, \ldots, R_t$  denote the hyperplanes and regions, respectively, of the arrangement. Let  $S = \mathbf{Q}[h_1, \ldots, h_s]$ , a polynomial ring with indeterminate  $h_i$  corresponding to hyperplane  $H_i$ . The Varchenko matrix is the  $t \times t$  matrix with i, j-th entry the product of those  $h_k$  such that  $H_k$  separates  $R_i$  and  $R_j$ .

## INPUT:

• names – string or list/tuple/iterable of strings. The variable names for the polynomial ring S.

#### **OUTPUT**:

The Varchenko matrix.

#### **EXAMPLES:**

## vertices(exclude\_sandwiched=False)

Return the vertices.

The vertices are the zero-dimensional faces, see face\_vector().

## INPUT:

• exclude\_sandwiched – boolean (default: False). Whether to exclude hyperplanes that are sandwiched between parallel hyperplanes. Useful if you only need the convex hull.

## **OUTPUT**:

The vertices in a sorted tuple. Each vertex is returned as a vector in the ambient vector space.

#### **EXAMPLES:**

```
sage: A = hyperplane_arrangements.Shi(3).essentialization()
sage: A.dimension()
sage: A.face_vector()
(6, 21, 16)
sage: A.vertices()
((-2/3, 1/3), (-1/3, -1/3), (0, -1), (0, 0), (1/3, -2/3), (2/3, -1/3))
sage: point2d(A.vertices(), size=20) + A.plot() # optional - sage.plot
Graphics object consisting of 7 graphics primitives
sage: H.\langle x,y\rangle = HyperplaneArrangements(QQ)
sage: chessboard = []
sage: N = 8
sage: for x0 in range(N+1):
          for y0 in range(N+1):
. . . . .
              chessboard.extend([x-x0, y-y0])
sage: chessboard = H(chessboard)
```

```
sage: len(chessboard.vertices())
81
sage: chessboard.vertices(exclude_sandwiched=True)
((0, 0), (0, 8), (8, 0), (8, 8))
```

# whitney\_data()

Return the Whitney numbers.

#### See also:

whitney\_number(), doubly\_indexed\_whitney\_number()

#### **OUTPUT**:

A pair of integer matrices. The two matrices are the doubly-indexed Whitney numbers of the first or second kind, respectively. The i, j-th entry is the i, j-th doubly-indexed Whitney number.

#### **EXAMPLES:**

```
sage: A = hyperplane_arrangements.Shi(3)
sage: A.whitney_data()
(
[ 1 -6 9] [ 1 6 6]
[ 0 6 -15] [ 0 6 15]
[ 0 0 6], [ 0 0 6]
)
```

## whitney\_number(k, kind=1)

Return the k-th Whitney number.

If kind=1, this number is obtained by summing the Möbius function values mu(0, x) over all x in the intersection poset with rank(x) = k.

If kind=2, this number is the number of elements x, y in the intersection poset such that  $x \le y$  with ranks i and j, respectively.

See [GZ1983] for more details.

## INPUT:

- k integer
- kind 1 or 2 (default: 1)

## **OUTPUT**:

Integer. The k-th Whitney number.

#### See also:

doubly\_indexed\_whitney\_number() whitney\_data()

# **EXAMPLES:**

```
sage: A = hyperplane_arrangements.Shi(3)
sage: A.whitney_number(0)
1
sage: A.whitney_number(1)
-6
sage: A.whitney_number(2)
```

```
sage: A.characteristic_polynomial()
x^3 - 6*x^2 + 9*x
sage: A.whitney_number(1,kind=2)
6
sage: p = A.intersection_poset()
sage: r = p.rank_function()
sage: len([i for i in p if r(i) == 1])
6
```

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

Hyperplane arrangements.

For more information on hyperplane arrangements, see sage.geometry.hyperplane\_arrangement.

#### INPUT:

- base\_ring ring; the base ring
- names tuple of strings; the variable names

## **EXAMPLES:**

```
sage: H.<x,y> = HyperplaneArrangements(QQ)
sage: x
Hyperplane x + 0*y + 0
sage: x + y
Hyperplane x + y + 0
sage: H(x, y, x-1, y-1)
Arrangement <y - 1 | y | x - 1 | x>
```

### **Element**

alias of HyperplaneArrangementElement

## ambient\_space()

Return the ambient space.

The ambient space is the parent of hyperplanes. That is, new hyperplanes are always constructed internally from the ambient space instance.

## **EXAMPLES:**

```
sage: L.<x, y> = HyperplaneArrangements(QQ)
sage: L.ambient_space()([(1,0), 0])
Hyperplane x + 0*y + 0
sage: L.ambient_space()([(1,0), 0]) == x
True
```

#### base\_ring()

Return the base ring.

## **OUTPUT**:

The base ring of the hyperplane arrangement.

## **EXAMPLES:**

```
sage: L.<x,y> = HyperplaneArrangements(QQ)
sage: L.base_ring()
Rational Field
```

# change\_ring(base\_ring)

Return hyperplane arrangements over a different base ring.

#### INPUT:

• base\_ring – a ring; the new base ring.

#### **OUTPUT**:

A new HyperplaneArrangements instance over the new base ring.

#### **EXAMPLES:**

## gen(i)

Return the *i*-th coordinate hyperplane.

## INPUT:

• i – integer

#### **OUTPUT:**

A linear expression.

# **EXAMPLES:**

## gens()

Return the coordinate hyperplanes.

## **OUTPUT**:

A tuple of linear expressions, one for each linear variable.

#### **EXAMPLES:**

```
sage: L = HyperplaneArrangements(QQ, ('x', 'y', 'z'))
sage: L.gens()
(Hyperplane x + 0*y + 0*z + 0,
Hyperplane 0*x + y + 0*z + 0,
Hyperplane 0*x + 0*y + z + 0)
```

## ngens()

Return the number of linear variables.

#### **OUTPUT**:

An integer.

**EXAMPLES:** 

# 1.2 Library of Hyperplane Arrangements

A collection of useful or interesting hyperplane arrangements. See <u>sage.geometry.hyperplane\_arrangement.</u> arrangement for details about how to construct your own hyperplane arrangements.

The library of hyperplane arrangements.

Catalan(n, K=Rational Field, names=None)

Return the Catalan arrangement.

INPUT:

- n integer
- K field (default: **Q**)
- names tuple of strings or None (default); the variable names for the ambient space

**OUTPUT** 

The arrangement of 3n(n-1)/2 hyperplanes  $\{x_i - x_j = -1, 0, 1 : 1 \le i \le j \le n\}$ .

**EXAMPLES:** 

```
sage: hyperplane_arrangements.Catalan(5)
Arrangement of 30 hyperplanes of dimension 5 and rank 4
```

## **G\_Shi**(*G*, *K*=*Rational Field*, *names*=*None*)

Return the Shi hyperplane arrangement of a graph G.

INPUT:

- **G** graph
- K field (default: **Q**)
- names tuple of strings or None (default); the variable names for the ambient space

**OUTPUT**:

The Shi hyperplane arrangement of the given graph G.

**EXAMPLES:** 

```
sage: G = graphs.CompleteGraph(5)
sage: hyperplane_arrangements.G_Shi(G)
Arrangement of 20 hyperplanes of dimension 5 and rank 4
sage: g = graphs.HouseGraph()
sage: hyperplane_arrangements.G_Shi(g)
Arrangement of 12 hyperplanes of dimension 5 and rank 4
sage: a = hyperplane_arrangements.G_Shi(graphs.WheelGraph(4)); a
Arrangement of 12 hyperplanes of dimension 4 and rank 3
```

## **G\_semiorder**(*G*, *K*=*Rational Field*, *names*=*None*)

Return the semiorder hyperplane arrangement of a graph.

## INPUT:

- G graph
- $K field (default: \mathbf{Q})$
- names tuple of strings or None (default); the variable names for the ambient space

#### **OUTPUT**:

The semiorder hyperplane arrangement of a graph G is the arrangement  $\{x_i - x_j = -1, 1\}$  where ij is an edge of G.

#### **EXAMPLES:**

```
sage: G = graphs.CompleteGraph(5)
sage: hyperplane_arrangements.G_semiorder(G)
Arrangement of 20 hyperplanes of dimension 5 and rank 4
sage: g = graphs.HouseGraph()
sage: hyperplane_arrangements.G_semiorder(g)
Arrangement of 12 hyperplanes of dimension 5 and rank 4
```

## **Ish**(*n*, *K*=*Rational Field*, *names*=*None*)

Return the Ish arrangement.

## INPUT:

- n integer
- K field (default:QQ)
- names tuple of strings or None (default); the variable names for the ambient space

## **OUTPUT**:

The Ish arrangement, which is the set of n(n-1) hyperplanes.

$${x_i - x_j = 0 : 1 \le i \le j \le n} \cup {x_1 - x_j = i : 1 \le i \le j \le n}.$$

## **EXAMPLES:**

```
sage: a = hyperplane_arrangements.Ish(3); a
Arrangement of 6 hyperplanes of dimension 3 and rank 2
sage: a.characteristic_polynomial()
x^3 - 6*x^2 + 9*x
sage: b = hyperplane_arrangements.Shi(3)
sage: b.characteristic_polynomial()
x^3 - 6*x^2 + 9*x
```

#### **REFERENCES:**

• [AR2012]

**Shi** (*data*, *K=Rational Field*, *names=None*, *m=1*)

Return the Shi arrangement.

#### INPUT:

- data either an integer or a Cartan type (or coercible into; see "CartanType")
- K field (default:QQ)
- names tuple of strings or None (default); the variable names for the ambient space
- m integer (default: 1)

#### **OUTPUT**:

- If data is an integer n, return the Shi arrangement in dimension n, i.e. the set of n(n-1) hyperplanes:  $\{x_i x_j = 0, 1 : 1 \le i \le j \le n\}$ . This corresponds to the Shi arrangement of Cartan type  $A_{n-1}$ .
- If data is a Cartan type, return the Shi arrangement of given type.
- If m > 1, return the m-extended Shi arrangement of given type.

The m-extended Shi arrangement of a given crystallographic Cartan type is defined by the inner product  $\langle a, x \rangle = k$  for  $-m < k \le m$  and  $a \in \Phi^+$  is a positive root of the root system  $\Phi$ .

## **EXAMPLES:**

```
sage: hyperplane_arrangements.Shi(4)
Arrangement of 12 hyperplanes of dimension 4 and rank 3
sage: hyperplane_arrangements.Shi("A3")
Arrangement of 12 hyperplanes of dimension 4 and rank 3
sage: hyperplane_arrangements.Shi("A3",m=2)
Arrangement of 24 hyperplanes of dimension 4 and rank 3
sage: hyperplane_arrangements.Shi("B4")
Arrangement of 32 hyperplanes of dimension 4 and rank 4
sage: hyperplane_arrangements.Shi("B4",m=3)
Arrangement of 96 hyperplanes of dimension 4 and rank 4
sage: hyperplane_arrangements.Shi("C3")
Arrangement of 18 hyperplanes of dimension 3 and rank 3
sage: hyperplane_arrangements.Shi("D4",m=3)
Arrangement of 72 hyperplanes of dimension 4 and rank 4
sage: hyperplane_arrangements.Shi("E6")
Arrangement of 72 hyperplanes of dimension 8 and rank 6
sage: hyperplane_arrangements.Shi("E6",m=2)
Arrangement of 144 hyperplanes of dimension 8 and rank 6
```

If the Cartan type is not crystallographic, the Shi arrangement is not defined:

The characteristic polynomial is pre-computed using the results of [Ath1996]:

```
sage: hyperplane_arrangements.Shi("A3").characteristic_polynomial()
x^4 - 12*x^3 + 48*x^2 - 64*x
sage: hyperplane_arrangements.Shi("A3",m=2).characteristic_polynomial()
x^4 - 24*x^3 + 192*x^2 - 512*x
sage: hyperplane_arrangements.Shi("C3").characteristic_polynomial()
x^3 - 18*x^2 + 108*x - 216
sage: hyperplane_arrangements.Shi("E6").characteristic_polynomial()
x^8 - 72*x^7 + 2160*x^6 - 34560*x^5 + 311040*x^4 - 1492992*x^3 + 2985984*x^2
sage: hyperplane_arrangements.Shi("B4",m=3).characteristic_polynomial()
x^4 - 96*x^3 + 3456*x^2 - 55296*x + 331776
```

## bigraphical(G, A=None, K=Rational Field, names=None)

Return a bigraphical hyperplane arrangement.

## INPUT:

- G graph
- A list, matrix, dictionary (default: None gives semiorder), or the string 'generic'
- K field (default: **Q**)
- names tuple of strings or None (default); the variable names for the ambient space

#### **OUTPUT**:

The hyperplane arrangement with hyperplanes  $x_i - x_j = A[i, j]$  and  $x_j - x_i = A[j, i]$  for each edge  $v_i, v_j$  of G. The indices i, j are the indices of elements of G. vertices().

#### **EXAMPLES:**

```
sage: G = graphs.CycleGraph(4)
sage: G.edges(sort=True)
[(0, 1, None), (0, 3, None), (1, 2, None), (2, 3, None)]
sage: G.edges(sort=True, labels=False)
[(0, 1), (0, 3), (1, 2), (2, 3)]
sage: A = {0:{1:1, 3:2}, 1:{0:3, 2:0}, 2:{1:2, 3:1}, 3:{2:0, 0:2}}
sage: HA = hyperplane_arrangements.bigraphical(G, A)
sage: HA.n_regions()
63
sage: hyperplane_arrangements.bigraphical(G, 'generic').n_regions()
65
sage: hyperplane_arrangements.bigraphical(G).n_regions()
```

#### REFERENCES:

• [HP2016]

### **braid**(*n*, *K*=*Rational Field*, *names*=*None*)

The braid arrangement.

## INPUT:

- n integer
- K field (default: QQ)
- names tuple of strings or None (default); the variable names for the ambient space

#### **OUTPUT**:

The hyperplane arrangement consisting of the n(n-1)/2 hyperplanes  $\{x_i - x_j = 0 : 1 \le i \le j \le n\}$ .

## **EXAMPLES:**

```
sage: hyperplane_arrangements.braid(4)
Arrangement of 6 hyperplanes of dimension 4 and rank 3
```

#### coordinate(n, K=Rational Field, names=None)

Return the coordinate hyperplane arrangement.

#### INPUT:

- n integer
- K field (default: **Q**)
- names tuple of strings or None (default); the variable names for the ambient space

#### **OUTPUT:**

The coordinate hyperplane arrangement, which is the central hyperplane arrangement consisting of the coordinate hyperplanes  $x_i = 0$ .

#### **EXAMPLES:**

```
sage: hyperplane_arrangements.coordinate(5)
Arrangement of 5 hyperplanes of dimension 5 and rank 5
```

# graphical(G, K=Rational Field, names=None)

Return the graphical hyperplane arrangement of a graph G.

## INPUT:

- G graph
- $K field (default: \mathbf{Q})$
- names tuple of strings or None (default); the variable names for the ambient space

#### **OUTPUT**:

The graphical hyperplane arrangement of a graph G, which is the arrangement  $\{x_i - x_j = 0\}$  for all edges ij of the graph G.

## **EXAMPLES:**

```
sage: G = graphs.CompleteGraph(5)
sage: hyperplane_arrangements.graphical(G)
Arrangement of 10 hyperplanes of dimension 5 and rank 4
sage: g = graphs.HouseGraph()
sage: hyperplane_arrangements.graphical(g)
Arrangement of 6 hyperplanes of dimension 5 and rank 4
```

## **linial**(*n*, *K*=*Rational Field*, *names*=*None*)

Return the linial hyperplane arrangement.

#### INPUT:

- n integer
- K field (default: **Q**)
- names tuple of strings or None (default); the variable names for the ambient space

## **OUTPUT**:

The linial hyperplane arrangement is the set of hyperplanes  $\{x_i - x_j = 1 : 1 \le i < j \le n\}$ .

## **EXAMPLES:**

```
sage: a = hyperplane_arrangements.linial(4); a
Arrangement of 6 hyperplanes of dimension 4 and rank 3
sage: a.characteristic_polynomial()
x^4 - 6*x^3 + 15*x^2 - 14*x
```

## **semiorder**(*n*, *K*=*Rational Field*, *names*=*None*)

Return the semiorder arrangement.

## INPUT:

- n integer
- $K field (default: \mathbf{Q})$
- names tuple of strings or None (default); the variable names for the ambient space

#### OUTPUT:

The semiorder arrangement, which is the set of n(n-1) hyperplanes  $\{x_i - x_j = -1, 1 : 1 \le i \le j \le n\}$ .

#### **EXAMPLES:**

```
sage: hyperplane_arrangements.semiorder(4)
Arrangement of 12 hyperplanes of dimension 4 and rank 3
```

sage.geometry.hyperplane\_arrangement.library.make\_parent(base\_ring, dimension, names=None)
Construct the parent for the hyperplane arrangements.

For internal use only.

## INPUT:

- base\_ring a ring
- dimension integer
- names None (default) or a list/tuple/iterable of strings

## **OUTPUT**:

A new HyperplaneArrangements instance.

## **EXAMPLES:**

```
sage: from sage.geometry.hyperplane_arrangement.library import make_parent
sage: make_parent(QQ, 3)
Hyperplane arrangements in 3-dimensional linear space over
Rational Field with coordinates t0, t1, t2
```

# 1.3 Hyperplanes

**Note:** If you want to learn about Sage's hyperplane arrangements then you should start with *sage.geometry.* hyperplane\_arrangement. This module is used to represent the individual hyperplanes, but you should never construct the classes from this module directly (but only via the *HyperplaneArrangements*.

A linear expression, for example, 3x + 3y - 5z - 7 stands for the hyperplane with the equation x + 3y - 5z = 7. To create it in Sage, you first have to create a *HyperplaneArrangements* object to define the variables x, y, z:

```
sage: H.<x,y,z> = HyperplaneArrangements(QQ)
sage: h = 3*x + 2*y - 5*z - 7; h
Hyperplane 3*x + 2*y - 5*z - 7
sage: h.coefficients()
[-7, 3, 2, -5]
sage: h.normal()
(3, 2, -5)
sage: h.constant_term()
-7
sage: h.change_ring(GF(3))
Hyperplane 0*x + 2*y + z + 2
sage: h.point()
(21/38, 7/19, -35/38)
sage: h.linear_part()
Vector space of degree 3 and dimension 2 over Rational Field
Basis matrix:
Γ
  1
       0 3/5]
  0
       1 2/5]
```

Another syntax to create hyperplanes is to specify coefficients and a constant term:

```
sage: V = H.ambient_space(); V
3-dimensional linear space over Rational Field with coordinates x, y, z
sage: h in V
True
sage: V([3, 2, -5], -7)
Hyperplane 3*x + 2*y - 5*z - 7
```

Or constant term and coefficients together in one list/tuple/iterable:

```
sage: V([-7, 3, 2, -5])
Hyperplane 3*x + 2*y - 5*z - 7
sage: v = vector([-7, 3, 2, -5]); v
(-7, 3, 2, -5)
sage: V(v)
Hyperplane 3*x + 2*y - 5*z - 7
```

Note that the constant term comes first, which matches the notation for Sage's *Polyhedron()* 

```
sage: Polyhedron(ieqs=[(4,1,2,3)]).Hrepresentation()
(An inequality (1, 2, 3) x + 4 >= 0,)
```

The difference between hyperplanes as implemented in this module and hyperplane arrangements is that:

- hyperplane arrangements contain multiple hyperplanes (of course),
- linear expressions are a module over the base ring, and these module structure is inherited by the hyperplanes.

The latter means that you can add and multiply by a scalar:

```
sage: h = 3*x + 2*y - 5*z - 7; h
Hyperplane 3*x + 2*y - 5*z - 7
sage: -h
Hyperplane -3*x - 2*y + 5*z + 7
sage: h + x
Hyperplane 4*x + 2*y - 5*z - 7
sage: h + 7
Hyperplane 3*x + 2*y - 5*z + 0
sage: 3*h
Hyperplane 9*x + 6*y - 15*z - 21
sage: h * RDF(3)
Hyperplane 9.0*x + 6.0*y - 15.0*z - 21.0
```

Which you can't do with hyperplane arrangements:

```
sage: arrangement = H(h, x, y, x+y-1); arrangement
Arrangement <y | x | x + y - 1 | 3*x + 2*y - 5*z - 7>
sage: arrangement + x
Traceback (most recent call last):
...
TypeError: unsupported operand parent(s) for +:
'Hyperplane arrangements in 3-dimensional linear space
    over Rational Field with coordinates x, y, z' and
'Hyperplane arrangements in 3-dimensional linear space
    over Rational Field with coordinates x, y, z'
```

 $Bases: \ sage.geometry.linear\_expression.LinearExpressionModule$ 

The ambient space for hyperplanes.

This class is the parent for the *Hyperplane* instances.

## **Element**

alias of Hyperplane

# change\_ring(base\_ring)

Return a ambient vector space with a changed base ring.

INPUT:

• base\_ring – a ring; the new base ring

**OUTPUT**:

A new AmbientVectorSpace.

**EXAMPLES:** 

```
sage: M.<y> = HyperplaneArrangements(QQ)
sage: V = M.ambient_space()
```

(continues on next page)

1.3. Hyperplanes 47

```
sage: V.change_ring(RR)
1-dimensional linear space over Real Field with 53 bits of precision with

→coordinate y
```

## dimension()

Return the ambient space dimension.

**OUTPUT**:

An integer.

**EXAMPLES:** 

```
sage: M.<x,y> = HyperplaneArrangements(QQ)
sage: x.parent().dimension()
2
sage: x.parent() is M.ambient_space()
True
sage: x.dimension()
1
```

## symmetric\_space()

Construct the symmetric space of self.

Consider a hyperplane arrangement A in the vector space  $V = k^n$ , for some field k. The symmetric space is the symmetric algebra  $S(V^*)$  as the polynomial ring  $k[x_1, x_2, \ldots, x_n]$  where  $(x_1, x_2, \ldots, x_n)$  is a basis for V.

## **EXAMPLES:**

```
sage: H.<x,y,z> = HyperplaneArrangements(QQ)
sage: A = H.ambient_space()
sage: A.symmetric_space()
Multivariate Polynomial Ring in x, y, z over Rational Field
```

A hyperplane.

You should always use AmbientVectorSpace to construct instances of this class.

INPUT:

- parent the parent Ambient Vector Space
- coefficients a vector of coefficients of the linear variables
- constant the constant term for the linear expression

## EXAMPLES:

```
sage: H.<x,y> = HyperplaneArrangements(QQ)
sage: x+y-1
Hyperplane x + y - 1

sage: ambient = H.ambient_space()
sage: ambient._element_constructor_(x+y-1)
Hyperplane x + y - 1
```

For technical reasons, we must allow the degenerate cases of an empty space and of a full space:

```
sage: 0*x
Hyperplane 0*x + 0*y + 0
sage: 0*x + 1
Hyperplane 0*x + 0*y + 1
sage: x + 0 == x + ambient(0)  # because coercion requires them
True
```

## dimension()

The dimension of the hyperplane.

OUTPUT:

An integer.

**EXAMPLES:** 

```
sage: H.<x,y,z> = HyperplaneArrangements(QQ)
sage: h = x + y + z - 1
sage: h.dimension()
2
```

## intersection(other)

The intersection of self with other.

#### INPUT:

• other – a hyperplane, a polyhedron, or something that defines a polyhedron

# **OUTPUT**:

A polyhedron.

## **EXAMPLES:**

```
sage: H.<x,y,z> = HyperplaneArrangements(QQ)
sage: h = x + y + z - 1
sage: h.intersection(x - y)
A 1-dimensional polyhedron in QQ^3 defined as the convex hull of 1 vertex and 1
\rightarrowline
sage: h.intersection(polytopes.cube())
A 2-dimensional polyhedron in QQ^3 defined as the convex hull of 3 vertices
```

## linear\_part()

The linear part of the affine space.

**OUTPUT**:

Vector subspace of the ambient vector space, parallel to the hyperplane.

## **EXAMPLES:**

```
sage: H.<x,y,z> = HyperplaneArrangements(QQ)
sage: h = x + 2*y + 3*z - 1
sage: h.linear_part()
Vector space of degree 3 and dimension 2 over Rational Field
Basis matrix:
[ 1 0 -1/3]
[ 0 1 -2/3]
```

1.3. Hyperplanes 49

## linear\_part\_projection(point)

Orthogonal projection onto the linear part.

#### INPUT:

• point – vector of the ambient space, or anything that can be converted into one; not necessarily on the hyperplane

#### **OUTPUT:**

Coordinate vector of the projection of point with respect to the basis of *linear\_part()*. In particular, the length of this vector is one less than the ambient space dimension.

## **EXAMPLES:**

```
sage: H.<x,y,z> = HyperplaneArrangements(QQ)
sage: h = x + 2*y + 3*z - 4
sage: h.linear_part()
Vector space of degree 3 and dimension 2 over Rational Field
Basis matrix:
  1
        0 - 1/3
        1 - 2/3
   0
sage: p1 = h.linear_part_projection(0); p1
(0, 0)
sage: p2 = h.linear_part_projection([3,4,5]); p2
(8/7, 2/7)
sage: h.linear_part().basis()
(1, 0, -1/3),
(0, 1, -2/3)
sage: p3 = h.linear_part_projection([1,1,1]); p3
(4/7, 1/7)
```

## normal()

Return the normal vector.

#### **OUTPUT**:

A vector over the base ring.

# **EXAMPLES:**

```
sage: H.<x, y, z> = HyperplaneArrangements(QQ)
sage: x.normal()
(1, 0, 0)
sage: x.A(), x.b()
((1, 0, 0), 0)
sage: (x + 2*y + 3*z + 4).normal()
(1, 2, 3)
```

## orthogonal\_projection(point)

Return the orthogonal projection of a point.

#### INPUT:

• point – vector of the ambient space, or anything that can be converted into one; not necessarily on the hyperplane

## **OUTPUT**:

A vector in the ambient vector space that lies on the hyperplane.

In finite characteristic, a ValueError is raised if the the norm of the hyperplane normal is zero.

## **EXAMPLES:**

```
sage: H.<x,y,z> = HyperplaneArrangements(QQ)
sage: h = x + 2*y + 3*z - 4
sage: p1 = h.orthogonal_projection(0); p1
(2/7, 4/7, 6/7)
sage: p1 in h
True
sage: p2 = h.orthogonal_projection([3,4,5]); p2
(10/7, 6/7, 2/7)
sage: p1 in h
True
sage: p3 = h.orthogonal_projection([1,1,1]); p3
(6/7, 5/7, 4/7)
sage: p3 in h
True
```

## plot(\*\*kwds)

Plot the hyperplane.

## **OUTPUT**:

A graphics object.

#### **EXAMPLES:**

```
sage: L.<x, y> = HyperplaneArrangements(QQ)
sage: (x+y-2).plot() # optional - sage.plot
Graphics object consisting of 2 graphics primitives
```

# point()

Return the point closest to the origin.

#### **OUTPUT**:

A vector of the ambient vector space. The closest point to the origin in the  $L^2$ -norm.

In finite characteristic a random point will be returned if the norm of the hyperplane normal vector is zero.

# **EXAMPLES:**

```
sage: H.<x,y,z> = HyperplaneArrangements(QQ)
sage: h = x + 2*y + 3*z - 4
sage: h.point()
(2/7, 4/7, 6/7)
sage: h.point() in h
True

sage: H.<x,y,z> = HyperplaneArrangements(GF(3))
sage: h = 2*x + y + z + 1
sage: h.point()
(1, 0, 0)
sage: h.point().base_ring()
Finite Field of size 3
```

(continues on next page)

1.3. Hyperplanes 51

```
sage: H.<x,y,z> = HyperplaneArrangements(GF(3))
sage: h = x + y + z + 1
sage: h.point()
(2, 0, 0)
```

## polyhedron()

Return the hyperplane as a polyhedron.

#### **OUTPUT:**

A Polyhedron() instance.

## **EXAMPLES:**

```
sage: H.<x,y,z> = HyperplaneArrangements(QQ)
sage: h = x + 2*y + 3*z - 4
sage: P = h.polyhedron(); P
A 2-dimensional polyhedron in QQ^3 defined as the convex hull of 1 vertex and 2
\rightarrowlines
sage: P.Hrepresentation()
(An equation (1, 2, 3) x - 4 == 0,)
sage: P.Vrepresentation()
(A line in the direction (0, 3, -2),
A line in the direction (3, 0, -1),
A vertex at (0, 0, 4/3))
```

## primitive(signed=True)

Return hyperplane defined by primitive equation.

## INPUT:

• signed – boolean (optional, default: True); whether to preserve the overall sign

#### **OUTPUT**:

Hyperplane whose linear expression has common factors and denominators cleared. That is, the same hyperplane (with the same sign) but defined by a rescaled equation. Note that different linear expressions must define different hyperplanes as comparison is used in caching.

If signed, the overall rescaling is by a positive constant only.

#### **EXAMPLES:**

```
sage: H.<x,y> = HyperplaneArrangements(QQ)
sage: h = -1/3*x + 1/2*y - 1; h
Hyperplane -1/3*x + 1/2*y - 1
sage: h.primitive()
Hyperplane -2*x + 3*y - 6
sage: h == h.primitive()
False
sage: (4*x + 8).primitive()
Hyperplane x + 0*y + 2

sage: (4*x - y - 8).primitive(signed=True) # default
Hyperplane 4*x - y - 8
```

```
sage: (4*x - y - 8).primitive(signed=False)
Hyperplane -4*x + y + 8
```

#### to\_symmetric\_space()

Return self considered as an element in the corresponding symmetric space.

**EXAMPLES:** 

```
sage: L.<x, y> = HyperplaneArrangements(QQ)
sage: h = -1/3*x + 1/2*y
sage: h.to_symmetric_space()
-1/3*x + 1/2*y

sage: hp = -1/3*x + 1/2*y - 1
sage: hp.to_symmetric_space()
Traceback (most recent call last):
...
ValueError: the hyperplane must pass through the origin
```

# 1.4 Affine Subspaces of a Vector Space

An affine subspace of a vector space is a translation of a linear subspace. The affine subspaces here are only used internally in hyperplane arrangements. You should not use them for interactive work or return them to the user.

**EXAMPLES**:

```
sage: from sage.geometry.hyperplane_arrangement.affine_subspace import AffineSubspace
sage: a = AffineSubspace([1,0,0,0], QQ^4)
sage: a.dimension()
sage: a.point()
(1, 0, 0, 0)
sage: a.linear_part()
Vector space of dimension 4 over Rational Field
sage: a
Affine space p + W where:
 p = (1, 0, 0, 0)
 W = Vector space of dimension 4 over Rational Field
sage: b = AffineSubspace((1,0,0,0), matrix(QQ, [[1,2,3,4]]).right_kernel())
sage: c = AffineSubspace((0,2,0,0), matrix(QQ, [[0,0,1,2]]).right_kernel())
sage: b.intersection(c)
Affine space p + W where:
 p = (-3, 2, 0, 0)
 W = Vector space of degree 4 and dimension 2 over Rational Field
Basis matrix:
[ 1 0 -1 1/2]
Γ 0
     1 -2
               17
sage: b < a</pre>
True
sage: c < b</pre>
False
```

```
sage: A = AffineSubspace([8,38,21,250], VectorSpace(GF(19),4))
sage: A
Affine space p + W where:
    p = (8, 0, 2, 3)
    W = Vector space of dimension 4 over Finite Field of size 19
```

# class sage.geometry.hyperplane\_arrangement.affine\_subspace.AffineSubspace(p, V)

Bases: sage.structure.sage\_object.SageObject

An affine subspace.

## INPUT:

- p list/tuple/iterable representing a point on the affine space
- V vector subspace

#### **OUTPUT**:

Affine subspace parallel to V and passing through p.

## **EXAMPLES:**

```
sage: from sage.geometry.hyperplane_arrangement.affine_subspace import

AffineSubspace
sage: a = AffineSubspace([1,0,0,0], VectorSpace(QQ,4))
sage: a
Affine space p + W where:
  p = (1, 0, 0, 0)
  W = Vector space of dimension 4 over Rational Field
```

# dimension()

Return the dimension of the affine space.

**OUTPUT**:

An integer.

**EXAMPLES:** 

```
sage: from sage.geometry.hyperplane_arrangement.affine_subspace import

AffineSubspace
sage: a = AffineSubspace([1,0,0,0], VectorSpace(QQ,4))
sage: a.dimension()
4
```

#### intersection(other)

Return the intersection of self with other.

INPUT:

• other - an AffineSubspace

**OUTPUT**:

A new affine subspace, (or None if the intersection is empty).

**EXAMPLES:** 

```
sage: from sage.geometry.hyperplane_arrangement.affine_subspace import_
→AffineSubspace
sage: V = VectorSpace(QQ,3)
sage: U = V.subspace([(1,0,0), (0,1,0)])
sage: W = V.subspace([(0,1,0), (0,0,1)])
sage: A = AffineSubspace((0,0,0), U)
sage: B = AffineSubspace((1,1,1), W)
sage: A.intersection(B)
Affine space p + W where:
 p = (1, 1, 0)
 W = Vector space of degree 3 and dimension 1 over Rational Field
Basis matrix:
[0 1 0]
sage: C = AffineSubspace((0,0,1), U)
sage: A.intersection(C)
sage: C = AffineSubspace((7,8,9), U.complement())
sage: A.intersection(C)
Affine space p + W where:
 p = (7, 8, 0)
 W = Vector space of degree 3 and dimension 0 over Rational Field
Basis matrix:
sage: A.intersection(C).intersection(B)
sage: D = AffineSubspace([1,2,3], VectorSpace(GF(5),3))
sage: E = AffineSubspace([3,4,5], VectorSpace(GF(5),3))
sage: D.intersection(E)
Affine space p + W where:
 p = (3, 4, 0)
 W = Vector space of dimension 3 over Finite Field of size 5
```

## linear\_part()

Return the linear part of the affine space.

**OUTPUT**:

A vector subspace of the ambient space.

**EXAMPLES:** 

## point()

Return a point p in the affine space.

**OUTPUT**:

A point of the affine space as a vector in the ambient space.

#### **EXAMPLES:**

```
sage: from sage.geometry.hyperplane_arrangement.affine_subspace import_

AffineSubspace
sage: A = AffineSubspace([2,3,1], VectorSpace(QQ,3))
sage: A.point()
(2, 3, 1)
```

# 1.5 Plotting of Hyperplane Arrangements

#### PLOT OPTIONS:

Beside the usual plot options (enter plot?), the plot command for hyperplane arrangements includes the following:

- hyperplane\_colors Color or list of colors, one for each hyperplane (default: equally spread range of hues).
- hyperplane\_labels Boolean, 'short', 'long' (default: False). If False, no labels are shown; if 'short' or 'long', the hyperplanes are given short or long labels, respectively. If True, the hyperplanes are given long labels.
- label\_colors Color or list of colors, one for each hyperplane (default: black).
- label\_fontsize Size for hyperplane\_label font (default: 14). This does not work for 3d plots.
- label\_offsets Amount be which labels are offset from h.point() for each hyperplane h. The format is different for each dimension: if the hyperplanes have dimension 0, the offset can be a single number or a list of numbers, one for each hyperplane; if the hyperplanes have dimension 1, the offset can be a single 2-tuple, or a list of 2-tuples, one for each hyperplane; if the hyperplanes have dimension 2, the offset can be a single 3-tuple or a list of 3-tuples, one for each hyperplane. (Defaults: 0-dim: 0.1, 1-dim: (0,1), 2-dim: (0,0,0.2)).
- hyperplane\_legend Boolean, 'short', 'long' (default: 'long'; in 3-d: False). If False, no legend is shown; if True, 'short', or 'long', the legend is shown with the default, long, or short labeling, respectively. (For arrangements of lines or planes, only.)
- hyperplane\_opacities A number or list of numbers, one for each hyperplane, between 0 and 1. Only applies to 3d plots.
- point\_sizes Number or list of numbers, one for each hyperplane giving the sizes of points in a zero-dimensional arrangement (default: 50).
- ranges Range for the parameters or a list of ranges of parameters, one for each hyperplane, for the parametric plots of the hyperplanes. If a single positive number r is given for ranges, then all parameters run from -r to r. Otherwise, for a line in the plane, the range has the form [a,b] (default: [-3,3]), and for a plane in 3-space, the range has the form [[a,b],[c,d]] (default: [[-3,3],[-3,3]]). The ranges are centered around hyperplane\_arrangement.point().

### **EXAMPLES**:

```
sage: c.plot(ranges=10) # optional - sage.plot
Graphics3d Object
sage: c.plot(ranges=[[9.5,10], [-3,3]]) # optional - sage.plot
Graphics3d Object
sage: c.plot(ranges=[[[9.5,10], [-3,3]], [[-6,6], [-5,5]]]) # optional - sage.plot
Graphics3d Object
sage: H2.<s,t> = HyperplaneArrangements(QQ)
sage: h = H2([(1,1),0], [(1,-1),0], [(0,1),2])
sage: h.plot(ranges=20) # optional - sage.plot
Graphics object consisting of 3 graphics primitives
sage: h.plot(ranges=[-1, 10]) # optional - sage.plot
Graphics object consisting of 3 graphics primitives
sage: h.plot(ranges=[[-1, 1], [-5, 5], [-1, 10]]) # optional - sage.plot
Graphics object consisting of 3 graphics primitives
sage: a = hyperplane_arrangements.coordinate(3)
sage: opts = {'hyperplane_colors':['yellow', 'green', 'blue']}
sage: opts['hyperplane_labels'] = True
sage: opts['label_offsets'] = [(0,2,2), (2,0,2), (2,2,0)]
sage: opts['hyperplane_legend'] = False
sage: opts['hyperplane_opacities'] = 0.7
sage: a.plot(**opts) # optional - sage.plot
Graphics3d Object
sage: opts['hyperplane_labels'] = 'short'
sage: a.plot(**opts) # optional - sage.plot
Graphics3d Object
sage: H.<u> = HyperplaneArrangements(QQ)
sage: pts = H(3*u+4, 2*u+5, 7*u+1)
sage: pts.plot(hyperplane_colors=['yellow','black','blue']) # optional - sage.plot
Graphics object consisting of 3 graphics primitives
sage: pts.plot(point_sizes=[50,100,200], hyperplane_colors='blue') # optional - sage.
Graphics object consisting of 3 graphics primitives
sage: H.<x,y,z> = HyperplaneArrangements(QQ)
sage: a = H(x, y+1, y+2)
sage: a.plot(hyperplane_labels=True,label_colors='blue',label_fontsize=18) # optional -_
⇒sage.plot
Graphics3d Object
sage: a.plot(hyperplane_labels=True,label_colors=['red','green','black']) # optional -_
⇒sage.plot
Graphics3d Object
```

Create plot of a 3d legend for an arrangement of planes in 3-space. The length parameter determines whether short or long labels are used in the legend.

INPUT:

• hyperplane\_arrangement – a hyperplane arrangement

- hyperplane\_colors list of colors
- length either 'short' or 'long'

#### **OUTPUT:**

· A graphics object.

#### **EXAMPLES:**

```
sage: a = hyperplane_arrangements.semiorder(3)
sage: from sage.geometry.hyperplane_arrangement.plot import legend_3d
sage: legend_3d(a, list(colors.values())[:6],length='long')
Graphics object consisting of 6 graphics primitives

sage: b = hyperplane_arrangements.semiorder(4)
sage: c = b.essentialization()
sage: legend_3d(c, list(colors.values())[:12], length='long')
Graphics object consisting of 12 graphics primitives

sage: legend_3d(c, list(colors.values())[:12], length='short')
Graphics object consisting of 12 graphics primitives

sage: p = legend_3d(c, list(colors.values())[:12], length='short')
sage: p.set_legend_options(ncol=4)
sage: type(p)
<class 'sage.plot.graphics.Graphics'>
```

sage.geometry.hyperplane\_arrangement.plot.plot(hyperplane\_arrangement, \*\*kwds)
Return a plot of the hyperplane arrangement.

If the arrangement is in 4 dimensions but inessential, a plot of the essentialization is returned.

**Note:** This function is available as the *plot()* method of hyperplane arrangements. You should not call this function directly, only through the method.

## INPUT:

- hyperplane\_arrangement the hyperplane arrangement to plot
- \*\*kwds plot options: see sage.geometry.hyperplane\_arrangement.plot.

#### **OUTPUT:**

A graphics object of the plot.

## **EXAMPLES:**

```
sage: B = hyperplane_arrangements.semiorder(4)
sage: B.plot() # optional - sage.plot
Displaying the essentialization.
Graphics3d Object
```

sage.geometry.hyperplane\_arrangement.plot.plot.plot\_hyperplane(hyperplane, \*\*kwds)
Return the plot of a single hyperplane.

## INPUT:

• \*\*kwds - plot options: see below

## **OUTPUT**:

A graphics object of the plot.

## **Plot Options**

Beside the usual plot options (enter plot?), the plot command for hyperplanes includes the following:

- hyperplane\_label Boolean value or string (default: True). If True, the hyperplane is labeled with its equation, if a string, it is labeled by that string, otherwise it is not labeled.
- label\_color (Default: 'black') Color for hyperplane label.
- label\_fontsize Size for hyperplane\_label font (default: 14) (does not work in 3d, yet).
- label\_offset (Default: 0-dim: 0.1, 1-dim: (0,1), 2-dim: (0,0,0.2)) Amount by which label is offset from hyperplane.point().
- point\_size (Default: 50) Size of points in a zero-dimensional arrangement or of an arrangement over a finite field.
- ranges Range for the parameters for the parametric plot of the hyperplane. If a single positive number r is given for the value of ranges, then the ranges for all parameters are set to [-r, r]. Otherwise, for a line in the plane, ranges has the form [a, b] (default: [-3,3]), and for a plane in 3-space, the ranges has the form [[a, b], [c, d]] (default: [[-3,3], [-3,3]]). (The ranges are centered around hyperplane.point().)

#### **EXAMPLES:**

```
sage: H1.<x> = HyperplaneArrangements(QQ)
sage: a = 3*x + 4
sage: a.plot()
                  # indirect doctest # optional - sage.plot
Graphics object consisting of 3 graphics primitives
sage: a.plot(point_size=100,hyperplane_label='hello') # optional - sage.plot
Graphics object consisting of 3 graphics primitives
sage: H2.\langle x,y\rangle = HyperplaneArrangements(QQ)
sage: b = 3*x + 4*y + 5
sage: b.plot() # optional - sage.plot
Graphics object consisting of 2 graphics primitives
sage: b.plot(ranges=(1,5),label_offset=(2,-1)) # optional - sage.plot
Graphics object consisting of 2 graphics primitives
sage: opts = {'hyperplane_label':True, 'label_color':'green',
              'label_fontsize':24, 'label_offset':(0,1.5)}
sage: b.plot(**opts) # optional - sage.plot
Graphics object consisting of 2 graphics primitives
sage: H3.<x,y,z> = HyperplaneArrangements(QQ)
sage: c = 2*x + 3*y + 4*z + 5
sage: c.plot() # optional - sage.plot
Graphics3d Object
sage: c.plot(label_offset=(1,0,1), color='green', label_color='red', frame=False)
→# optional - sage.plot
Graphics3d Object
sage: d = -3*x + 2*y + 2*z + 3
sage: d.plot(opacity=0.8) # optional - sage.plot
Graphics3d Object
```

```
sage: e = 4*x + 2*z + 3
sage: e.plot(ranges=[[-1,1],[0,8]], label_offset=(2,2,1), aspect_ratio=1) #_
→optional - sage.plot
Graphics3d Object
```

**CHAPTER** 

**TWO** 

# **POLYHEDRAL COMPUTATIONS**

# 2.1 Polyhedra

# 2.1.1 Library of commonly used, famous, or interesting polytopes

This module gathers several constructors of polytopes that can be reached through polytopes.<tab>. For example, here is the hypercube in dimension 5:

```
sage: polytopes.hypercube(5)
A 5-dimensional polyhedron in ZZ^5 defined as the convex hull of 32 vertices
```

The following constructions are available

Birkhoff_polytope()
associahedron()
bitruncated_six_hundred_cell()
buckyball()
<pre>cantellated_one_hundred_twenty_cell()</pre>
<pre>cantellated_six_hundred_cell()</pre>
<pre>cantitruncated_one_hundred_twenty_cell()</pre>
<pre>cantitruncated_six_hundred_cell()</pre>
<pre>cross_polytope()</pre>
cube()
cuboctahedron()
cyclic_polytope()
dodecahedron()
flow_polytope()
Gosset_3_21()
<pre>grand_antiprism()</pre>
<pre>great_rhombicuboctahedron()</pre>
hypercube()
hypersimplex()
icosahedron()
icosidodecahedron()
Kirkman_icosahedron()
octahedron()
<pre>omnitruncated_one_hundred_twenty_cell()</pre>
<pre>omnitruncated_six_hundred_cell()</pre>
one_hundred_twenty_cell()
continues on poyt page

Table 1 – continued from previous page

```
parallelotope()
pentakis_dodecahedron()
permutahedron()
generalized_permutahedron()
rectified_one_hundred_twenty_cell()
rectified_six_hundred_cell()
regular_polygon()
rhombic_dodecahedron()
rhombicosidodecahedron()
runcinated_one_hundred_twenty_cell()
runcitruncated_one_hundred_twenty_cell()
runcitruncated_six_hundred_cell()
simplex()
six_hundred_cell()
small_rhombicuboctahedron()
snub_cube()
snub_dodecahedron()
tetrahedron()
truncated_cube()
truncated_dodecahedron()
truncated_icosidodecahedron()
truncated_tetrahedron()
truncated_octahedron()
truncated_one_hundred_twenty_cell()
truncated_six_hundred_cell()
twenty_four_cell()
```

# class sage.geometry.polyhedron.library.Polytopes

Bases: object

A class of constructors for commonly used, famous, or interesting polytopes.

# Birkhoff\_polytope(n, backend=None)

Return the Birkhoff polytope with n! vertices.

The vertices of this polyhedron are the (flattened) n by n permutation matrices. So the ambient vector space has dimension  $n^2$  but the dimension of the polyhedron is  $(n-1)^2$ .

## INPUT:

- n a positive integer giving the size of the permutation matrices.
- backend the backend to use to create the polytope.

#### See also:

 $sage.matrix.matrix2.\texttt{Matrix.as\_sum\_of\_permutations()} - return \ the \ current \ matrix \ as \ a \ sum \ of \ permutation \ matrices$ 

### **EXAMPLES:**

```
sage: b3 = polytopes.Birkhoff_polytope(3)
sage: b3.f_vector()
(1, 6, 15, 18, 9, 1)
sage: b3.ambient_dim(), b3.dim()
(9, 4)
```

### Gosset\_3\_21(backend=None)

Return the Gosset  $3_{21}$  polytope.

The Gosset  $3_{21}$  polytope is a uniform 7-polytope. It has 56 vertices, and 702 facets:  $126 \ 3_{11}$  and 576 6-simplex. For more information, see the Wikipedia article  $3_{21}$  polytope.

#### INPUT:

• backend – the backend to use to create the polytope.

#### **EXAMPLES:**

```
sage: g = polytopes.Gosset_3_21(); g
A 7-dimensional polyhedron in ZZ^8 defined as the convex hull of 56 vertices
sage: g.f_vector() # not tested (~16s)
(1, 56, 756, 4032, 10080, 12096, 6048, 702, 1)
```

## Kirkman\_icosahedron(backend=None)

Return the Kirkman icosahedron.

The Kirkman icosahedron is a 3-polytope with integer coordinates:  $(\pm 9, \pm 6, \pm 6)$ ,  $(\pm 12, \pm 4, 0)$ ,  $(0, \pm 12, \pm 8)$ ,  $(\pm 6, 0, \pm 12)$ . See [Fe2012] for more information.

## INPUT:

• backend – the backend to use to create the polytope.

# **EXAMPLES:**

```
sage: ki = polytopes.Kirkman_icosahedron()
sage: ki.f_vector()
(1, 20, 38, 20, 1)

sage: ki.volume()
6528

sage: vertices = ki.vertices()
sage: edges = [[vector(edge[0]),vector(edge[1])] for edge in ki.bounded_edges()]
sage: edge_lengths = [norm(edge[0]-edge[1]) for edge in edges]
sage: sorted(set(edge_lengths))
[7, 8, 9, 11, 12, 14, 16]
```

2.1. Polyhedra 63

#### bitruncated\_six\_hundred\_cell(exact=True, backend=None)

Return the bitruncated 600-cell.

The bitruncated 600-cell is a 4-dimensional 4-uniform polytope in the  $H_4$  family. It has 3600 vertices. For more information see Wikipedia article Bitruncated 600-cell.

**Warning:** The coordinates are exact by default. The computation with inexact coordinates (using the backend 'cdd') returns a numerical inconsistency error, and thus cannot be computed.

### INPUT:

- exact (boolean, default True) if True use exact coordinates instead of floating point approximations.
- backend the backend to use to create the polytope.

#### **EXAMPLES:**

```
sage: polytopes.runcinated_six_hundred_cell(exact=True,backend='normaliz') #

→ not tested - very long time
A 4-dimensional polyhedron in AA^4 defined as the convex hull of 3600 vertices
```

## buckyball(exact=True, base\_ring=None, backend=None)

Return the bucky ball.

The bucky ball, also known as the truncated icosahedron is an Archimedean solid. It has 32 faces and 60 vertices.

#### See also:

icosahedron()

#### INPUT:

- exact (boolean, default True) If False use an approximate ring for the coordinates.
- base\_ring the ring in which the coordinates will belong to. If it is not provided and exact=True it will be a the number field  $\mathbf{Q}[\phi]$  where  $\phi$  is the golden ratio and if exact=False it will be the real double field.
- backend the backend to use to create the polytope.

### **EXAMPLES:**

```
sage: bb = polytopes.buckyball() # long time - 6secs

-# optional - sage.rings.number_field
sage: bb.f_vector() # long time

-# optional - sage.rings.number_field
(1, 60, 90, 32, 1)
sage: bb.base_ring() # long time

-# optional - sage.rings.number_field
Number Field in sqrt5 with defining polynomial x^2 - 5 with sqrt5 = 2.

-236067977499790?
```

A much faster implementation using floating point approximations:

```
sage: bb = polytopes.buckyball(exact=False)
sage: bb.f_vector()
(1, 60, 90, 32, 1)
(certifues on part page)
```

```
sage: bb.base_ring()
Real Double Field
```

Its facets are 5 regular pentagons and 6 regular hexagons:

```
sage: sum(1 for f in bb.facets() if len(f.vertices()) == 5)
12
sage: sum(1 for f in bb.facets() if len(f.vertices()) == 6)
20
```

## cantellated\_one\_hundred\_twenty\_cell(exact=True, backend=None)

Return the cantellated 120-cell.

The cantellated 120-cell is a 4-dimensional 4-uniform polytope in the  $H_4$  family. It has 3600 vertices. For more information see Wikipedia article Cantellated 120-cell.

**Warning:** The coordinates are exact by default. The computation with inexact coordinates (using the backend 'cdd') returns a numerical inconsistency error, and thus cannot be computed.

#### INPUT:

- exact (boolean, default True) if True use exact coordinates instead of floating point approximations.
- backend the backend to use to create the polytope.

#### **EXAMPLES:**

```
sage: polytopes.cantellated_one_hundred_twenty_cell(backend='normaliz') # not
    → tested - long time
A 4-dimensional polyhedron in AA^4 defined as the convex hull of 3600 vertices
```

## cantellated\_six\_hundred\_cell(exact=False, backend=None)

Return the cantellated 600-cell.

The cantellated 600-cell is a 4-dimensional 4-uniform polytope in the  $H_4$  family. It has 3600 vertices. For more information see Wikipedia article Cantellated 600-cell.

**Warning:** The coordinates are inexact by default. The computation with inexact coordinates (using the backend 'cdd') issues a UserWarning on inconsistencies.

## INPUT:

- exact (boolean, default False) if True use exact coordinates instead of floating point approximations
- backend the backend to use to create the polytope.

### **EXAMPLES:**

```
sage: polytopes.cantellated_six_hundred_cell() # not tested - very long time
doctest:warning
...
UserWarning: This polyhedron data is numerically complicated; cdd
could not convert between the inexact V and H representation
```

(continues on next page)

2.1. Polyhedra 65

```
without loss of data. The resulting object might show inconsistencies.
A 4-dimensional polyhedron in RDF^4 defined as the convex hull of 3600 vertices
```

It is possible to use the backend 'normaliz' to get an exact representation:

```
sage: polytopes.cantellated_six_hundred_cell(exact=True,backend='normaliz') #

→ not tested - long time
A 4-dimensional polyhedron in AA^4 defined as the convex hull of 3600 vertices
```

## cantitruncated\_one\_hundred\_twenty\_cell(exact=True, backend=None)

Return the cantitruncated 120-cell.

The cantitruncated 120-cell is a 4-dimensional 4-uniform polytope in the  $H_4$  family. It has 7200 vertices. For more information see Wikipedia article Cantitruncated 120-cell.

**Warning:** The coordinates are exact by default. The computation with inexact coordinates (using the backend 'cdd') returns a numerical inconsistency error, and thus cannot be computed.

#### INPUT:

- exact (boolean, default True) if True use exact coordinates instead of floating point approximations.
- backend the backend to use to create the polytope.

## **EXAMPLES:**

#### cantitruncated\_six\_hundred\_cell(exact=True, backend=None)

Return the cantitruncated 600-cell.

The cantitruncated 600-cell is a 4-dimensional 4-uniform polytope in the  $H_4$  family. It has 7200 vertices. For more information see Wikipedia article Cantitruncated 600-cell.

**Warning:** The coordinates are exact by default. The computation with inexact coordinates (using the backend 'cdd') returns a numerical inconsistency error, and thus cannot be computed.

#### INPUT:

- exact (boolean, default True) if True use exact coordinates instead of floating point approximations.
- backend the backend to use to create the polytope.

## **EXAMPLES:**

#### cross\_polytope(dim, backend=None)

Return a cross-polytope in dimension dim.

A cross-polytope is a higher dimensional generalization of the octahedron. It is the convex hull of the 2d points  $(\pm 1, 0, \ldots, 0)$ ,  $(0, \pm 1, \ldots, 0)$ , Idots,  $(0, 0, \ldots, \pm 1)$ . See the Wikipedia article Cross-polytope for more information.

#### INPUT:

- dim integer. The dimension of the cross-polytope.
- backend the backend to use to create the polytope.

#### **EXAMPLES:**

```
sage: four_cross = polytopes.cross_polytope(4)
sage: four_cross.f_vector()
(1, 8, 24, 32, 16, 1)
sage: four_cross.is_simple()
False
```

#### **cube**(*intervals=None*, *backend=None*)

Return the cube.

The cube is the Platonic solid that is obtained as the convex hull of the eight  $\pm 1$  vectors of length 3 (by default). Alternatively, the cube is the product of three intervals from intervals.

#### See also:

## hypercube()

## INPUT:

- intervals list (default=None). It takes the following possible inputs:
  - If the input is None (the default), returns the convex hull of the eight  $\pm 1$  vectors of length three.
  - 'zero\_one' (string). Return the 0/1-cube.
  - a list of 3 lists of length 2. The cube will be a product of these three intervals.
- backend the backend to use to create the polytope.

#### **OUTPUT**:

A cube as a polyhedron object.

# **EXAMPLES:**

Return the  $\pm 1$ -cube:

```
sage: c = polytopes.cube()
sage: c
A 3-dimensional polyhedron in ZZ^3 defined as the convex hull of 8 vertices
sage: c.f_vector()
(1, 8, 12, 6, 1)
sage: c.volume()
8
sage: c.plot() # optional - sage.plot
Graphics3d Object
```

# Return the 0/1-cube:

```
sage: cc = polytopes.cube(intervals ='zero_one')
sage: cc.vertices_list()
```

2.1. Polyhedra 67

```
[[1, 0, 0],

[1, 1, 0],

[1, 1, 1],

[1, 0, 1],

[0, 0, 1],

[0, 0, 0],

[0, 1, 0],

[0, 1, 1]]
```

## cuboctahedron(backend=None)

Return the cuboctahedron.

The cuboctahedron is an Archimedean solid with 12 vertices and 14 faces dual to the rhombic dodecahedron. It can be defined as the convex hull of the twelve vertices  $(0, \pm 1, \pm 1)$ ,  $(\pm 1, 0, \pm 1)$  and  $(\pm 1, \pm 1, 0)$ . For more information, see the Wikipedia article Cuboctahedron.

#### INPUT:

• backend – the backend to use to create the polytope.

## See also:

rhombic\_dodecahedron()

#### **EXAMPLES:**

```
sage: co = polytopes.cuboctahedron()
sage: co.f_vector()
(1, 12, 24, 14, 1)
```

Its facets are 8 triangles and 6 squares:

```
sage: sum(1 for f in co.facets() if len(f.vertices()) == 3)
8
sage: sum(1 for f in co.facets() if len(f.vertices()) == 4)
6
```

Some more computation:

```
sage: co.volume()
20/3
sage: co.ehrhart_polynomial() # optional - latte_int
20/3*t^3 + 8*t^2 + 10/3*t + 1
```

# cyclic\_polytope(dim, n, base\_ring=Rational Field, backend=None)

Return a cyclic polytope.

A cyclic polytope of dimension dim with n vertices is the convex hull of the points (t,t^2,...,t^dim) with  $t \in \{0,1,...,n-1\}$ . For more information, see the Wikipedia article Cyclic\_polytope.

## INPUT:

- dim positive integer. the dimension of the polytope.
- n positive integer. the number of vertices.
- base\_ring either QQ (default) or RDF.
- backend the backend to use to create the polytope.

#### **EXAMPLES:**

```
sage: c = polytopes.cyclic_polytope(4,10)
sage: c.f_vector()
(1, 10, 45, 70, 35, 1)
```

dodecahedron(exact=True, base\_ring=None, backend=None)

Return a dodecahedron.

The dodecahedron is the Platonic solid dual to the *icosahedron()*.

#### INPUT:

- exact (boolean, default True) If False use an approximate ring for the coordinates.
- base\_ring (optional) the ring in which the coordinates will belong to. Note that this ring must contain  $\sqrt(5)$ . If it is not provided and exact=True it will be the number field  $\mathbf{Q}[\sqrt(5)]$  and if exact=False it will be the real double field.
- backend the backend to use to create the polytope.

#### **EXAMPLES:**

Here is an error with a field that does not contain  $\sqrt{(5)}$ :

# static edge\_polytope(backend=None)

Return the edge polytope of self.

The edge polytope (EP) of a Graph on n vertices is the polytope in  $\mathbb{Z}^n$  defined as the convex hull of  $e_i + e_j$  for each edge (i, j). Here  $e_1, \ldots, e_n$  denotes the standard basis.

### INPUT:

• backend — string or None (default); the backend to use; see sage.geometry.polyhedron.
constructor.Polyhedron()

**EXAMPLES:** 

The EP of a 4-cycle is a square:

```
sage: G = graphs.CycleGraph(4)
sage: P = G.edge_polytope(); P
A 2-dimensional polyhedron in ZZ^4 defined as the convex hull of 4 vertices
```

The EP of a complete graph on 4 vertices is cross polytope:

```
sage: G = graphs.CompleteGraph(4)
sage: P = G.edge_polytope(); P
A 3-dimensional polyhedron in ZZ^4 defined as the convex hull of 6 vertices
sage: P.is_combinatorially_isomorphic(polytopes.cross_polytope(3))
True
```

The EP of a graph is isomorphic to the subdirect sum of its connected components EPs:

```
sage: n = randint(3, 6)
sage: G1 = graphs.RandomGNP(n, 0.2)
sage: n = randint(3, 6)
sage: G2 = graphs.RandomGNP(n, 0.2)
sage: G = G1.disjoint_union(G2)
sage: P = G.edge_polytope()
sage: P1 = G1.edge_polytope()
sage: P2 = G2.edge_polytope()
sage: P.is_combinatorially_isomorphic(P1.subdirect_sum(P2))
True
```

All trees on n vertices have isomorphic EPs:

```
sage: n = randint(4, 10)
sage: G1 = graphs.RandomTree(n)
sage: G2 = graphs.RandomTree(n)
sage: P1 = G1.edge_polytope()
sage: P2 = G2.edge_polytope()
sage: P1.is_combinatorially_isomorphic(P2)
True
```

However, there are still many different EPs:

```
sage: len(list(graphs(5)))
34
sage: polys = []
sage: for G in graphs(5):
      P = G.edge_polytope()
          for P1 in polys:
               if P.is_combinatorially_isomorphic(P1):
. . . . . .
                   break
. . . . . .
....:
          else:
. . . . . .
               polys.append(P)
sage: len(polys)
19
```

**static flow\_polytope**(*edges=None*, *ends=None*, *backend=None*)

Return the flow polytope of a digraph.

The flow polytope of a directed graph is the polytope consisting of all nonnegative flows on the graph with a given set S of sources and a given set T of sinks.

A *flow* on a directed graph G with a given set S of sources and a given set T of sinks means an assignment of a nonnegative real to each edge of G such that the flow is conserved in each vertex outside of S and T, and there is a unit of flow entering each vertex in S and a unit of flow leaving each vertex in T. These flows clearly form a polytope in the space of all assignments of reals to the edges of G.

The polytope is empty unless the sets S and T are equinumerous.

By default, S is taken to be the set of all sources (i.e., vertices of indegree 0) of G, and T is taken to be the set of all sinks (i.e., vertices of outdegree 0) of G. If a different choice of S and T is desired, it can be specified using the optional ends parameter.

The polytope is returned as a polytope in  $\mathbb{R}^m$ , where m is the number of edges of the digraph self. The k-th coordinate of a point in the polytope is the real assigned to the k-th edge of self. The order of the edges is the one returned by self.edges(sort=True). If a different order is desired, it can be specified using the optional edges parameter.

The faces and volume of these polytopes are of interest. Examples of these polytopes are the Chan-Robbins-Yuen polytope and the Pitman-Stanley polytope [PS2002].

#### INPUT:

- edges list (default: None); a list of edges of self. If not specified, the list of all edges of self is used with the default ordering of self.edges(sort=True). This determines which coordinate of a point in the polytope will correspond to which edge of self. It is also possible to specify a list which contains not all edges of self; this results in a polytope corresponding to the flows which are 0 on all remaining edges. Notice that the edges entered here must be in the precisely same format as outputted by self.edges(); so, if self.edges() outputs an edge in the form (1, 3, None), then (1, 3) will not do!
- ends (optional, default: (self.sources(), self.sinks())) a pair (S,T) of an iterable S and an iterable T.
- backend string or None (default); the backend to use; see sage.geometry.polyhedron.
  constructor.Polyhedron()

**Note:** Flow polytopes can also be built through the polytopes.<tab> object:

```
sage: polytopes.flow_polytope(digraphs.Path(5))
A 0-dimensional polyhedron in QQ^4 defined as the convex hull of 1 vertex
```

#### **EXAMPLES:**

A commutative square:

```
sage: G = DiGraph({1: [2, 3], 2: [4], 3: [4]})
sage: fl = G.flow_polytope(); fl
A 1-dimensional polyhedron in QQ^4 defined as the convex hull
of 2 vertices
sage: fl.vertices()
(A vertex at (0, 1, 0, 1), A vertex at (1, 0, 1, 0))
```

Using a different order for the edges of the graph:

```
sage: f1 = G.flow_polytope(edges=G.edges(key=lambda x: x[0] - x[1])); f1
A 1-dimensional polyhedron in QQ^4 defined as the convex hull of 2 vertices
sage: fl.vertices()
(A vertex at (0, 1, 1, 0), A vertex at (1, 0, 0, 1))
```

A tournament on 4 vertices:

```
sage: H = digraphs.TransitiveTournament(4)
sage: fl = H.flow_polytope(); fl
A 3-dimensional polyhedron in QQ^6 defined as the convex hull
of 4 vertices
sage: fl.vertices()
(A vertex at (0, 0, 1, 0, 0, 0),
A vertex at (0, 1, 0, 0, 0, 1),
A vertex at (1, 0, 0, 0, 1, 0),
A vertex at (1, 0, 0, 1, 0, 1)
```

Restricting to a subset of the edges:

```
sage: fl = H.flow_polytope(edges=[(0, 1, None), (1, 2, None),
                                  (2, 3, None), (0, 3, None)])
....:
sage: fl
A 1-dimensional polyhedron in QQ^4 defined as the convex hull
of 2 vertices
sage: fl.vertices()
(A vertex at (0, 0, 0, 1), A vertex at (1, 1, 1, 0))
```

Using a different choice of sources and sinks:

72

```
sage: fl = H.flow_polytope(ends=([1], [3])); fl
A 1-dimensional polyhedron in QQ^6 defined as the convex hull
of 2 vertices
sage: fl.vertices()
(A vertex at (0, 0, 0, 1, 0, 1), A vertex at (0, 0, 0, 0, 1, 0))
sage: fl = H.flow_polytope(ends=([0, 1], [3])); fl
The empty polyhedron in QQ^6
sage: fl = H.flow_polytope(ends=([3], [0])); fl
The empty polyhedron in QQ^6
sage: fl = H.flow_polytope(ends=([0, 1], [2, 3])); fl
A 3-dimensional polyhedron in QQ^6 defined as the convex hull
of 5 vertices
sage: fl.vertices()
(A vertex at (0, 0, 1, 1, 0, 0),
A vertex at (0, 1, 0, 0, 1, 0),
A vertex at (1, 0, 0, 2, 0, 1),
A vertex at (1, 0, 0, 1, 1, 0),
A vertex at (0, 1, 0, 1, 0, 1)
sage: fl = H.flow_polytope(edges=[(0, 1, None), (1, 2, None),
                                  (2, 3, None), (0, 2, None),
. . . . :
                                  (1, 3, None)],
. . . . :
                           ends=([0, 1], [2, 3])); fl
A 2-dimensional polyhedron in QQ^5 defined as the convex hull
of 4 vertices
```

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```
sage: fl.vertices()
(A vertex at (0, 0, 0, 1, 1),
  A vertex at (1, 2, 1, 0, 0),
  A vertex at (1, 1, 0, 0, 1),
  A vertex at (0, 1, 1, 1, 0))
```

A digraph with one source and two sinks:

```
sage: Y = DiGraph({1: [2], 2: [3, 4]})
sage: Y.flow_polytope()
The empty polyhedron in QQ^3
```

A digraph with one vertex and no edge:

```
sage: Z = DiGraph({1: []})
sage: Z.flow_polytope()
A 0-dimensional polyhedron in QQ^0 defined as the convex hull
of 1 vertex
```

A digraph with multiple edges (trac ticket #28837):

```
sage: G = DiGraph([(0, 1), (0,1)], multiedges=True)
sage: G
Multi-digraph on 2 vertices
sage: P = G.flow_polytope()
sage: P
A 1-dimensional polyhedron in QQ^2 defined as the convex hull of 2 vertices
sage: P.vertices()
(A vertex at (1, 0), A vertex at (0, 1))
sage: P.lines()
()
```

generalized\_permutahedron(coxeter\_type, point=None, exact=True, regular=False, backend=None)

Return the generalized permutahedron of type coxeter\_type as the convex hull of the orbit of point in the fundamental cone.

This generalized permutahedron lies in the vector space used in the geometric representation, that is, in the default case, the dimension of generalized permutahedron equals the dimension of the space.

### INPUT:

- coxeter\_type a Coxeter type; given as a pair [type,rank], where type is a letter and rank is the number of generators.
- point a list (default: None); a point given by its coordinates in the weight basis. If None is given, the point (1, 1, 1, ...) is used.
- exact (boolean, default True) if False use floating point approximations instead of exact coordinates
- regular boolean (default: False); whether to apply a linear transformation making the vertex figures isometric.
- backend backend to use to create the polytope; (default: None)

**EXAMPLES:** 

```
sage: perm_a3 = polytopes.generalized_permutahedron(['A',3]); perm_a3
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 24 vertices
```

You can put the starting point along the hyperplane of the first generator:

```
sage: perm_a3_011 = polytopes.generalized_permutahedron(['A',3],[0,1,1]); perm_
→a3_011
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 12 vertices
sage: perm_a3_110 = polytopes.generalized_permutahedron(['A',3],[1,1,0]); perm_
→a3_110
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 12 vertices
sage: perm_a3_110.is_combinatorially_isomorphic(perm_a3_011)
sage: perm_a3_101 = polytopes.generalized_permutahedron(['A',3],[1,0,1]); perm_
→a3 101
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 12 vertices
sage: perm_a3_110.is_combinatorially_isomorphic(perm_a3_101)
False
sage: perm_a3_011.f_vector()
(1, 12, 18, 8, 1)
sage: perm_a3_101.f_vector()
(1, 12, 24, 14, 1)
```

The usual output does not necessarily give a polyhedron with isometric vertex figures:

```
sage: perm_a2 = polytopes.generalized_permutahedron(['A',2])
sage: perm_a2.vertices()
(A vertex at (-1, -1),
   A vertex at (-1, 0),
   A vertex at (0, -1),
   A vertex at (0, 1),
   A vertex at (1, 0),
   A vertex at (1, 1))
```

Setting regular=True applies a linear transformation to get isometric vertex figures and the result is inscribed. Even though there are traces of small numbers, the internal computations are done using an exact embedded NumberField:

```
sage: perm_a2_reg = polytopes.generalized_permutahedron(['A',2],regular=True)
sage: V = sorted(perm_a2_reg.vertices()); V
                                                     # random
[A vertex at (-1, 0),
A vertex at (-1/2, -0.866025403784439?),
A vertex at (-1/2, 0.866025403784439?),
A vertex at (1/2, -0.866025403784439?),
A vertex at (1/2, 0.866025403784439?),
A vertex at (1.00000000000000, 0.?e-18)]
sage: for v in V:
          for x in v:
. . . . .
. . . . :
              x.exactify()
sage: V
[A vertex at (-1, 0),
A vertex at (-1/2, -0.866025403784439?),
A vertex at (-1/2, 0.866025403784439?),
```

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```
A vertex at (1/2, -0.866025403784439?),
A vertex at (1/2, 0.866025403784439?),
A vertex at (1, 0)]

sage: perm_a2_reg.is_inscribed()

True

sage: perm_a3_reg = polytopes.generalized_permutahedron(['A',3],regular=True)

$\time$ long time

sage: perm_a3_reg.is_inscribed()

$\time$ long time

True
```

The same is possible with vertices in RDF:

```
sage: perm_a2_inexact = polytopes.generalized_permutahedron(['A',2],exact=False)
sage: sorted(perm_a2_inexact.vertices())
[A vertex at (-1.0, -1.0),
A vertex at (-1.0, 0.0),
A vertex at (0.0, -1.0),
A vertex at (0.0, 1.0),
A vertex at (1.0, 0.0),
A vertex at (1.0, 1.0)]
sage: perm_a2_inexact_reg = polytopes.generalized_permutahedron(['A',2],
→exact=False,regular=True)
sage: sorted(perm_a2_inexact_reg.vertices())
[A vertex at (-1.0, 0.0),
A vertex at (-0.5, -0.8660254038),
A vertex at (-0.5, 0.8660254038),
A vertex at (0.5, -0.8660254038),
A vertex at (0.5, 0.8660254038),
A vertex at (1.0, 0.0)]
```

It works also with types with non-rational coordinates:

It is faster with the backend 'normaliz':

The backend 'normaliz' allows further faster computation in the non-rational case:

#### See also:

- permutahedron()
- permutahedron()

```
grand_antiprism(exact=True, backend=None, verbose=False)
```

Return the grand antiprism.

The grand antiprism is a 4-dimensional non-Wythoffian uniform polytope. The coordinates were taken from http://eusebeia.dyndns.org/4d/gap. For more information, see the Wikipedia article Grand antiprism.

**Warning:** The coordinates are exact by default. The computation with exact coordinates is not as fast as with floating point approximations. If you find this method to be too slow, consider using floating point approximations

## INPUT:

- exact (boolean, default True) if False use floating point approximations instead of exact coordinates
- backend the backend to use to create the polytope.

#### **EXAMPLES:**

```
sage: gap = polytopes.grand_antiprism() # not tested - very long time
sage: gap # not tested - very long time
A 4-dimensional polyhedron in (Number Field in sqrt5 with defining
polynomial x^2 - 5 with sqrt5 = 2.236067977499790?)^4 defined as
the convex hull of 100 vertices
```

Computation with the backend 'normaliz' is instantaneous:

Computation with approximated coordinates is also faster, but inexact:

```
sage: gap = polytopes.grand_antiprism(exact=False) # random
sage: gap
A 4-dimensional polyhedron in RDF^4 defined as the convex hull of 100 vertices
sage: gap.f_vector()
(1, 100, 500, 720, 320, 1)
sage: len(list(gap.bounded_edges()))
500
```

## great\_rhombicuboctahedron(exact=True, base\_ring=None, backend=None)

Return the great rhombicuboctahedron.

The great rhombicuboctahedron (or truncated cuboctahedron) is an Archimedean solid with 48 vertices and 26 faces. For more information see the Wikipedia article Truncated\_cuboctahedron.

#### INPUT:

- exact (boolean, default True) If False use an approximate ring for the coordinates.
- base\_ring the ring in which the coordinates will belong to. If it is not provided and exact=True it will be a the number field  $\mathbf{Q}[\phi]$  where  $\phi$  is the golden ratio and if exact=False it will be the real double field.
- backend the backend to use to create the polytope.

#### **EXAMPLES:**

```
sage: gr = polytopes.great_rhombicuboctahedron() # long time ~ 3sec #
    →optional - sage.rings.number_field
sage: gr.f_vector() # long time #
    →optional - sage.rings.number_field
(1, 48, 72, 26, 1)
```

A faster implementation is obtained by setting exact=False:

```
sage: gr = polytopes.great_rhombicuboctahedron(exact=False)
sage: gr.f_vector()
(1, 48, 72, 26, 1)
```

Its facets are 4 squares, 8 regular hexagons and 6 regular octagons:

```
sage: sum(1 for f in gr.facets() if len(f.vertices()) == 4)
12
sage: sum(1 for f in gr.facets() if len(f.vertices()) == 6)
8
sage: sum(1 for f in gr.facets() if len(f.vertices()) == 8)
6
```

# hypercube(dim, intervals=None, backend=None)

Return a hypercube of the given dimension.

The dim-dimensional hypercube is by default the convex hull of the  $2^{\text{dim}} \pm 1$  vectors of length dim. Alternatively, it is the product of dim line segments given in the intervals. For more information see the wikipedia article Wikipedia article Hypercube.

# INPUT:

- dim integer. The dimension of the hypercube.
- intervals (default = None). It takes the following possible inputs:

- If None (the default), it returns the  $\pm 1$ -cube of dimension dim.
- 'zero\_one' (string). Return the 0/1-cube.
- a list of length dim. Its elements are pairs of numbers (a, b) with a < b. The cube will be the product of these intervals.
- backend the backend to use to create the polytope.

#### **EXAMPLES:**

Create the  $\pm 1$ -hypercube of dimension 4:

```
sage: four_cube = polytopes.hypercube(4)
sage: four_cube.is_simple()
True
sage: four_cube.base_ring()
Integer Ring
sage: four_cube.volume()
16
sage: four_cube.ehrhart_polynomial() # optional - latte_int
16*t^4 + 32*t^3 + 24*t^2 + 8*t + 1
```

Return the 0/1-hypercube of dimension 4:

```
sage: z_cube = polytopes.hypercube(4,intervals = 'zero_one')
sage: z_cube.vertices()[0]
A vertex at (1, 0, 1, 1)
sage: z_cube.is_simple()
True
sage: z_cube.base_ring()
Integer Ring
sage: z_cube.volume()
1
sage: z_cube.ehrhart_polynomial() # optional - latte_int
t^4 + 4*t^3 + 6*t^2 + 4*t + 1
```

Return the 4-dimensional combinatorial cube that is the product of [0,3]^4:

```
sage: t_cube = polytopes.hypercube(4, intervals = [[0,3]]*4)
```

Checking that t\_cube is three times the previous 0/1-cube:

```
sage: t_cube == 3 * z_cube
True
```

hypersimplex(dim, k, project=False, backend=None)

Return the hypersimplex in dimension dim and parameter k.

The hypersimplex  $\Delta_{d,k}$  is the convex hull of the vertices made of k ones and d-k zeros. It lies in the d-1 hyperplane of vectors of sum k. If you want a projected version to  $\mathbf{R}^{d-1}$  (with floating point coordinates) then set  $\mathsf{project}$ =True in the options.

### See also:

```
simplex()
```

### INPUT:

• dim – the dimension

- n -the numbers (1, ..., n) are permuted
- project (boolean, default False) if True, the polytope is (isometrically) projected to a vector space of dimension dim-1. This operation turns the coordinates into floating point approximations and corresponds to the projection given by the matrix from zero\_sum\_projection().
- backend the backend to use to create the polytope.

#### **EXAMPLES:**

```
sage: h_4_2 = polytopes.hypersimplex(4, 2)
sage: h_4_2
A 3-dimensional polyhedron in ZZ^4 defined as the convex hull of 6 vertices
sage: h_4_2.f_vector()
(1, 6, 12, 8, 1)
sage: h_4_2.ehrhart_polynomial()  # optional - latte_int
2/3*t^3 + 2*t^2 + 7/3*t + 1
sage: TestSuite(h_4_2).run()

sage: h_7_3 = polytopes.hypersimplex(7, 3, project=True)
sage: h_7_3
A 6-dimensional polyhedron in RDF^6 defined as the convex hull of 35 vertices
sage: h_7_3.f_vector()
(1, 35, 210, 350, 245, 84, 14, 1)
sage: TestSuite(h_7_3).run(skip=["_test_pyramid", "_test_lawrence"])
```

icosahedron(exact=True, base\_ring=None, backend=None)

Return an icosahedron with edge length 1.

The icosahedron is one of the Platonic solids. It has 20 faces and is dual to the *dodecahedron()*.

## INPUT:

- exact (boolean, default True) If False use an approximate ring for the coordinates.
- base\_ring (optional) the ring in which the coordinates will belong to. Note that this ring must contain  $\sqrt(5)$ . If it is not provided and exact=True it will be the number field  $\mathbf{Q}[\sqrt(5)]$  and if exact=False it will be the real double field.
- backend the backend to use to create the polytope.

# **EXAMPLES:**

Its non exact version:

```
sage: ico = polytopes.icosahedron(exact=False)
sage: ico.base_ring()
Real Double Field
sage: ico.volume() # known bug (trac 18214)
2.181694990...
```

A version using AA < sage.rings.qqbar.AlgebraicRealField >:

```
sage: ico = polytopes.icosahedron(base_ring=AA)
                                                   # long time
      # optional - sage.rings.number_field
sage: ico.base_ring()
                                                   # long time
      # optional - sage.rings.number_field
Algebraic Real Field
sage: ico.volume()
                                                   # long time
      # optional - sage.rings.number_field
2.181694990624913?
```

Note that if base ring is provided it must contain the square root of 5. Otherwise you will get an error:

```
sage: polytopes.icosahedron(base_ring=QQ)
      # optional - sage.symbolic
Traceback (most recent call last):
TypeError: unable to convert 1/4*sqrt(5) + 1/4 to a rational
```

## icosidodecahedron(exact=True, backend=None)

Return the icosidodecahedron.

The Icosidodecahedron is a polyhedron with twenty triangular faces and twelve pentagonal faces. For more information see the Wikipedia article Icosidodecahedron.

#### INPUT:

- exact (boolean, default True) If False use an approximate ring for the coordinates.
- backend the backend to use to create the polytope.

### **EXAMPLES:**

```
sage: id = polytopes.icosidodecahedron()
          # optional - sage.rings.number_field
sage: id.f_vector()
          # optional - sage.rings.number_field
(1, 30, 60, 32, 1)
```

## icosidodecahedron\_V2(exact=True, base\_ring=None, backend=None)

Return the icosidodecahedron.

The icosidodecahedron is an Archimedean solid. It has 32 faces and 30 vertices. For more information, see the Wikipedia article Icosidodecahedron.

### INPUT:

- exact (boolean, default True) If False use an approximate ring for the coordinates.
- base\_ring the ring in which the coordinates will belong to. If it is not provided and exact=True it will be a the number field  $\mathbf{Q}[\phi]$  where  $\phi$  is the golden ratio and if exact=False it will be the real double field.
- backend the backend to use to create the polytope.

## **EXAMPLES:**

```
sage: id = polytopes.icosidodecahedron_V2()
                                                  # long time - 6secs
sage: id.f_vector()
                                      # long time
                                                                        (continues on next page)
```

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```
(1, 30, 60, 32, 1)

sage: id.base_ring() # long time

Number Field in sqrt5 with defining polynomial x^2 - 5 with sqrt5 = 2.

→236067977499790?
```

A much faster implementation using floating point approximations:

```
sage: id = polytopes.icosidodecahedron_V2(exact=False)
sage: id.f_vector()
(1, 30, 60, 32, 1)
sage: id.base_ring()
Real Double Field
```

Its facets are 20 triangles and 12 regular pentagons:

```
sage: sum(1 for f in id.facets() if len(f.vertices()) == 3)
20
sage: sum(1 for f in id.facets() if len(f.vertices()) == 5)
12
```

#### octahedron(backend=None)

Return the octahedron.

The octahedron is a Platonic solid with 6 vertices and 8 faces dual to the cube. It can be defined as the convex hull of the six vertices  $(0,0,\pm 1)$ ,  $(\pm 1,0,0)$  and  $(0,\pm 1,0)$ . For more information, see the Wikipedia article Octahedron.

#### INPUT:

• backend – the backend to use to create the polytope.

**EXAMPLES:** 

```
sage: co = polytopes.octahedron()
sage: co.f_vector()
(1, 6, 12, 8, 1)
```

Its facets are 8 triangles:

```
sage: sum(1 for f in co.facets() if len(f.vertices()) == 3)
8
```

Some more computation:

```
sage: co.volume()
4/3
sage: co.ehrhart_polynomial() # optional - latte_int
4/3*t^3 + 2*t^2 + 8/3*t + 1
```

## omnitruncated\_one\_hundred\_twenty\_cell(exact=True, backend=None)

Return the omnitruncated 120-cell.

The omnitruncated 120-cell is a 4-dimensional 4-uniform polytope in the  $H_4$  family. It has 14400 vertices. For more information see Wikipedia article Omnitruncated 120-cell.

**Warning:** The coordinates are exact by default. The computation with inexact coordinates (using the backend 'cdd') returns a numerical inconsistency error, and thus cannot be computed.

#### INPUT:

- exact (boolean, default True) if True use exact coordinates instead of floating point approximations.
- backend the backend to use to create the polytope.

#### **EXAMPLES:**

#### omnitruncated\_six\_hundred\_cell(exact=True, backend=None)

Return the omnitruncated 120-cell.

The omnitruncated 120-cell is a 4-dimensional 4-uniform polytope in the  $H_4$  family. It has 14400 vertices. For more information see Wikipedia article Omnitruncated 120-cell.

**Warning:** The coordinates are exact by default. The computation with inexact coordinates (using the backend 'cdd') returns a numerical inconsistency error, and thus cannot be computed.

#### INPUT:

- exact (boolean, default True) if True use exact coordinates instead of floating point approximations.
- backend the backend to use to create the polytope.

### **EXAMPLES:**

one\_hundred\_twenty\_cell(exact=True, backend=None, construction='coxeter')

Return the 120-cell.

The 120-cell is a 4-dimensional 4-uniform polytope in the  $H_4$  family. It has 600 vertices and 120 facets. For more information see Wikipedia article 120-cell.

**Warning:** The coordinates are exact by default. The computation with inexact coordinates (using the backend 'cdd') returns a numerical inconsistency error, and thus cannot be computed.

## INPUT:

- exact (boolean, default True) if True use exact coordinates instead of floating point approximations.
- backend the backend to use to create the polytope.
- construction the construction to use (string, default 'coxeter'); the other possibility is 'as\_permutahedron'.

## `EXAMPLES:

The classical construction given by Coxeter in [Cox1969] is given by:

```
sage: polytopes.one_hundred_twenty_cell() # not

→tested - long time ~15 sec.
A 4-dimensional polyhedron in (Number Field in sqrt5 with defining
polynomial x^2 - 5 with sqrt5 = 2.236067977499790?)^4 defined as
the convex hull of 600 vertices
```

The 'normaliz' is faster:

It is also possible to realize it using the generalized permutahedron of type  $H_4$ :

### parallelotope(generators, backend=None)

Return the zonotope, or parallelotope, spanned by the generators.

The parallelotope is the multi-dimensional generalization of a parallelogram (2 generators) and a parallelepiped (3 generators).

### INPUT:

- generators a list of vectors of same dimension
- backend the backend to use to create the polytope.

### **EXAMPLES:**

```
sage: polytopes.parallelotope([ (1,0), (0,1) ])
A 2-dimensional polyhedron in ZZ^2 defined as the convex hull of 4 vertices
sage: polytopes.parallelotope([[1,2,3,4],[0,1,0,7],[3,1,0,2],[0,0,1,0]])
A 4-dimensional polyhedron in ZZ^4 defined as the convex hull of 16 vertices

sage: K = QuadraticField(2, 'sqrt2')
sage: sqrt2 = K.gen()
sage: P = polytopes.parallelotope([ (1,sqrt2), (1,-1) ]); P
A 2-dimensional polyhedron in (Number Field in sqrt2 with defining
polynomial x^2 - 2 with sqrt2 = 1.414213562373095?)^2 defined as
the convex hull of 4 vertices
```

#### **pentakis\_dodecahedron**(exact=True, base\_ring=None, backend=None)

Return the pentakis dodecahedron.

The pentakis dodecahedron (orkisdodecahedron) is a face-regular, vertex-uniform polytope dual to the truncated icosahedron. It has 60 facets and 32 vertices. See the Wikipedia article Pentakis\_dodecahedron for more information.

INPUT:

- exact (boolean, default True) If False use an approximate ring for the coordinates.
- base\_ring the ring in which the coordinates will belong to. If it is not provided and exact=True it will be a the number field  $\mathbf{Q}[\phi]$  where  $\phi$  is the golden ratio and if exact=False it will be the real double field.
- backend the backend to use to create the polytope.

#### **EXAMPLES:**

```
sage: pd = polytopes.pentakis_dodecahedron() # long time - ~10 sec
sage: pd.n_vertices() # long time
32
sage: pd.n_inequalities() # long time
60
```

A much faster implementation is obtained when setting exact=False:

```
sage: pd = polytopes.pentakis_dodecahedron(exact=False)
sage: pd.n_vertices()
32
sage: pd.n_inequalities()
60
```

The 60 are triangles:

```
sage: all(len(f.vertices()) == 3 for f in pd.facets())
True
```

# permutahedron(n, project=False, backend=None)

Return the standard permutahedron of (1, ..., n).

The permutahedron (or permutohedron) is the convex hull of the permutations of  $\{1, \ldots, n\}$  seen as vectors. The edges between the permutations correspond to multiplication on the right by an elementary transposition in the SymmetricGroup.

If we take the graph in which the vertices correspond to vertices of the polyhedron, and edges to edges, we get the BubbleSortGraph().

#### INPUT:

- n integer
- project (boolean, default False) if True, the polytope is (isometrically) projected to a vector space of dimension dim-1. This operation turns the coordinates into floating point approximations and corresponds to the projection given by the matrix from zero\_sum\_projection().
- backend the backend to use to create the polytope.

#### **EXAMPLES:**

```
sage: perm4 = polytopes.permutahedron(4)
sage: perm4
A 3-dimensional polyhedron in ZZ^4 defined as the convex hull of 24 vertices
sage: perm4.is_lattice_polytope()
True
sage: perm4.ehrhart_polynomial() # optional - latte_int
16*t^3 + 15*t^2 + 6*t + 1
```

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```
sage: perm4 = polytopes.permutahedron(4, project=True)
sage: perm4
A 3-dimensional polyhedron in RDF^3 defined as the convex hull of 24 vertices
sage: perm4.plot() # optional - sage.plot
Graphics3d Object
sage: perm4.graph().is_isomorphic(graphs.BubbleSortGraph(4))
True
```

As both Hrepresentation an Vrepresentation are known, the permutahedron can be set up with both using the backend field. The following takes very very long time to recompute, e.g. with backend ppl:

#### See also:

• BubbleSortGraph()

# rectified\_one\_hundred\_twenty\_cell(exact=True, backend=None)

Return the rectified 120-cell.

The rectified 120-cell is a 4-dimensional 4-uniform polytope in the  $H_4$  family. It has 1200 vertices. For more information see Wikipedia article Rectified 120-cell.

**Warning:** The coordinates are exact by default. The computation with inexact coordinates (using the backend 'cdd') returns a numerical inconsistency error, and thus cannot be computed.

## INPUT:

- exact (boolean, default True) if True use exact coordinates instead of floating point approximations.
- backend the backend to use to create the polytope.

### **EXAMPLES:**

```
sage: polytopes.rectified_one_hundred_twenty_cell(backend='normaliz') # not

→ tested - long time
A 4-dimensional polyhedron in AA^4 defined as the convex hull of 1200 vertices
```

# rectified\_six\_hundred\_cell(exact=True, backend=None)

Return the rectified 600-cell.

The rectified 600-cell is a 4-dimensional 4-uniform polytope in the  $H_4$  family. It has 720 vertices. For more information see Wikipedia article Rectified 600-cell.

**Warning:** The coordinates are exact by default. The computation with inexact coordinates (using the backend 'cdd') returns a numerical inconsistency error, and thus cannot be computed.

INPUT:

- exact (boolean, default True) if True use exact coordinates instead of floating point approximations.
- backend the backend to use to create the polytope.

### **EXAMPLES:**

### **regular\_polygon**(*n*, *exact=True*, *base\_ring=None*, *backend=None*)

Return a regular polygon with n vertices.

### INPUT:

- n a positive integer, the number of vertices.
- exact (boolean, default True) if False floating point numbers are used for coordinates.
- base\_ring a ring in which the coordinates will lie. It is None by default. If it is not provided and exact is True then it will be the field of real algebraic number, if exact is False it will be the real double field.
- backend the backend to use to create the polytope.

### **EXAMPLES:**

```
sage: octagon = polytopes.regular_polygon(8)
             # optional - sage.rings.number_field
sage: octagon
             # optional - sage.rings.number_field
A 2-dimensional polyhedron in AA^2 defined as the convex hull of 8 vertices
sage: octagon.n_vertices()
             # optional - sage.rings.number_field
8
sage: v = octagon.volume()
             # optional - sage.rings.number_field
sage: v
             # optional - sage.rings.number_field
2.828427124746190?
sage: v == 2*QQbar(2).sqrt()
             # optional - sage.rings.number_field
True
```

Its non exact version:

```
sage: polytopes.regular_polygon(3, exact=False).vertices()
(A vertex at (0.0, 1.0),
  A vertex at (0.8660254038, -0.5),
  A vertex at (-0.8660254038, -0.5))
sage: polytopes.regular_polygon(25, exact=False).n_vertices()
25
```

### rhombic\_dodecahedron(backend=None)

Return the rhombic dodecahedron.

The rhombic dodecahedron is a polytope dual to the cuboctahedron. It has 14 vertices and 12 faces. For more information see the Wikipedia article Rhombic\_dodecahedron.

INPUT:

• backend – the backend to use to create the polytope.

#### See also:

cuboctahedron()

### **EXAMPLES:**

```
sage: rd = polytopes.rhombic_dodecahedron()
sage: rd.f_vector()
(1, 14, 24, 12, 1)
```

Its facets are 12 quadrilaterals (not all identical):

```
sage: sum(1 for f in rd.facets() if len(f.vertices()) == 4)
12
```

Some more computations:

**rhombicosidodecahedron**(exact=True, base\_ring=None, backend=None)

Return the rhombicosidodecahedron.

The rhombicosidodecahedron is an Archimedean solid. It has 62 faces and 60 vertices. For more information, see the Wikipedia article Rhombicosidodecahedron.

### INPUT:

- exact (boolean, default True) If False use an approximate ring for the coordinates.
- base\_ring the ring in which the coordinates will belong to. If it is not provided and exact=True it will be a the number field  $\mathbf{Q}[\phi]$  where  $\phi$  is the golden ratio and if exact=False it will be the real double field.
- backend the backend to use to create the polytope.

### **EXAMPLES:**

A much faster implementation using floating point approximations:

```
sage: rid = polytopes.rhombicosidodecahedron(exact=False)
sage: rid.f_vector()
(1, 60, 120, 62, 1)
sage: rid.base_ring()
Real Double Field
```

Its facets are 20 triangles, 30 squares and 12 pentagons:

```
sage: sum(1 for f in rid.facets() if len(f.vertices()) == 3)
20
sage: sum(1 for f in rid.facets() if len(f.vertices()) == 4)
30
sage: sum(1 for f in rid.facets() if len(f.vertices()) == 5)
12
```

### runcinated\_one\_hundred\_twenty\_cell(exact=False, backend=None)

Return the runcinated 120-cell.

The runcinated 120-cell is a 4-dimensional 4-uniform polytope in the  $H_4$  family. It has 2400 vertices. For more information see Wikipedia article Runcinated 120-cell.

**Warning:** The coordinates are inexact by default. The computation with inexact coordinates (using the backend 'cdd') issues a UserWarning on inconsistencies.

#### INPUT:

- exact (boolean, default False) if True use exact coordinates instead of floating point approximations.
- backend the backend to use to create the polytope.

#### **EXAMPLES:**

It is possible to use the backend 'normaliz' to get an exact representation:

## runcitruncated\_one\_hundred\_twenty\_cell(exact=False, backend=None)

Return the runcitruncated 120-cell.

The runcitruncated 120-cell is a 4-dimensional 4-uniform polytope in the  $H_4$  family. It has 7200 vertices. For more information see Wikipedia article Runcitruncated 120-cell.

**Warning:** The coordinates are inexact by default. The computation with inexact coordinates (using the backend 'cdd') issues a UserWarning on inconsistencies.

#### INPUT:

exact - (boolean, default False) if True use exact coordinates instead of floating point approximations.

• backend – the backend to use to create the polytope.

#### **EXAMPLES:**

It is possible to use the backend 'normaliz' to get an exact representation:

## runcitruncated\_six\_hundred\_cell(exact=True, backend=None)

Return the runcitruncated 600-cell.

The runcitruncated 600-cell is a 4-dimensional 4-uniform polytope in the  $H_4$  family. It has 7200 vertices. For more information see Wikipedia article Runcitruncated 600-cell.

**Warning:** The coordinates are exact by default. The computation with inexact coordinates (using the backend 'cdd') returns a numerical inconsistency error, and thus cannot be computed.

## INPUT:

- exact (boolean, default True) if True use exact coordinates instead of floating point approximations.
- backend the backend to use to create the polytope.

## **EXAMPLES:**

simplex(dim=3, project=False, base\_ring=None, backend=None)

Return the dim dimensional simplex.

The *d*-simplex is the convex hull in  $\mathbf{R}^{d+1}$  of the standard basis  $(1,0,\ldots,0)$ ,  $(0,1,\ldots,0)$ , Idots,  $(0,0,\ldots,1)$ . For more information, see the Wikipedia article Simplex.

### INPUT:

- dim The dimension of the simplex, a positive integer.
- project (boolean, default False) if True, the polytope is (isometrically) projected to a vector space of dimension dim-1. This corresponds to the projection given by the matrix from zero\_sum\_projection(). By default, this operation turns the coordinates into floating point approximations (see base\_ring).
- base\_ring the base ring to use to create the polytope. If project is False, this defaults to **Z**. Otherwise, it defaults to RDF.

• backend – the backend to use to create the polytope.

#### See also:

tetrahedron()

### **EXAMPLES:**

```
sage: s5 = polytopes.simplex(5)
sage: s5
A 5-dimensional polyhedron in ZZ^6 defined as the convex hull of 6 vertices
sage: s5.f_vector()
(1, 6, 15, 20, 15, 6, 1)
sage: s5 = polytopes.simplex(5, project=True)
sage: s5
A 5-dimensional polyhedron in RDF^5 defined as the convex hull of 6 vertices
```

Its volume is  $\sqrt{d+1}/d!$ :

```
sage: s5 = polytopes.simplex(5, project=True)
sage: s5.volume()  # abs tol 1e-10
0.0204124145231931
sage: sqrt(6.) / factorial(5)
0.0204124145231931

sage: s6 = polytopes.simplex(6, project=True)
sage: s6.volume()  # abs tol 1e-10
0.00367465459870082
sage: sqrt(7.) / factorial(6)
0.00367465459870082
```

Computation in algebraic reals:

## six\_hundred\_cell(exact=False, backend=None)

Return the standard 600-cell polytope.

The 600-cell is a 4-dimensional regular polytope. In many ways this is an analogue of the icosahedron.

**Warning:** The coordinates are not exact by default. The computation with exact coordinates takes a huge amount of time.

## INPUT:

- exact (boolean, default False) if True use exact coordinates instead of floating point approximations
- backend the backend to use to create the polytope.

**EXAMPLES:** 

```
sage: p600 = polytopes.six_hundred_cell()
sage: p600
A 4-dimensional polyhedron in RDF^4 defined as the convex hull of 120 vertices
sage: p600.f_vector() # long time ~2sec
(1, 120, 720, 1200, 600, 1)
```

Computation with exact coordinates is currently too long to be useful:

### **small\_rhombicuboctahedron**(exact=True, base\_ring=None, backend=None)

Return the (small) rhombicuboctahedron.

The rhombicuboctahedron is an Archimedean solid with 24 vertices and 26 faces. See the Wikipedia article Rhombicuboctahedron for more information.

#### INPUT:

- exact (boolean, default True) If False use an approximate ring for the coordinates.
- base\_ring the ring in which the coordinates will belong to. If it is not provided and exact=True it will be a the number field  $\mathbf{Q}[\phi]$  where  $\phi$  is the golden ratio and if exact=False it will be the real double field.
- backend the backend to use to create the polytope.

#### **EXAMPLES:**

The faces are 8 equilateral triangles and 18 squares:

```
sage: sum(1 for f in sr.facets() if len(f.vertices()) == 3)  # optional -
    sage.rings.number_field
8
sage: sum(1 for f in sr.facets() if len(f.vertices()) == 4)  # optional -
    sage.rings.number_field
18
```

Its non exact version:

```
sage: sr = polytopes.small_rhombicuboctahedron(False)
sage: sr
A 3-dimensional polyhedron in RDF^3 defined as the convex hull of
24 vertices
```

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Wikipedia article Snub cube.

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```
sage: sr.f_vector()
(1, 24, 48, 26, 1)
```

**snub\_cube**(*exact=False*, *base\_ring=None*, *backend=None*, *verbose=False*)
Return a snub cube.

The snub cube is an Archimedean solid. It has 24 vertices and 38 faces. For more information see the

The constant z used in constructing this polytope is the reciprocal of the tribonacci constant, that is, the solution of the equation  $x^3 + x^2 + x - 1 = 0$ . See Wikipedia article Generalizations\_of\_Fibonacci\_numbers#Tribonacci\_numbers.

#### INPUT:

- exact (boolean, default False) if True use exact coordinates instead of floating point approximations
- base\_ring the field to use. If None (the default), construct the exact number field needed (if exact is True) or default to RDF (if exact is True).
- backend the backend to use to create the polytope. If None (the default), the backend will be selected automatically.

#### **EXAMPLES:**

```
sage: sc_inexact = polytopes.snub_cube(exact=False); sc_inexact
→# optional - sage.groups
A 3-dimensional polyhedron in RDF^3 defined as the convex hull of 24 vertices
sage: sc_inexact.f_vector()
→# optional - sage.groups
(1, 24, 60, 38, 1)
sage: sc_exact = polytopes.snub_cube(exact=True)
                                                           # long time
→# optional - sage.groups sage.rings.number_field
sage: sc_exact.f_vector()
                                                           # long time
→# optional - sage.groups sage.rings.number_field
(1, 24, 60, 38, 1)
sage: sorted(sc_exact.vertices())
                                                           # long time
→# optional - sage.groups sage.rings.number_field
[A vertex at (-1, -z, -z^2),
A vertex at (-1, -z^2, z),
A vertex at (-1, z^2, -z),
A vertex at (-1, z, z^2),
A vertex at (-z, -1, z^2),
A vertex at (-z, -z^2, -1),
A vertex at (-z, z^2, 1),
A vertex at (-z, 1, -z^2),
A vertex at (-z^2, -1, -z),
A vertex at (-z^2, -z, 1),
A vertex at (-z^2, z, -1),
A vertex at (-z^2, 1, z),
A vertex at (z^2, -1, z),
A vertex at (z^2, -z, -1),
A vertex at (z^2, z, 1),
A vertex at (z^2, 1, -z),
A vertex at (z, -1, -z^2),
```

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```
A vertex at (z, -z^2, 1),
A vertex at (z, z^2, -1),
A vertex at (z, 1, z^2),
A vertex at (1, -z, z^2),
A vertex at (1, -z, z^2),
A vertex at (1, z^2, z),
A vertex at (1, z^2, z),
A vertex at (1, z, -z^2)]

sage: sc_exact.is_combinatorially_isomorphic(sc_inexact) # long time

# optional - sage.groups sage.rings.number_field

True
```

# snub\_dodecahedron(base\_ring=None, backend=None, verbose=False)

Return the snub dodecahedron.

The snub dodecahedron is an Archimedean solid. It has 92 faces and 60 vertices. For more information, see the Wikipedia article Snub\_dodecahedron.

### INPUT:

- base\_ring the ring in which the coordinates will belong to. If it is not provided it will be the real double field.
- backend the backend to use to create the polytope.

#### **EXAMPLES:**

Only the backend using the optional normaliz package can construct the snub dodecahedron in reasonable time:

Its facets are 80 triangles and 12 pentagons:

## static symmetric\_edge\_polytope(backend=None)

Return the symmetric edge polytope of self.

The symmetric edge polytope (SEP) of a Graph on n vertices is the polytope in  $\mathbb{Z}^n$  defined as the convex hull of  $e_i - e_j$  and  $e_j - e_i$  for each edge (i, j). Here  $e_1, \dots, e_n$  denotes the standard basis.

#### INPUT:

• backend — string or None (default); the backend to use; see sage.geometry.polyhedron.
constructor.Polyhedron()

#### **EXAMPLES:**

The SEP of a 4-cycle is a cube:

```
sage: G = graphs.CycleGraph(4)
sage: P = G.symmetric_edge_polytope(); P
A 3-dimensional polyhedron in ZZ^4 defined as the convex hull of 8 vertices
sage: P.is_combinatorially_isomorphic(polytopes.cube())
True
```

The SEP of a complete graph on 4 vertices is a cuboctahedron:

```
sage: G = graphs.CompleteGraph(4)
sage: P = G.symmetric_edge_polytope(); P
A 3-dimensional polyhedron in ZZ^4 defined as the convex hull of 12 vertices
sage: P.is_combinatorially_isomorphic(polytopes.cuboctahedron())
True
```

The SEP of a graph with edges on n vertices has dimension n minus the number of connected components:

```
sage: n = randint(5, 12)
sage: G = Graph()
sage: while not G.num_edges():
...: G = graphs.RandomGNP(n, 0.2)
sage: P = G.symmetric_edge_polytope()
sage: P.ambient_dim() == n
True
sage: P.dim() == n - G.connected_components_number()
True
```

The SEP of a graph is isomorphic to the subdirect sum of its connected components SEP's:

```
sage: n = randint(3, 6)
sage: G1 = graphs.RandomGNP(n, 0.2)
sage: n = randint(3, 6)
sage: G2 = graphs.RandomGNP(n, 0.2)
sage: G = G1.disjoint_union(G2)
sage: P = G.symmetric_edge_polytope()
sage: P1 = G1.symmetric_edge_polytope()
sage: P2 = G2.symmetric_edge_polytope()
sage: P.is_combinatorially_isomorphic(P1.subdirect_sum(P2))
True
```

All trees on n vertices have isomorphic SEPs:

```
sage: n = randint(4, 10)
sage: G1 = graphs.RandomTree(n)
sage: G2 = graphs.RandomTree(n)
sage: P1 = G1.symmetric_edge_polytope()
sage: P2 = G2.symmetric_edge_polytope()
sage: P1.is_combinatorially_isomorphic(P2)
True
```

However, there are still many different SEPs:

```
sage: len(list(graphs(5)))
34
sage: polys = []
sage: for G in graphs(5):
          P = G.symmetric_edge_polytope()
           for P1 in polys:
               if P.is_combinatorially_isomorphic(P1):
. . . . .
. . . . .
                    break
          else:
. . . . :
               polys.append(P)
. . . . :
sage: len(polys)
25
```

A non-trivial example of two graphs with isomorphic SEPs:

```
sage: G1 = graphs.CycleGraph(4)
sage: G1.add_edges([[0, 5], [5, 2], [1, 6], [6, 2]])
sage: G2 = copy(G1)
sage: G1.add_edges([[2, 7], [7, 3]])
sage: G2.add_edges([[0, 7], [7, 3]])
sage: G1.is_isomorphic(G2)
False
sage: P1 = G1.symmetric_edge_polytope()
sage: P2 = G2.symmetric_edge_polytope()
sage: P1.is_combinatorially_isomorphic(P2)
True
```

Apparently, glueing two graphs together on a vertex gives isomorphic SEPs:

```
sage: n = randint(3, 7)
sage: g1 = graphs.RandomGNP(n, 0.2)
sage: g2 = graphs.RandomGNP(n, 0.2)
sage: G = g1.disjoint_union(g2)
sage: H = copy(G)
sage: G.merge_vertices(((0, randrange(n)), (1, randrange(n))))
sage: H.merge_vertices(((0, randrange(n)), (1, randrange(n))))
sage: PG = G.symmetric_edge_polytope()
sage: PH = H.symmetric_edge_polytope()
sage: PG.is_combinatorially_isomorphic(PH)
True
```

# tetrahedron(backend=None)

Return the tetrahedron.

The tetrahedron is a Platonic solid with 4 vertices and 4 faces dual to itself. It can be defined as the convex hull of the 4 vertices (0,0,0), (1,1,0), (1,0,1) and (0,1,1). For more information, see the Wikipedia article Tetrahedron.

### INPUT:

• backend – the backend to use to create the polytope.

#### See also:

```
simplex()
```

**EXAMPLES:** 

```
sage: co = polytopes.tetrahedron()
sage: co.f_vector()
(1, 4, 6, 4, 1)
```

Its facets are 4 triangles:

```
sage: sum(1 for f in co.facets() if len(f.vertices()) == 3)
4
```

Some more computation:

```
sage: co.volume()
1/3
sage: co.ehrhart_polynomial() # optional - latte_int
1/3*t^3 + t^2 + 5/3*t + 1
```

**truncated\_cube**(exact=True, base\_ring=None, backend=None)

Return the truncated cube.

The truncated cube is an Archimedean solid with 24 vertices and 14 faces. It can be defined as the convex hull of the 24 vertices  $(\pm x, \pm 1, \pm 1), (\pm 1, \pm x, \pm 1), (\pm 1, \pm x, \pm 1)$  where  $x = \sqrt(2) - 1$ . For more information, see the Wikipedia article Truncated\_cube.

INPUT:

- exact (boolean, default True) If False use an approximate ring for the coordinates.
- base\_ring the ring in which the coordinates will belong to. If it is not provided and exact=True it will be a the number field  $\mathbf{Q}[\sqrt{2}]$  and if exact=False it will be the real double field.
- backend the backend to use to create the polytope.

**EXAMPLES:** 

```
sage: co = polytopes.truncated_cube()
    # optional - sage.rings.number_field
sage: co.f_vector()
    # optional - sage.rings.number_field
(1, 24, 36, 14, 1)
```

Its facets are 8 triangles and 6 octogons:

```
sage: sum(1 for f in co.facets() if len(f.vertices()) == 3)

    # optional - sage.rings.number_field
8
sage: sum(1 for f in co.facets() if len(f.vertices()) == 8)

    # optional - sage.rings.number_field
6
```

Some more computation:

**truncated\_dodecahedron**(exact=True, base\_ring=None, backend=None)

Return the truncated dodecahedron.

The truncated dodecahedron is an Archimedean solid. It has 32 faces and 60 vertices. For more information, see the Wikipedia article Truncated dodecahedron.

#### INPUT:

- exact (boolean, default True) If False use an approximate ring for the coordinates.
- base\_ring the ring in which the coordinates will belong to. If it is not provided and exact=True it will be a the number field  $\mathbf{Q}[\phi]$  where  $\phi$  is the golden ratio and if exact=False it will be the real double field.
- backend the backend to use to create the polytope.

#### **EXAMPLES:**

Its facets are 20 triangles and 12 regular decagons:

```
sage: sum(1 for f in td.facets() if len(f.vertices()) == 3)
20
sage: sum(1 for f in td.facets() if len(f.vertices()) == 10)
12
```

The faster implementation using floating point approximations does not fully work unfortunately, see https://github.com/cddlib/cddlib/pull/7 for a detailed discussion of this case:

```
sage: td = polytopes.truncated_dodecahedron(exact=False) # random
doctest:warning
...
UserWarning: This polyhedron data is numerically complicated; cdd
could not convert between the inexact V and H representation
without loss of data. The resulting object might show
inconsistencies.
sage: td.f_vector()
Traceback (most recent call last):
...
ValueError: not all vertices are intersections of facets
sage: td.base_ring()
Real Double Field
```

# truncated\_icosidodecahedron(exact=True, base\_ring=None, backend=None)

Return the truncated icosidodecahedron.

The truncated icosidodecahedron is an Archimedean solid. It has 62 faces and 120 vertices. For more information, see the Wikipedia article Truncated\_icosidodecahedron.

### INPUT:

- exact (boolean, default True) If False use an approximate ring for the coordinates.
- base\_ring the ring in which the coordinates will belong to. If it is not provided and exact=True it will be a the number field  $\mathbf{Q}[\phi]$  where  $\phi$  is the golden ratio and if exact=False it will be the real double field.

• backend – the backend to use to create the polytope.

#### **EXAMPLES:**

The implementation using floating point approximations is much faster:

```
sage: ti = polytopes.truncated_icosidodecahedron(exact=False) # random
sage: ti.f_vector()
(1, 120, 180, 62, 1)
sage: ti.base_ring()
Real Double Field
```

Its facets are 30 squares, 20 hexagons and 12 decagons:

```
sage: sum(1 for f in ti.facets() if len(f.vertices()) == 4)
30
sage: sum(1 for f in ti.facets() if len(f.vertices()) == 6)
20
sage: sum(1 for f in ti.facets() if len(f.vertices()) == 10)
12
```

## truncated\_octahedron(backend=None)

Return the truncated octahedron.

The truncated octahedron is an Archimedean solid with 24 vertices and 14 faces. It can be defined as the convex hull off all the permutations of  $(0, \pm 1, \pm 2)$ . For more information, see the Wikipedia article Truncated\_octahedron.

This is also known as the permutohedron of dimension 3.

# INPUT:

• backend – the backend to use to create the polytope.

#### **EXAMPLES:**

```
sage: co = polytopes.truncated_octahedron()
sage: co.f_vector()
(1, 24, 36, 14, 1)
```

Its facets are 6 squares and 8 hexagons:

```
sage: sum(1 for f in co.facets() if len(f.vertices()) == 4)
6
sage: sum(1 for f in co.facets() if len(f.vertices()) == 6)
8
```

Some more computation:

```
sage: co.volume()
32
sage: co.ehrhart_polynomial() # optional - latte_int
32*t^3 + 18*t^2 + 6*t + 1
```

## truncated\_one\_hundred\_twenty\_cell(exact=True, backend=None)

Return the truncated 120-cell.

The truncated 120-cell is a 4-dimensional 4-uniform polytope in the  $H_4$  family. It has 2400 vertices. For more information see Wikipedia article Truncated 120-cell.

**Warning:** The coordinates are exact by default. The computation with inexact coordinates (using the backend 'cdd') returns a numerical inconsistency error, and thus cannot be computed.

## INPUT:

- exact (boolean, default True) if True use exact coordinates instead of floating point approximations.
- backend the backend to use to create the polytope.

#### **EXAMPLES:**

## truncated\_six\_hundred\_cell(exact=False, backend=None)

Return the truncated 600-cell.

The truncated 600-cell is a 4-dimensional 4-uniform polytope in the  $H_4$  family. It has 1440 vertices. For more information see Wikipedia article Truncated 600-cell.

**Warning:** The coordinates are not exact by default. The computation with exact coordinates takes a huge amount of time.

#### INPUT:

- exact (boolean, default False) if True use exact coordinates instead of floating point approximations
- backend the backend to use to create the polytope.

#### **EXAMPLES:**

```
sage: polytopes.truncated_six_hundred_cell() # not tested - long time
A 4-dimensional polyhedron in RDF^4 defined as the convex hull of 1440 vertices
```

It is possible to use the backend 'normaliz' to get an exact representation:

#### truncated\_tetrahedron(backend=None)

Return the truncated tetrahedron.

The truncated tetrahedron is an Archimedean solid with 12 vertices and 8 faces. It can be defined as the convex hull off all the permutations of  $(\pm 1, \pm 1, \pm 3)$  with an even number of minus signs. For more information, see the Wikipedia article Truncated tetrahedron.

## INPUT:

• backend – the backend to use to create the polytope.

#### **EXAMPLES:**

```
sage: co = polytopes.truncated_tetrahedron()
sage: co.f_vector()
(1, 12, 18, 8, 1)
```

Its facets are 4 triangles and 4 hexagons:

```
sage: sum(1 for f in co.facets() if len(f.vertices()) == 3)
4
sage: sum(1 for f in co.facets() if len(f.vertices()) == 6)
4
```

Some more computation:

```
sage: co.volume()
184/3
sage: co.ehrhart_polynomial() # optional - latte_int
184/3*t^3 + 28*t^2 + 26/3*t + 1
```

## twenty\_four\_cell(backend=None)

Return the standard 24-cell polytope.

The 24-cell polyhedron (also called icositetrachoron or octaplex) is a regular polyhedron in 4-dimension. For more information see the Wikipedia article 24-cell.

#### INPUT:

• backend – the backend to use to create the polytope.

# **EXAMPLES:**

```
sage: p24 = polytopes.twenty_four_cell()
sage: p24.f_vector()
(1, 24, 96, 96, 24, 1)
sage: v = next(p24.vertex_generator())
sage: for adj in v.neighbors(): print(adj)
A vertex at (-1/2, -1/2, -1/2, 1/2)
A vertex at (-1/2, -1/2, 1/2, -1/2)
A vertex at (-1, 0, 0, 0)
A vertex at (-1/2, 1/2, -1/2, -1/2)
A vertex at (0, -1, 0, 0)
A vertex at (0, 0, -1, 0)
A vertex at (0, 0, 0, -1)
A vertex at (1/2, -1/2, -1/2, -1/2)
sage: p24.volume()
```

#### **zonotope**(generators, backend=None)

Return the zonotope, or parallelotope, spanned by the generators.

The parallelotope is the multi-dimensional generalization of a parallelogram (2 generators) and a parallelepiped (3 generators).

### INPUT:

- generators a list of vectors of same dimension
- backend the backend to use to create the polytope.

#### **EXAMPLES:**

```
sage: polytopes.parallelotope([ (1,0), (0,1) ])
A 2-dimensional polyhedron in ZZ^2 defined as the convex hull of 4 vertices
sage: polytopes.parallelotope([[1,2,3,4],[0,1,0,7],[3,1,0,2],[0,0,1,0]])
A 4-dimensional polyhedron in ZZ^4 defined as the convex hull of 16 vertices

sage: K = QuadraticField(2, 'sqrt2')
sage: sqrt2 = K.gen()
sage: P = polytopes.parallelotope([ (1,sqrt2), (1,-1) ]); P
A 2-dimensional polyhedron in (Number Field in sqrt2 with defining
polynomial x^2 - 2 with sqrt2 = 1.414213562373095?)^2 defined as
the convex hull of 4 vertices
```

Return the polytope associated to the list of vectors forming a Gale transform.

This function is the inverse of gale\_transform() up to projective transformation.

## INPUT:

- vectors the vectors of the Gale transform
- $\bullet$  base\_ring string (default: None); the base ring to be used for the construction
- backend string (default: *None*); the backend to use to create the polytope

**Note:** The order of the input vectors will not be preserved.

If the center of the (input) vectors is the origin, the function is much faster and might give a nicer representation of the polytope.

If this is not the case, the vectors will be scaled (each by a positive scalar) accordingly to obtain the polytope.

## See also:

:func`~sage.geometry.polyhedron.library.gale\_transform\_to\_primal`.

## **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.library import gale_transform_to_polytope
sage: points = polytopes.octahedron().gale_transform()
sage: points
((0, -1), (-1, 0), (1, 1), (1, 1), (-1, 0), (0, -1))
sage: P = gale_transform_to_polytope(points); P
A 3-dimensional polyhedron in ZZ^3 defined as the convex hull of 6 vertices
```

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```
sage: P.vertices()
(A vertex at (-1, 0, 0),
  A vertex at (0, -1, 0),
  A vertex at (0, 0, -1),
  A vertex at (0, 0, 1),
  A vertex at (0, 1, 0),
  A vertex at (1, 0, 0))
```

One can specify the base ring:

```
sage: gale_transform_to_polytope(
          [(1,1), (-1,-1), (1,0),
           (-1,0), (1,-1), (-2,1)]).vertices()
(A vertex at (-25, 0, 0),
A vertex at (-15, 50, -60),
A vertex at (0, -25, 0),
A vertex at (0, 0, -25),
A vertex at (16, -35, 54),
A vertex at (24, 10, 31))
sage: gale_transform_to_polytope(
         [(1,1), (-1,-1), (1,0),
          (-1,0), (1,-1), (-2,1)],
. . . . :
          base_ring=RDF).vertices()
. . . . :
(A vertex at (-0.64, 1.4, -2.16),
A vertex at (-0.96, -0.4, -1.24),
A vertex at (0.6, -2.0, 2.4),
A vertex at (1.0, 0.0, 0.0),
A vertex at (0.0, 1.0, 0.0),
A vertex at (0.0, 0.0, 1.0)
```

One can also specify the backend:

```
sage: gale_transform_to_polytope(
....:     [(1,1), (-1,-1), (1,0),
....:     (-1,0), (1,-1), (-2,1)],
....:     backend='field').backend()
'field'
sage: gale_transform_to_polytope(
....:     [(1,1), (-1,-1), (1,0),
....:     (-1,0), (1,-1), (-2,1)],
....:     backend='cdd', base_ring=RDF).backend()
'cdd'
```

A gale transform corresponds to a polytope if and only if every oriented (linear) hyperplane has at least two vectors on each side. See Theorem 6.19 of [Zie2007]. If this is not the case, one of two errors is raised.

If there is such a hyperplane with no vector on one side, the vectors are not totally cyclic:

```
sage: gale_transform_to_polytope([(0,1), (1,1), (1,0), (-1,0)])
Traceback (most recent call last):
...
ValueError: input vectors not totally cyclic
```

If every hyperplane has at least one vector on each side, then the gale transform corresponds to a point config-

uration. It corresponds to a polytope if and only if this point configuration is convex and if and only if every hyperplane contains at least two vectors of the gale transform on each side.

If this is not the case, an error is raised:

```
sage: gale_transform_to_polytope([(0,1), (1,1), (1,0), (-1,-1)])
Traceback (most recent call last):
...
ValueError: the gale transform does not correspond to a polytope
```

Return a point configuration dual to a totally cyclic vector configuration.

This is the dehomogenized vector configuration dual to the input. The dual vector configuration is acyclic and can therefore be dehomogenized as the input is totally cyclic.

#### INPUT:

- vectors the ordered vectors of the Gale transform
- base\_ring string (default: *None*); the base ring to be used for the construction
- backend string (default: *None*); the backend to be use to construct a polyhedral, used internally in case the center is not the origin, see *Polyhedron()*

OUTPUT: An ordered point configuration as list of vectors.

**Note:** If the center of the (input) vectors is the origin, the function is much faster and might give a nicer representation of the point configuration.

If this is not the case, the vectors will be scaled (each by a positive scalar) accordingly.

## ALGORITHM:

Step 1: If the center of the (input) vectors is not the origin, we do an appropriate transformation to make it so.

Step 2: We add a row of ones on top of Matrix(vectors). The right kernel of this larger matrix is the dual configuration space, and a basis of this space provides the dual point configuration.

More concretely, the dual vector configuration (inhomogeneous) is obtained by taking a basis of the right kernel of Matrix(vectors). If the center of the (input) vectors is the origin, there exists a basis of the right kernel of the form [[1], [V]], where [1] represents a row of ones. Then, V is a dehomogenization and thus the dual point configuration.

To extend [1] to a basis of Matrix(vectors), we add a row of ones to Matrix(vectors) and calculate a basis of the right kernel of the obtained matrix.

## **REFERENCES:**

For more information, see Section 6.4 of [Zie2007] or Definition 2.5.1 and Definition 4.1.35 of [DLRS2010].

### See also:

:func`~sage.geometry.polyhedron.library.gale\_transform\_to\_polytope`.

### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.library import gale_transform_to_primal
sage: points = ((0, -1), (-1, 0), (1, 1), (1, 1), (-1, 0), (0, -1))
sage: gale_transform_to_primal(points)
[(0, 0, 1), (0, 1, 0), (1, 0, 0), (-1, 0, 0), (0, -1, 0), (0, 0, -1)]
```

One can specify the base ring:

```
sage: gale_transform_to_primal(
          [(1,1), (-1,-1), (1,0),
. . . . . .
. . . . :
           (-1,0), (1,-1), (-2,1)]
[(16, -35, 54),
(24, 10, 31),
(-15, 50, -60),
(-25, 0, 0),
(0, -25, 0),
(0, 0, -25)]
sage: gale_transform_to_primal(
          [(1,1),(-1,-1),(1,0),(-1,0),(1,-1),(-2,1)], base_ring=RDF)
[(-0.640000000000001, 1.4, -2.1600000000000000),
(-0.9600000000000000, -0.39999999999999, -1.24000000000000000)
(0.6000000000000001, -2.0, 2.4000000000000000),
(1.0, 0.0, 0.0),
(0.0, 1.0, 0.0),
(0.0, 0.0, 1.0)
```

One can also specify the backend to be used internally:

```
sage: gale_transform_to_primal(
. . . . . .
          [(1,1), (-1,-1), (1,0),
. . . . :
            (-1,0), (1,-1), (-2,1)], backend='field')
[(48, -71, 88),
(84, -28, 99),
(-77, 154, -132),
(-55, 0, 0),
(0, -55, 0),
(0, 0, -55)
sage: gale_transform_to_primal(
                                                             # optional - pynormaliz
          [(1,1), (-1,-1), (1,0),
. . . . . .
           (-1,0), (1,-1), (-2,1)], backend='normaliz')
. . . . . .
[(16, -35, 54),
(24, 10, 31),
(-15, 50, -60),
(-25, 0, 0),
(0, -25, 0),
 (0, 0, -25)
```

The input vectors should be totally cyclic:

```
sage: gale_transform_to_primal([(0,1), (1,0), (1,1), (-1,0)])
Traceback (most recent call last):
...
ValueError: input vectors not totally cyclic
```

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```
sage: gale_transform_to_primal(
....: [(1,1,0), (-1,-1,0), (1,0,0),
....: (-1,0,0), (1,-1,0), (-2,1,0)], backend='field')
Traceback (most recent call last):
...
ValueError: input vectors not totally cyclic
```

sage.geometry.polyhedron.library.project\_points(\*points, \*\*kwds)

Projects a set of points into a vector space of dimension one less.

#### INPUT:

- points... the points to project.
- base\_ring (defaults to RDF if keyword is None or not provided in kwds) the base ring to use.

The projection is isometric to the orthogonal projection on the hyperplane made of zero sum vector. Hence, if the set of points have all equal sums, then their projection is isometric (as a set of points).

The projection used is the matrix given by zero\_sum\_projection().

#### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.library import project_points
sage: project_points([2,-1,3,2])  # abs tol 1e-15
[(2.1213203435596424, -2.041241452319315, -0.577350269189626)]
sage: project_points([1,2,3],[3,3,5])  # abs tol 1e-15
[(-0.7071067811865475, -1.2247448713915892), (0.0, -1.6329931618554523)]
```

These projections are compatible with the restriction. More precisely, given a vector v, the projection of v restricted to the first i coordinates will be equal to the projection of the first i + 1 coordinates of v:

```
sage: project_points([1,2]) # abs tol 1e-15
[(-0.7071067811865475)]
sage: project_points([1,2,3]) # abs tol 1e-15
[(-0.7071067811865475, -1.2247448713915892)]
sage: project_points([1,2,3,4]) # abs tol 1e-15
[(-0.7071067811865475, -1.2247448713915892, -1.7320508075688776)]
sage: project_points([1,2,3,4,0]) # abs tol 1e-15
[(-0.7071067811865475, -1.2247448713915892, -1.7320508075688776, 2.23606797749979)]
```

Check that it is (almost) an isometry:

Example with exact computation:

sage.geometry.polyhedron.library.zero\_sum\_projection(d, base\_ring=None)

Return a matrix corresponding to the projection on the orthogonal of  $(1, 1, \dots, 1)$  in dimension d.

The projection maps the orthonormal basis  $(1,-1,0,\ldots,0)/\sqrt(2)$ ,  $(1,1,-1,0,\ldots,0)/\sqrt(3)$ , Idots,  $(1,1,\ldots,1,-1)/\sqrt(d)$  to the canonical basis in  $\mathbf{R}^{d-1}$ .

### **OUTPUT**:

A matrix of dimensions  $(d-1) \times d$  defined over base\_ring (default: RDF).

#### **EXAMPLES:**

Exact computation in AA:

## 2.1.2 Polyhedra

In this module, a polyhedron is a convex (possibly unbounded) set in Euclidean space cut out by a finite set of linear inequalities and linear equations. Note that the dimension of the polyhedron can be less than the dimension of the ambient space. There are two complementary representations of the same data:

**H(alf-space/Hyperplane)-representation** This describes a polyhedron as the common solution set of a finite number of

- linear inequalities  $A\vec{x} + b \ge 0$ , and
- linear equations  $C\vec{x} + d = 0$ .

**V(ertex)-representation** The other representation is as the convex hull of vertices (and rays and lines to all for unbounded polyhedra) as generators. The polyhedron is then the Minkowski sum

$$P = \text{conv}\{v_1, \dots, v_k\} + \sum_{i=1}^{m} \mathbf{R}_{+} r_i + \sum_{j=1}^{n} \mathbf{R} \ell_j$$

where

- vertices  $v_1, \ldots, v_k$  are a finite number of points. Each vertex is specified by an arbitrary vector, and two points are equal if and only if the vector is the same.
- rays  $r_1, \ldots, r_m$  are a finite number of directions (directions of infinity). Each ray is specified by a non-zero vector, and two rays are equal if and only if the vectors are the same up to rescaling with a positive constant.
- lines  $\ell_1, \ldots, \ell_n$  are a finite number of unoriented directions. In other words, a line is equivalent to the set  $\{r, -r\}$  for a ray r. Each line is specified by a non-zero vector, and two lines are equivalent if and only if the vectors are the same up to rescaling with a non-zero (possibly negative) constant.

When specifying a polyhedron, you can input a non-minimal set of inequalities/equations or generating vertices/rays/lines. The non-minimal generators are usually called points, non-extremal rays, and non-extremal lines, but for our purposes it is more convenient to always talk about vertices/rays/lines. Sage will remove any superfluous representation objects and always return a minimal representation. For example, (0,0) is a superfluous vertex here:

```
sage: triangle = Polyhedron(vertices=[(0,2), (-1,0), (1,0), (0,0)])
sage: triangle.vertices()
(A vertex at (-1, 0), A vertex at (1, 0), A vertex at (0, 2))
```

#### See also:

If one only needs to keep track of a system of linear system of inequalities, one should also consider the class for mixed integer linear programming.

• Mixed Integer Linear Programming

## **Unbounded Polyhedra**

A polytope is defined as a bounded polyhedron. In this case, the minimal representation is unique and a vertex of the minimal representation is equivalent to a 0-dimensional face of the polytope. This is why one generally does not distinguish vertices and 0-dimensional faces. But for non-bounded polyhedra we have to allow for a more general notion of "vertex" in order to make sense of the Minkowski sum presentation:

```
sage: half_plane = Polyhedron(ieqs=[(0,1,0)])
sage: half_plane.Hrepresentation()
(An inequality (1, 0) x + 0 >= 0,)
sage: half_plane.Vrepresentation()
(A line in the direction (0, 1), A ray in the direction (1, 0), A vertex at (0, 0))
```

Note how we need a point in the above example to anchor the ray and line. But any point on the boundary of the half-plane would serve the purpose just as well. Sage picked the origin here, but this choice is not unique. Similarly, the choice of ray is arbitrary but necessary to generate the half-plane.

Finally, note that while rays and lines generate unbounded edges of the polyhedron they are not in a one-to-one correspondence with them. For example, the infinite strip has two infinite edges (1-faces) but only one generating line:

```
sage: strip = Polyhedron(vertices=[(1,0),(-1,0)], lines=[(0,1)])
sage: strip.Hrepresentation()
(An inequality (1, 0) x + 1 >= 0, An inequality (-1, 0) x + 1 >= 0)
sage: strip.lines()
(A line in the direction (0, 1),)
sage: [f.ambient_V_indices() for f in strip.faces(1)]
[(0, 2), (0, 1)]
sage: for face in strip.faces(1):
...:     print(face.ambient_V_indices())
```

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#### **EXAMPLES:**

```
sage: trunc_quadr = Polyhedron(vertices=[[1,0],[0,1]], rays=[[1,0],[0,1]])
sage: trunc_quadr
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 2 vertices and 2 rays
sage: v = next(trunc_quadr.vertex_generator()) # the first vertex in the internal_
→enumeration
sage: v
A vertex at (0, 1)
sage: v.vector()
(0, 1)
sage: list(v)
[0, 1]
sage: len(v)
sage: v[0] + v[1]
sage: v.is_vertex()
True
sage: type(v)
<class 'sage.geometry.polyhedron.representation.Vertex'>
sage: type( v() )
<class 'sage.modules.vector_rational_dense.Vector_rational_dense'>
sage: v.polyhedron()
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 2 vertices and 2 rays
sage: r = next(trunc_quadr.ray_generator())
sage: r
A ray in the direction (0, 1)
sage: r.vector()
(0, 1)
sage: list( v.neighbors() )
[A ray in the direction (0, 1), A vertex at (1, 0)]
```

Inequalities  $A\vec{x} + b > 0$  (and, similarly, equations) are specified by a list [b, A]:

```
sage: Polyhedron(ieqs=[(0,1,0),(0,0,1),(1,-1,-1)]).Hrepresentation()
(An inequality (-1, -1) x + 1 >= 0,
An inequality (1, 0) x + 0 >= 0,
An inequality (0, 1) x + 0 >= 0)
```

See Polyhedron() for a detailed description of all possible ways to construct a polyhedron.

## **Base Rings**

The base ring of the polyhedron can be specified by the base\_ring optional keyword argument. If not specified, a suitable common base ring for all coordinates and coefficients will be chosen automatically. Important cases are:

- base\_ring=QQ uses a fast implementation for exact rational numbers.
- base\_ring=ZZ is similar to QQ, but the resulting polyhedron object will have extra methods for lattice polyhedra.
- base\_ring=RDF uses floating point numbers, this is fast but susceptible to numerical errors.

Polyhedra with symmetries often are defined over some algebraic field extension of the rationals. As a simple example, consider the equilateral triangle whose vertex coordinates involve  $\sqrt{3}$ . An exact way to work with roots in Sage is the Algebraic Real Field

Without specifying the base\_ring, the sqrt(3) would be a symbolic ring element and, therefore, the polyhedron defined over the symbolic ring. This is currently not supported as SR is not exact:

Even faster than all algebraic real numbers (the field AA) is to take the smallest extension field. For the equilateral triangle, that would be:

**Warning:** Be careful when you construct polyhedra with floating point numbers. The only available backend for such computation is cdd which uses machine floating point numbers which have limited precision. If the input consists of floating point numbers and the base\_ring is not specified, the base ring is set to be the RealField with the precision given by the minimal bit precision of the input. Then, if the obtained minimum is 53 bits of precision, the constructor converts automatically the base ring to RDF. Otherwise, it returns an error:

```
sage: Polyhedron(vertices = [[1.12345678901234, 2.12345678901234]])
A 0-dimensional polyhedron in RDF^2 defined as the convex hull of 1 vertex
sage: Polyhedron(vertices = [[1.12345678901234, 2.123456789012345]])
A 0-dimensional polyhedron in RDF^2 defined as the convex hull of 1 vertex
```

```
sage: Polyhedron(vertices = [[1.123456789012345, 2.123456789012345]])
Traceback (most recent call last):
...
ValueError: the only allowed inexact ring is 'RDF' with backend 'cdd'
The strongly suggested method to input floating point numbers is to specify the base_ring to be RDF:

sage: Polyhedron(vertices = [[1.123456789012345, 2.123456789012345]], base_ring=RDF)
A 0-dimensional polyhedron in RDF^2 defined as the convex hull of 1 vertex
```

## See also:

Parents for polyhedra

#### Base classes

Depending on the chosen base ring, a specific class is used to represent the polyhedron object.

## See also:

- Base class for polyhedra
- Base class for polyhedra over integers
- Base class for polyhedra over rationals
- Base class for polyhedra over RDF

The most important base class is **Base class for polyhedra** from which other base classes and backends inherit.

## **Backends**

There are different backends available to deal with polyhedron objects.

## See also:

- cdd backend for polyhedra
- · field backend for polyhedra
- normaliz backend for polyhedra
- ppl backend for polyhedra

**Note:** Depending on the backend used, it may occur that different methods are available or not.

## **Appendix**

### REFERENCES:

Komei Fukuda's FAQ in Polyhedral Computation

## **AUTHORS:**

- Marshall Hampton: first version, bug fixes, and various improvements, 2008 and 2009
- Arnaud Bergeron: improvements to triangulation and rendering, 2008
- Sebastien Barthelemy: documentation improvements, 2008
- Volker Braun: refactoring, handle non-compact case, 2009 and 2010
- Andrey Novoseltsev: added lattice\_from\_incidences, 2010
- Volker Braun: rewrite to use PPL instead of cddlib, 2011
- Volker Braun: Add support for arbitrary subfields of the reals

Construct a polyhedron object.

You may either define it with vertex/ray/line or inequalities/equations data, but not both. Redundant data will automatically be removed (unless minimize=False), and the complementary representation will be computed.

#### INPUT:

- vertices list of points. Each point can be specified as any iterable container of base\_ring elements. If rays or lines are specified but no vertices, the origin is taken to be the single vertex.
- rays list of rays. Each ray can be specified as any iterable container of base\_ring elements.
- lines list of lines. Each line can be specified as any iterable container of base\_ring elements.
- ieqs list of inequalities. Each line can be specified as any iterable container of base\_ring elements. An entry equal to [-1,7,3,4] represents the inequality  $7x_1 + 3x_2 + 4x_3 \ge 1$ .
- eqns list of equalities. Each line can be specified as any iterable container of base\_ring elements. An entry equal to [-1,7,3,4] represents the equality  $7x_1 + 3x_2 + 4x_3 = 1$ .
- base\_ring a sub-field of the reals implemented in Sage. The field over which the polyhedron will be defined. For QQ and algebraic extensions, exact arithmetic will be used. For RDF, floating point numbers will be used. Floating point arithmetic is faster but might give the wrong result for degenerate input.
- ambient\_dim integer. The ambient space dimension. Usually can be figured out automatically from the H/Vrepresentation dimensions.
- backend string or None (default). The backend to use. Valid choices are
  - 'cdd': use cdd (backend\_cdd) with Q or R coefficients depending on base\_ring
  - 'normaliz': use normaliz (backend\_normaliz) with Z or Q coefficients depending on base\_ring
  - 'polymake': use polymake (backend\_polymake) with Q, R or QuadraticField coefficients depending on base\_ring
  - 'ppl': use ppl (backend\_ppl) with **Z** or **Q** coefficients depending on base\_ring
  - 'field': use python implementation (backend\_field) for any field

Some backends support further optional arguments:

- minimize boolean (default: True); whether to immediately remove redundant H/V-representation data; currently not used.
- verbose boolean (default: False); whether to print verbose output for debugging purposes; only supported by the cdd and normaliz backends
- mutable boolean (default: False); whether the polyhedron is mutable

#### **OUTPUT:**

The polyhedron defined by the input data.

#### **EXAMPLES:**

Construct some polyhedra:

```
sage: square_from_vertices = Polyhedron(vertices = [[1, 1], [1, -1], [-1, 1], [-1, -
→1]])
sage: square_from_ieqs = Polyhedron(ieqs = [[1, 0, 1], [1, 1, 0], [1, 0, -1], [1, -
\rightarrow 1, 0]])
sage: list(square_from_ieqs.vertex_generator())
[A vertex at (1, -1),
A vertex at (1, 1),
A vertex at (-1, 1),
A vertex at (-1, -1)
sage: list(square_from_vertices.inequality_generator())
[An inequality (1, 0) x + 1 \ge 0,
An inequality (0, 1) \times + 1 >= 0,
An inequality (-1, 0) x + 1 \ge 0,
An inequality (0, -1) \times + 1 >= 0
sage: p = Polyhedron(vertices = [[1.1, 2.2], [3.3, 4.4]], base_ring=RDF)
sage: p.n_inequalities()
```

The same polyhedron given in two ways:

```
sage: p = Polyhedron(ieqs = [[0,1,0,0],[0,0,1,0]])
sage: p.Vrepresentation()
(A line in the direction (0, 0, 1),
    A ray in the direction (1, 0, 0),
    A ray in the direction (0, 1, 0),
    A vertex at (0, 0, 0))
sage: q = Polyhedron(vertices=[[0,0,0]], rays=[[1,0,0],[0,1,0]], lines=[[0,0,1]])
sage: q.Hrepresentation()
(An inequality (1, 0, 0) x + 0 >= 0,
    An inequality (0, 1, 0) x + 0 >= 0)
```

Finally, a more complicated example. Take  $\mathbb{R}^6_{>0}$  with coordinates  $a, b, \ldots, f$  and

- The inequality  $e + b \ge c + d$
- The inequality  $e + c \ge b + d$
- The equation a + b + c + d + e + f = 31

(continues on next page)

```
sage: P = Polyhedron(ieqs=positive_coords.inequalities() + (
...: [0,0,1,-1,-1,1,0], [0,0,-1,1,-1,1,0]), eqns=[[-31,1,1,1,1,1,1]])
sage: P
A 5-dimensional polyhedron in QQ^6 defined as the convex hull of 7 vertices
sage: P.dim()
5
sage: P.Vrepresentation()
(A vertex at (31, 0, 0, 0, 0, 0), A vertex at (0, 0, 0, 0, 0, 31),
A vertex at (0, 0, 0, 0, 31, 0), A vertex at (0, 0, 31/2, 0, 31/2, 0),
A vertex at (0, 31/2, 31/2, 0, 0, 0), A vertex at (0, 31/2, 0, 0, 31/2, 0),
A vertex at (0, 0, 0, 31/2, 31/2, 0))
```

Regular icosahedron, centered at 0 with edge length 2, with vertices given by the cyclic shifts of  $(0, \pm 1, \pm (1 + \sqrt{(5)})/2)$ , cf. Wikipedia article Regular\_icosahedron. It needs a number field:

```
sage: R0.< r0> = QQ[]
                                                                           # optional -
→ sage.rings.number_field
sage: R1.\langle r1 \rangle = \text{NumberField}(r0^2-5, \text{embedding}=AA(5)**(1/2))
                                                                           # optional -
→ sage.rings.number_field
sage: gold = (1+r1)/2
                                                                           # optional -
→ sage.rings.number_field
sage: v = [[0, 1, gold], [0, 1, -gold], [0, -1, gold], [0, -1, -gold]]
                                                                          # optional -
→ sage.rings.number_field
                                      # optional - sage.combinat
sage: pp = Permutation((1, 2, 3))
                                                                           # optional -
→ sage.rings.number_field
sage: icosah = Polyhedron(
                                           # optional - sage.combinat
                                                                           # optional -
→ sage.rings.number_field
         [(pp^2).action(w)  for w in v] + [pp.action(w)  for w in v] + v,
         base_ring=R1)
sage: len(icosah.faces(2))
                                            # optional - sage.combinat
                                                                          # optional -
→ sage.rings.number_field
```

When the input contains elements of a Number Field, they require an embedding:

```
sage: K = NumberField(x^2-2, 's')
                                                                         # optional -
→ sage.rings.number_field
sage: s = K.0
                                                                         # optional -
→ sage.rings.number_field
sage: L = NumberField(x^3-2,'t')
                                                                         # optional -
→ sage.rings.number_field
sage: t = L.0
                                                                         # optional -
→ sage.rings.number_field
sage: P = Polyhedron(vertices = [[0,s],[t,0]])
                                                                         # optional -
→ sage.rings.number_field
Traceback (most recent call last):
ValueError: invalid base ring
```

Create a mutable polyhedron:

```
sage: P = Polyhedron(vertices=[[0, 1], [1, 0]], mutable=True)
sage: P.is_mutable()

(continues on next page)
```

```
True
sage: hasattr(P, "_Vrepresentation")
False
sage: P.Vrepresentation()
(A vertex at (0, 1), A vertex at (1, 0))
sage: hasattr(P, "_Vrepresentation")
True
```

#### Note:

- Once constructed, a Polyhedron object is immutable.
- Although the option base\_ring=RDF allows numerical data to be used, it might not give the right answer for degenerate input data the results can depend upon the tolerance setting of cdd.

#### See also:

Library of polytopes

# 2.1.3 Parents for Polyhedra

Construct a suitable parent class for polyhedra

### INPUT:

- base\_ring A ring. Currently there are backends for Z, Q, and R.
- ambient\_dim integer. The ambient space dimension.
- ambient\_space A free module.
- backend string. The name of the backend for computations. There are several backends implemented:
  - backend="ppl" uses the Parma Polyhedra Library
  - backend="cdd" uses CDD
  - backend="normaliz" uses normaliz
  - backend="polymake" uses polymake
  - backend="field" a generic Sage implementation

#### **OUTPUT:**

A parent class for polyhedra over the given base ring if the backend supports it. If not, the parent base ring can be larger (for example,  $\mathbf{Q}$  instead of  $\mathbf{Z}$ ). If there is no implementation at all, a ValueError is raised.

## **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.parent import Polyhedra
sage: Polyhedra(AA, 3)
Polyhedra in AA^3
sage: Polyhedra(ZZ, 3)
Polyhedra in ZZ^3
```

(continues on next page)

```
sage: type(_)
<class 'sage.geometry.polyhedron.parent.Polyhedra_ZZ_ppl_with_category'>
sage: Polyhedra(QQ, 3, backend='cdd')
Polyhedra in QQ^3
sage: type(_)
<class 'sage.geometry.polyhedron.parent.Polyhedra_QQ_cdd_with_category'>
```

CDD does not support integer polytopes directly:

```
sage: Polyhedra(ZZ, 3, backend='cdd')
Polyhedra in QQ^3
```

Using a more general form of the constructor:

```
sage: V = VectorSpace(QQ, 3)
sage: Polyhedra(V) is Polyhedra(QQ, 3)
True
sage: Polyhedra(V, backend='field') is Polyhedra(QQ, 3, 'field')
True
sage: Polyhedra(backend='field', ambient_space=V) is Polyhedra(QQ, 3, 'field')
True

sage: M = FreeModule(ZZ, 2)
sage: Polyhedra(M, backend='ppl') is Polyhedra(ZZ, 2, 'ppl')
True
```

## Element

alias of sage.geometry.polyhedron.backend\_cdd.Polyhedron\_QQ\_cdd

#### Element

alias of sage.geometry.polyhedron.backend\_normaliz.Polyhedron\_QQ\_normaliz

class sage.geometry.polyhedron.parent.Polyhedra\_QQ\_ppl(base\_ring, ambient\_dim, backend)
Bases: sage.geometry.polyhedron.parent.Polyhedra\_base

### **Element**

alias of sage.geometry.polyhedron.backend\_ppl.Polyhedron\_QQ\_ppl

## **Element**

alias of sage.geometry.polyhedron.backend\_cdd\_rdf.Polyhedron\_RDF\_cdd

#### **Element**

alias of sage.geometry.polyhedron.backend\_normaliz.Polyhedron\_ZZ\_normaliz

class sage.geometry.polyhedron.parent.Polyhedra\_ZZ\_ppl(base\_ring, ambient\_dim, backend)
 Bases: sage.geometry.polyhedron.parent.Polyhedra\_base

#### **Element**

alias of sage.geometry.polyhedron.backend\_ppl.Polyhedron\_ZZ\_ppl

class sage.geometry.polyhedron.parent.Polyhedra\_base(base\_ring, ambient\_dim, backend)

Bases: sage.structure.unique\_representation.UniqueRepresentation, sage.structure.parent.Parent

Polyhedra in a fixed ambient space.

#### INPUT:

- base\_ring either ZZ, QQ, or RDF. The base ring of the ambient module/vector space.
- ambient\_dim integer. The ambient space dimension.
- backend string. The name of the backend for computations. There are several backends implemented:
  - backend="pp1" uses the Parma Polyhedra Library
  - backend="cdd" uses CDD
  - backend="normaliz" uses normaliz
  - backend="polymake" uses polymake
  - backend="field" a generic Sage implementation

#### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.parent import Polyhedra
sage: Polyhedra(ZZ, 3)
Polyhedra in ZZ^3
```

## Hrepresentation\_space()

Return the linear space containing the H-representation vectors.

OUTPUT

A free module over the base ring of dimension  $ambient\_dim() + 1$ .

**EXAMPLES:** 

```
sage: from sage.geometry.polyhedron.parent import Polyhedra
sage: Polyhedra(ZZ, 2).Hrepresentation_space()
Ambient free module of rank 3 over the principal ideal domain Integer Ring
```

## Vrepresentation\_space()

Return the ambient vector space.

This is the vector space or module containing the Vrepresentation vectors.

**OUTPUT**:

A free module over the base ring of dimension ambient\_dim().

EXAMPLES:

```
sage: from sage.geometry.polyhedron.parent import Polyhedra
sage: Polyhedra(QQ, 4).Vrepresentation_space()
Vector space of dimension 4 over Rational Field
sage: Polyhedra(QQ, 4).ambient_space()
Vector space of dimension 4 over Rational Field
```

### ambient\_dim()

Return the dimension of the ambient space.

#### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.parent import Polyhedra
sage: Polyhedra(QQ, 3).ambient_dim()
3
```

### ambient\_space()

Return the ambient vector space.

This is the vector space or module containing the Vrepresentation vectors.

**OUTPUT**:

A free module over the base ring of dimension ambient\_dim().

#### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.parent import Polyhedra
sage: Polyhedra(QQ, 4).Vrepresentation_space()
Vector space of dimension 4 over Rational Field
sage: Polyhedra(QQ, 4).ambient_space()
Vector space of dimension 4 over Rational Field
```

#### an element()

Return a Polyhedron.

### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.parent import Polyhedra
sage: Polyhedra(QQ, 4).an_element()
A 4-dimensional polyhedron in QQ^4 defined as the convex hull of 5 vertices
```

#### backend()

Return the backend.

## **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.parent import Polyhedra
sage: Polyhedra(QQ, 3).backend()
'ppl'
```

**base\_extend**(base ring, backend=None, ambient dim=None)

Return the base extended parent.

## INPUT:

- base\_ring, backend see *Polyhedron()*.
- ambient\_dim if not None change ambient dimension accordingly.

### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.parent import Polyhedra
sage: Polyhedra(ZZ,3).base_extend(QQ)
Polyhedra in QQ^3
sage: Polyhedra(ZZ,3).an_element().base_extend(QQ)
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 4 vertices
```

(continues on next page)

```
sage: Polyhedra(QQ, 2).base_extend(ZZ)
Polyhedra in QQ^2
```

change\_ring(base\_ring, backend=None, ambient\_dim=None)

Return the parent with the new base ring.

## INPUT:

- base\_ring, backend see Polyhedron().
- ambient\_dim if not None change ambient dimension accordingly.

#### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.parent import Polyhedra
sage: Polyhedra(ZZ,3).change_ring(QQ)
Polyhedra in QQ^3
sage: Polyhedra(ZZ,3).an_element().change_ring(QQ)
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 4 vertices

sage: Polyhedra(RDF, 3).change_ring(QQ).backend()
'cdd'
sage: Polyhedra(QQ, 3).change_ring(ZZ, ambient_dim=4)
Polyhedra in ZZ^4
sage: Polyhedra(QQ, 3, backend='cdd').change_ring(QQ, ambient_dim=4).backend()
'cdd'
```

#### empty()

Return the empty polyhedron.

### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.parent import Polyhedra
sage: P = Polyhedra(QQ, 4)
sage: P.empty()
The empty polyhedron in QQ^4
sage: P.empty().is_empty()
True
```

#### list()

Return the two polyhedra in ambient dimension 0, raise an error otherwise

### **EXAMPLES:**

(continues on next page)

```
sage: P.cardinality()
2
```

### recycle(polyhedron)

Recycle the H/V-representation objects of a polyhedron.

This speeds up creation of new polyhedra by reusing objects. After recycling a polyhedron object, it is not in a consistent state any more and neither the polyhedron nor its H/V-representation objects may be used any more.

#### INPUT:

• polyhedron – a polyhedron whose parent is self.

#### **EXAMPLES:**

```
sage: p = Polyhedron([(0,0),(1,0),(0,1)])
sage: p.parent().recycle(p)
```

#### some\_elements()

Return a list of some elements of the semigroup.

### **EXAMPLES:**

## universe()

Return the entire ambient space as polyhedron.

#### EXAMPLES:

```
sage: from sage.geometry.polyhedron.parent import Polyhedra
sage: P = Polyhedra(QQ, 4)
sage: P.universe()
A 4-dimensional polyhedron in QQ^4 defined as the convex hull of 1 vertex and 4_____lines
sage: P.universe().is_universe()
True
```

### zero()

Return the polyhedron consisting of the origin, which is the neutral element for Minkowski addition.

## **EXAMPLES:**

(continues on next page)

```
A 0-dimensional polyhedron in QQ^4 defined as the convex hull of 1 vertex sage: p+p == p
True
```

class sage.geometry.polyhedron.parent.Polyhedra\_field(base\_ring, ambient\_dim, backend)

Bases: sage.geometry.polyhedron.parent.Polyhedra\_base

#### Element

alias of sage.geometry.polyhedron.backend\_field.Polyhedron\_field

class sage.geometry.polyhedron.parent.Polyhedra\_normaliz(base\_ring, ambient\_dim, backend)

Bases: sage.geometry.polyhedron.parent.Polyhedra\_base

#### Element

alias of sage.geometry.polyhedron.backend\_normaliz.Polyhedron\_normaliz

#### Element

alias of sage.geometry.polyhedron.backend\_polymake.Polyhedron\_polymake

sage.geometry.polyhedron.parent.does\_backend\_handle\_base\_ring(base\_ring, backend)
Return true, if backend can handle base\_ring.

#### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.parent import does_backend_handle_base_ring
sage: does_backend_handle_base_ring(QQ, 'ppl')
True
sage: does_backend_handle_base_ring(QQ[sqrt(5)], 'ppl')
False
sage: does_backend_handle_base_ring(QQ[sqrt(5)], 'field')
True
```

## 2.1.4 H(yperplane) and V(ertex) representation objects for polyhedra

**class** sage.geometry.polyhedron.representation.**Equation**(polyhedron\_parent)
Bases: sage.geometry.polyhedron.representation.Hrepresentation

A linear equation of the polyhedron. That is, the polyhedron is strictly smaller-dimensional than the ambient space, and contained in this hyperplane. Inherits from Hrepresentation.

#### contains(Vobj)

Tests whether the hyperplane defined by the equation contains the given vertex/ray/line.

## **EXAMPLES:**

```
sage: p = Polyhedron(vertices = [[0,0,0],[1,1,0],[1,2,0]])
sage: v = next(p.vertex_generator())
sage: v
A vertex at (0, 0, 0)
sage: a = next(p.equation_generator())
sage: a
An equation (0, 0, 1) x + 0 == 0
```

(continues on next page)

```
sage: a.contains(v)
True
```

#### interior\_contains(Vobj)

Tests whether the interior of the halfspace (excluding its boundary) defined by the inequality contains the given vertex/ray/line.

**Note:** Return False for any equation.

#### **EXAMPLES:**

```
sage: p = Polyhedron(vertices = [[0,0,0],[1,1,0],[1,2,0]])
sage: v = next(p.vertex_generator())
sage: v
A vertex at (0, 0, 0)
sage: a = next(p.equation_generator())
sage: a
An equation (0, 0, 1) x + 0 == 0
sage: a.interior_contains(v)
False
```

#### is\_equation()

Tests if this object is an equation. By construction, it must be.

### type()

Return the type (equation/inequality/vertex/ray/line) as an integer.

## OUTPUT:

Integer. One of PolyhedronRepresentation.INEQUALITY, .EQUATION, .VERTEX, .RAY, or .LINE.

### **EXAMPLES:**

```
sage: p = Polyhedron(vertices = [[0,0,0],[1,1,0],[1,2,0]])
sage: repr_obj = next(p.equation_generator())
sage: repr_obj.type()

1
sage: repr_obj.type() == repr_obj.INEQUALITY
False
sage: repr_obj.type() == repr_obj.EQUATION
True
sage: repr_obj.type() == repr_obj.VERTEX
False
sage: repr_obj.type() == repr_obj.RAY
False
sage: repr_obj.type() == repr_obj.LINE
False
```

## class sage.geometry.polyhedron.representation.Hrepresentation(polyhedron\_parent)

Bases: sage.geometry.polyhedron.representation.PolyhedronRepresentation

The internal base class for H-representation objects of a polyhedron. Inherits from PolyhedronRepresentation.

**A**()

Return the coefficient vector A in  $A\vec{x} + b$ .

**EXAMPLES:** 

```
sage: p = Polyhedron(ieqs = [[0,1,0],[0,0,1],[1,-1,0,],[1,0,-1]])
sage: pH = p.Hrepresentation(2)
sage: pH.A()
(1, 0)
```

## adjacent()

Alias for neighbors().

**b**()

Return the constant b in  $A\vec{x} + b$ .

**EXAMPLES:** 

```
sage: p = Polyhedron(ieqs = [[0,1,0],[0,0,1],[1,-1,0,],[1,0,-1]])
sage: pH = p.Hrepresentation(2)
sage: pH.b()
0
```

### eval(Vobj)

Evaluate the left hand side  $A\vec{x} + b$  on the given vertex/ray/line.

**EXAMPLES:** 

```
sage: triangle = Polyhedron(vertices=[[1,0],[0,1],[-1,-1]])
sage: ineq = next(triangle.inequality_generator())
sage: ineq
An inequality (2, -1) x + 1 >= 0
sage: [ ineq.eval(v) for v in triangle.vertex_generator() ]
[0, 0, 3]
sage: [ ineq * v for v in triangle.vertex_generator() ]
[0, 0, 3]
```

If you pass a vector, it is assumed to be the coordinate vector of a point:

```
sage: ineq.eval( vector(ZZ, [3,2]) )
5
```

## incident()

Return a generator for the incident H-representation objects, that is, the vertices/rays/lines satisfying the (in)equality.

**EXAMPLES:** 

```
sage: triangle = Polyhedron(vertices=[[1,0],[0,1],[-1,-1]])
sage: ineq = next(triangle.inequality_generator())
sage: ineq
An inequality (2, -1) x + 1 >= 0
sage: [ v for v in ineq.incident()]
[A vertex at (-1, -1), A vertex at (0, 1)]
sage: p = Polyhedron(vertices=[[0,0,0],[0,1,0],[0,0,1]], rays=[[1,-1,-1]])
sage: ineq = p.Hrepresentation(2)
sage: ineq
```

(continues on next page)

```
An inequality (1, 0, 1) x + 0 >= 0

sage: [ x for x in ineq.incident() ]

[A vertex at (0, 0, 0),

A vertex at (0, 1, 0),

A ray in the direction (1, -1, -1)]
```

## is\_H()

Return True if the object is part of a H-representation (inequality or equation).

**EXAMPLES:** 

```
sage: p = Polyhedron(ieqs = [[0,1,0],[0,0,1],[1,-1,0,],[1,0,-1]])
sage: pH = p.Hrepresentation(0)
sage: pH.is_H()
True
```

#### is\_equation()

Return True if the object is an equation of the H-representation.

**EXAMPLES:** 

## is\_incident(Vobj)

Return whether the incidence matrix element (Vobj,self) == 1

**EXAMPLES**:

### is\_inequality()

Return True if the object is an inequality of the H-representation.

**EXAMPLES:** 

```
sage: p = Polyhedron(ieqs = [[0,1,0],[0,0,1],[1,-1,0,],[1,0,-1]])
sage: pH = p.Hrepresentation(0)
sage: pH.is_inequality()
True
```

## neighbors()

Iterate over the adjacent facets (i.e. inequalities).

Only defined for inequalities.

**EXAMPLES:** 

## repr\_pretty(\*\*kwds)

Return a pretty representation of this equality/inequality.

## INPUT:

- prefix a string
- indices a tuple or other iterable
- latex a boolean

#### **OUTPUT**:

A string

#### **EXAMPLES:**

## class sage.geometry.polyhedron.representation.Inequality(polyhedron\_parent)

Bases: sage.geometry.polyhedron.representation.Hrepresentation

A linear inequality (supporting hyperplane) of the polyhedron. Inherits from Hrepresentation.

### contains(Vobj)

Tests whether the halfspace (including its boundary) defined by the inequality contains the given vertex/ray/line.

# **EXAMPLES:**

```
sage: p = polytopes.cross_polytope(3)
sage: i1 = next(p.inequality_generator())
sage: [i1.contains(q) for q in p.vertex_generator()]
[True, True, True, True, True]
sage: p2 = 3*polytopes.hypercube(3)
sage: [i1.contains(q) for q in p2.vertex_generator()]
[True, True, False, True, False, True, False, False]
```

## interior\_contains(Vobj)

Tests whether the interior of the halfspace (excluding its boundary) defined by the inequality contains the given vertex/ray/line.

**EXAMPLES:** 

```
sage: p = polytopes.cross_polytope(3)
sage: i1 = next(p.inequality_generator())
sage: [i1.interior_contains(q) for q in p.vertex_generator()]
[False, True, True, False, False, True]
sage: p2 = 3*polytopes.hypercube(3)
sage: [i1.interior_contains(q) for q in p2.vertex_generator()]
[True, True, False, True, False, True, False, False]
```

If you pass a vector, it is assumed to be the coordinate vector of a point:

```
sage: P = Polyhedron(vertices=[[1,1],[1,-1],[-1,1],[-1,-1]])
sage: p = vector(ZZ, [1,0] )
sage: [ ieq.interior_contains(p) for ieq in P.inequality_generator() ]
[True, True, False, True]
```

## is\_facet\_defining\_inequality(other)

Check if self defines a facet of other.

INPUT:

• other – a polyhedron

#### See also:

slack\_matrix() incidence\_matrix()

**EXAMPLES:** 

```
sage: P = Polyhedron(vertices=[[0,0,0],[0,1,0]], rays=[[1,0,0]])
sage: P.inequalities()
(An inequality (1, 0, 0) x + 0 >= 0,
An inequality (0, 1, 0) \times + 0 >= 0,
An inequality (0, -1, 0) x + 1 >= 0)
sage: Q = Polyhedron(ieqs=[[0,1,0,0]])
sage: Q.inequalities()[0].is_facet_defining_inequality(P)
True
sage: Q = Polyhedron(ieqs=[[0,2,0,3]])
sage: Q.inequalities()[0].is_facet_defining_inequality(P)
sage: Q = Polyhedron(ieqs=[[0,AA(2).sqrt(),0,3]])
                                                                     # optional -
→ sage.rings.number_field
sage: Q.inequalities()[0].is_facet_defining_inequality(P)
                                                                     # optional -
→ sage.rings.number_field
True
sage: Q = Polyhedron(ieqs=[[1,1,0,0]])
sage: Q.inequalities()[0].is_facet_defining_inequality(P)
False
```

```
sage: P = Polyhedron(vertices=[[0,0,0],[0,1,0]], lines=[[1,0,0]])
sage: P.inequalities()
(An inequality (0, 1, 0) x + 0 >= 0, An inequality (0, -1, 0) x + 1 >= 0)
sage: Q = Polyhedron(ieqs=[[0,1,0,0]])
sage: Q.inequalities()[0].is_facet_defining_inequality(P)
False
sage: Q = Polyhedron(ieqs=[[0,-1,0,0]])
```

(continues on next page)

```
sage: Q.inequalities()[0].is_facet_defining_inequality(P)
False
sage: Q = Polyhedron(ieqs=[[0,0,1,3]])
sage: Q.inequalities()[0].is_facet_defining_inequality(P)
True
```

## is\_inequality()

Return True since this is, by construction, an inequality.

#### **EXAMPLES:**

```
sage: p = Polyhedron(vertices = [[0,0,0],[1,1,0],[1,2,0]])
sage: a = next(p.inequality_generator())
sage: a.is_inequality()
True
```

#### outer\_normal()

Return the outer normal vector of self.

#### **OUTPUT:**

The normal vector directed away from the interior of the polyhedron.

#### **EXAMPLES:**

```
sage: p = Polyhedron(vertices = [[0,0,0],[1,1,0],[1,2,0]])
sage: a = next(p.inequality_generator())
sage: a.outer_normal()
(1, -1, 0)
```

#### type()

Return the type (equation/inequality/vertex/ray/line) as an integer.

## **OUTPUT**:

Integer. One of PolyhedronRepresentation.INEQUALITY, .EQUATION, .VERTEX, .RAY, or .LINE.

## **EXAMPLES:**

```
sage: p = Polyhedron(vertices = [[0,0,0],[1,1,0],[1,2,0]])
sage: repr_obj = next(p.inequality_generator())
sage: repr_obj.type()

sage: repr_obj.type() == repr_obj.INEQUALITY
True
sage: repr_obj.type() == repr_obj.EQUATION
False
sage: repr_obj.type() == repr_obj.VERTEX
False
sage: repr_obj.type() == repr_obj.RAY
False
sage: repr_obj.type() == repr_obj.LINE
False
```

class sage.geometry.polyhedron.representation.Line(polyhedron\_parent)

Bases: sage.geometry.polyhedron.representation.Vrepresentation

A line (Minkowski summand  $\simeq \mathbf{R}$ ) of the polyhedron. Inherits from Vrepresentation.

## evaluated\_on(Hobj)

Return  $A\vec{\ell}$ 

**EXAMPLES:** 

```
sage: p = Polyhedron(ieqs = [[1, 0, 0, 1],[1,1,0,0]])
sage: a = next(p.line_generator())
sage: h = next(p.inequality_generator())
sage: a.evaluated_on(h)
0
```

## homogeneous\_vector(base\_ring=None)

Return homogeneous coordinates for this line.

Since a line is given by a direction, this is the vector with a 0 appended.

#### INPUT:

• base\_ring – the base ring of the vector.

#### **EXAMPLES:**

```
sage: P = Polyhedron(vertices=[(2,0)], rays=[(1,0)], lines=[(3,2)])
sage: P.lines()[0].homogeneous_vector()
(3, 2, 0)
sage: P.lines()[0].homogeneous_vector(RDF)
(3.0, 2.0, 0.0)
```

#### is\_line()

Tests if the object is a line. By construction it must be.

#### type()

Return the type (equation/inequality/vertex/ray/line) as an integer.

#### **OUTPUT**

Integer. One of PolyhedronRepresentation.INEQUALITY, .EQUATION, .VERTEX, .RAY, or .LINE.

### **EXAMPLES:**

```
sage: p = Polyhedron(ieqs = [[1, 0, 0, 1],[1,1,0,0]])
sage: repr_obj = next(p.line_generator())
sage: repr_obj.type()
4
sage: repr_obj.type() == repr_obj.INEQUALITY
False
sage: repr_obj.type() == repr_obj.EQUATION
False
sage: repr_obj.type() == repr_obj.VERTEX
False
sage: repr_obj.type() == repr_obj.RAY
False
sage: repr_obj.type() == repr_obj.LINE
True
```

#### class sage.geometry.polyhedron.representation.PolyhedronRepresentation

Bases: sage.structure.sage\_object.SageObject

The internal base class for all representation objects of Polyhedron (vertices/rays/lines and inequalities/equations)

Note: You should not (and cannot) instantiate it yourself. You can only obtain them from a Polyhedron() class.

#### count(i)

Count the number of occurrences of i in the coordinates.

#### INPUT:

• i – Anything.

## **OUTPUT**:

Integer. The number of occurrences of i in the coordinates.

#### **EXAMPLES:**

```
sage: p = Polyhedron(vertices=[(0,1,1,2,1)])
sage: v = p.Vrepresentation(0); v
A vertex at (0, 1, 1, 2, 1)
sage: v.count(1)
3
```

### index()

Return an arbitrary but fixed number according to the internal storage order.

**Note:** H-representation and V-representation objects are enumerated independently. That is, amongst all vertices/rays/lines there will be one with index()==0, and amongst all inequalities/equations there will be one with index()==0, unless the polyhedron is empty or spans the whole space.

## **EXAMPLES:**

```
sage: s = Polyhedron(vertices=[[1],[-1]])
sage: first_vertex = next(s.vertex_generator())
sage: first_vertex.index()
0
sage: first_vertex == s.Vrepresentation(0)
True
```

## polyhedron()

Return the underlying polyhedron.

```
vector(base_ring=None)
```

Return the vector representation of the H/V-representation object.

## INPUT:

• base\_ring – the base ring of the vector.

### **OUTPUT**:

For a V-representation object, a vector of length  $ambient\_dim()$ . For a H-representation object, a vector of length  $ambient\_dim() + 1$ .

## **EXAMPLES:**

```
sage: s = polytopes.cuboctahedron()
sage: v = next(s.vertex_generator())
sage: v
A vertex at (-1, -1, 0)
sage: v.vector()
(-1, -1, 0)
sage: v()
(-1, -1, 0)
sage: type(v())
<class 'sage.modules.vector_integer_dense.Vector_integer_dense'>
```

Conversion to a different base ring can be forced with the optional argument:

```
sage: v.vector(RDF)
(-1.0, -1.0, 0.0)
sage: vector(RDF, v)
(-1.0, -1.0, 0.0)
```

## class sage.geometry.polyhedron.representation.Ray(polyhedron\_parent)

Bases: sage.geometry.polyhedron.representation.Vrepresentation

A ray of the polyhedron. Inherits from Vrepresentation.

## evaluated\_on(Hobj)

Return  $A\vec{r}$ 

**EXAMPLES:** 

```
sage: p = Polyhedron(ieqs = [[0,0,1],[0,1,0],[1,-1,0]])
sage: a = next(p.ray_generator())
sage: h = next(p.inequality_generator())
sage: a.evaluated_on(h)
0
```

## homogeneous\_vector(base\_ring=None)

Return homogeneous coordinates for this ray.

Since a ray is given by a direction, this is the vector with a 0 appended.

#### INPUT:

• base\_ring – the base ring of the vector.

## **EXAMPLES:**

```
sage: P = Polyhedron(vertices=[(2,0)], rays=[(1,0)], lines=[(3,2)])
sage: P.rays()[0].homogeneous_vector()
(1, 0, 0)
sage: P.rays()[0].homogeneous_vector(RDF)
(1.0, 0.0, 0.0)
```

#### is\_ray()

Tests if this object is a ray. Always True by construction.

**EXAMPLES:** 

```
sage: p = Polyhedron(ieqs = [[0,0,1],[0,1,0],[1,-1,0]])
sage: a = next(p.ray_generator())
sage: a.is_ray()
True
```

### type()

Return the type (equation/inequality/vertex/ray/line) as an integer.

#### **OUTPUT:**

Integer. One of PolyhedronRepresentation.INEQUALITY, .EQUATION, .VERTEX, .RAY, or .LINE.

### **EXAMPLES:**

```
sage: p = Polyhedron(ieqs = [[0,0,1],[0,1,0],[1,-1,0]])
sage: repr_obj = next(p.ray_generator())
sage: repr_obj.type()
3
sage: repr_obj.type() == repr_obj.INEQUALITY
False
sage: repr_obj.type() == repr_obj.EQUATION
False
sage: repr_obj.type() == repr_obj.VERTEX
False
sage: repr_obj.type() == repr_obj.RAY
True
sage: repr_obj.type() == repr_obj.LINE
False
```

## class sage.geometry.polyhedron.representation.Vertex(polyhedron\_parent)

Bases: sage.geometry.polyhedron.representation.Vrepresentation

A vertex of the polyhedron. Inherits from Vrepresentation.

## evaluated\_on(Hobj)

Return  $A\vec{x} + b$ 

## **EXAMPLES:**

```
sage: p = polytopes.hypercube(3)
sage: v = next(p.vertex_generator())
sage: h = next(p.inequality_generator())
sage: v
A vertex at (1, -1, -1)
sage: h
An inequality (-1, 0, 0) x + 1 >= 0
sage: v.evaluated_on(h)
0
```

### homogeneous\_vector(base\_ring=None)

Return homogeneous coordinates for this vertex.

Since a vertex is given by an affine point, this is the vector with a 1 appended.

#### INPUT:

• base\_ring – the base ring of the vector.

**EXAMPLES:** 

```
sage: P = Polyhedron(vertices=[(2,0)], rays=[(1,0)], lines=[(3,2)])
sage: P.vertices()[0].homogeneous_vector()
(2, 0, 1)
sage: P.vertices()[0].homogeneous_vector(RDF)
(2.0, 0.0, 1.0)
```

### is\_integral()

Return whether the coordinates of the vertex are all integral.

**OUTPUT**:

Boolean.

**EXAMPLES:** 

```
sage: p = Polyhedron([(1/2,3,5), (0,0,0), (2,3,7)])
sage: [ v.is_integral() for v in p.vertex_generator() ]
[True, False, True]
```

#### is\_vertex()

Tests if this object is a vertex. By construction it always is.

#### **EXAMPLES:**

```
sage: p = Polyhedron(ieqs = [[0,0,1],[0,1,0],[1,-1,0]])
sage: a = next(p.vertex_generator())
sage: a.is_vertex()
True
```

## type()

Return the type (equation/inequality/vertex/ray/line) as an integer.

**OUTPUT**:

Integer. One of PolyhedronRepresentation.INEQUALITY, .EQUATION, .VERTEX, .RAY, or .LINE.

## **EXAMPLES:**

```
sage: p = Polyhedron(vertices = [[0,0,0],[1,1,0],[1,2,0]])
sage: repr_obj = next(p.vertex_generator())
sage: repr_obj.type()
2
sage: repr_obj.type() == repr_obj.INEQUALITY
False
sage: repr_obj.type() == repr_obj.EQUATION
False
sage: repr_obj.type() == repr_obj.VERTEX
True
sage: repr_obj.type() == repr_obj.RAY
False
sage: repr_obj.type() == repr_obj.LINE
False
```

## class sage.geometry.polyhedron.representation.Vrepresentation(polyhedron\_parent)

 $Bases: \ sage. \ geometry. \ polyhedron. \ representation. \ Polyhedron \ Representation$ 

The base class for V-representation objects of a polyhedron. Inherits from PolyhedronRepresentation.

### adjacent()

Alias for neighbors().

#### incident()

Return a generator for the equations/inequalities that are satisfied on the given vertex/ray/line.

### **EXAMPLES:**

```
sage: triangle = Polyhedron(vertices=[[1,0],[0,1],[-1,-1]])
sage: ineq = next(triangle.inequality_generator())
sage: ineq
An inequality (2, -1) x + 1 >= 0
sage: [ v for v in ineq.incident()]
[A vertex at (-1, -1), A vertex at (0, 1)]
sage: p = Polyhedron(vertices=[[0,0,0],[0,1,0],[0,0,1]], rays=[[1,-1,-1]])
sage: ineq = p.Hrepresentation(2)
sage: ineq
An inequality (1, 0, 1) x + 0 >= 0
sage: [ x for x in ineq.incident() ]
[A vertex at (0, 0, 0),
    A vertex at (0, 1, 0),
    A ray in the direction (1, -1, -1)]
```

#### is\_V()

Return True if the object is part of a V-representation (a vertex, ray, or line).

## **EXAMPLES:**

```
sage: p = Polyhedron(vertices = [[0,0],[1,0],[0,3],[1,3]])
sage: v = next(p.vertex_generator())
sage: v.is_V()
True
```

## is\_incident(Hobj)

Return whether the incidence matrix element (self,Hobj) == 1

#### **EXAMPLES:**

```
sage: p = polytopes.hypercube(3)
sage: h1 = next(p.inequality_generator())
sage: h1
An inequality (-1, 0, 0) x + 1 >= 0
sage: v1 = next(p.vertex_generator())
sage: v1
A vertex at (1, -1, -1)
sage: v1.is_incident(h1)
True
```

#### is\_line()

Return True if the object is a line of the V-representation. This method is over-ridden by the corresponding method in the derived class Line.

#### **EXAMPLES:**

```
sage: p = Polyhedron(ieqs = [[1, 0, 0, 0, 1], [1, 1, 0, 0, 0], [1, 0, 1, 0, 0]])
sage: line1 = next(p.line_generator())
```

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```
sage: line1.is_line()
True
sage: v1 = next(p.vertex_generator())
sage: v1.is_line()
False
```

### is\_ray()

Return True if the object is a ray of the V-representation. This method is over-ridden by the corresponding method in the derived class Ray.

### **EXAMPLES:**

```
sage: p = Polyhedron(ieqs = [[1, 0, 0, 0, 1], [1, 1, 0, 0, 0], [1, 0, 1, 0, 0]])
sage: r1 = next(p.ray_generator())
sage: r1.is_ray()
True
sage: v1 = next(p.vertex_generator())
sage: v1
A vertex at (-1, -1, 0, -1)
sage: v1.is_ray()
False
```

#### is\_vertex()

Return True if the object is a vertex of the V-representation. This method is over-ridden by the corresponding method in the derived class Vertex.

## **EXAMPLES:**

```
sage: p = Polyhedron(vertices = [[0,0],[1,0],[0,3],[1,3]])
sage: v = next(p.vertex_generator())
sage: v.is_vertex()
True
sage: p = Polyhedron(ieqs = [[1, 0, 0, 0, 1], [1, 1, 0, 0, 0], [1, 0, 1, 0, 0]])
sage: r1 = next(p.ray_generator())
sage: r1.is_vertex()
False
```

### neighbors()

Return a generator for the adjacent vertices/rays/lines.

## **EXAMPLES:**

```
sage: p = Polyhedron(vertices = [[0,0],[1,0],[0,3],[1,4]])
sage: v = next(p.vertex_generator())
sage: next(v.neighbors())
A vertex at (0, 3)
```

sage.geometry.polyhedron.representation.repr\_pretty(coefficients, type, prefix='x', indices=None, latex=False, style='>=', split=False)

Return a pretty representation of equation/inequality represented by the coefficients.

### INPUT:

• coefficients – a tuple or other iterable

- type either 0 (PolyhedronRepresentation.INEQUALITY) or 1 (PolyhedronRepresentation. EQUATION)
- prefix a string
- indices a tuple or other iterable
- latex a boolean
- **split a boolean**; (**Default: False**). **If set to True**, the output is split into a 3-tuple containing the left-hand side, the relation, and the right-hand side of the object.
- style either "positive" (making all coefficients positive), or "<=" or ">=".

#### **OUTPUT**:

A string or 3-tuple of strings (depending on split).

#### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.representation import repr_pretty
sage: from sage.geometry.polyhedron.representation import PolyhedronRepresentation
sage: print(repr_pretty((0, 1, 0, 0), PolyhedronRepresentation.INEQUALITY))
x0 >= 0
sage: print(repr_pretty((1, 2, 1, 0), PolyhedronRepresentation.INEQUALITY))
2*x0 + x1 >= -1
sage: print(repr_pretty((1, -1, -1, 1), PolyhedronRepresentation.EQUATION))
-x0 - x1 + x2 == -1
```

# 2.1.5 Functions for plotting polyhedra

**class** sage.geometry.polyhedron.plot.**Projection**(*polyhedron*, *proj*=<*function projection\_func\_identity* at 0x7fcb57b6e670>)

```
Bases: sage.structure.sage_object.SageObject
```

The projection of a *Polyhedron*.

This class keeps track of the necessary data to plot the input polyhedron.

## coord\_index\_of(v)

Convert a coordinate vector to its internal index.

### **EXAMPLES:**

```
sage: p = polytopes.hypercube(3)
sage: proj = p.projection()
sage: proj.coord_index_of(vector((1,1,1)))
2
```

### coord\_indices\_of(v list)

Convert list of coordinate vectors to the corresponding list of internal indices.

## **EXAMPLES:**

```
sage: p = polytopes.hypercube(3)
sage: proj = p.projection()
sage: proj.coord_indices_of([vector((1,1,1)),vector((1,-1,1))])
[2, 3]
```

### coordinates\_of(coord\_index\_list)

Given a list of indices, return the projected coordinates.

**EXAMPLES:** 

```
sage: p = polytopes.simplex(4, project=True).projection()
sage: p.coordinates_of([1])
[[-0.7071067812, 0.4082482905, 0.2886751346, 0.2236067977]]
```

## identity()

Return the identity projection of the polyhedron.

**EXAMPLES**:

```
sage: p = polytopes.icosahedron(exact=False)
sage: from sage.geometry.polyhedron.plot import Projection
sage: pproj = Projection(p)
sage: ppid = pproj.identity()
sage: ppid.dimension
3
```

## render\_0d(point\_opts=None, line\_opts=None, polygon\_opts=None)

Return 0d rendering of the projection of a polyhedron into 2-dimensional ambient space.

INPUT:

See plot().

**OUTPUT**:

A 2-d graphics object.

**EXAMPLES:** 

## render\_1d(point\_opts=None, line\_opts=None, polygon\_opts=None)

Return 1d rendering of the projection of a polyhedron into 2-dimensional ambient space.

INPUT:

See plot().

**OUTPUT**:

A 2-d graphics object.

**EXAMPLES:** 

```
sage: Polyhedron([(0,), (1,)]).projection().render_1d() # optional - sage.plot
Graphics object consisting of 2 graphics primitives
```

render\_2d(point\_opts=None, line\_opts=None, polygon\_opts=None)

Return 2d rendering of the projection of a polyhedron into 2-dimensional ambient space.

**EXAMPLES:** 

```
sage: p1 = Polyhedron(vertices=[[1,1]], rays=[[1,1]])
sage: q1 = p1.projection()
sage: p2 = Polyhedron(vertices=[[1,0], [0,1], [0,0]])
sage: q2 = p2.projection()
sage: p3 = Polyhedron(vertices=[[1,2]])
sage: q3 = p3.projection()
sage: p4 = Polyhedron(vertices=[[2,0]], rays=[[1,-1]], lines=[[1,1]])
sage: q4 = p4.projection()
sage: q4 = p4.projection()
sage: q1.plot() + q2.plot() + q3.plot() + q4.plot() # optional - sage.plot
Graphics object consisting of 18 graphics primitives
```

**render\_3d**(point\_opts=None, line\_opts=None, polygon\_opts=None)

Return 3d rendering of a polyhedron projected into 3-dimensional ambient space.

#### **EXAMPLES**:

It correctly handles various degenerate cases:

```
sage: Polyhedron(lines=[[1,0,0],[0,1,0],[0,0,1]]).plot()
                                                                     # whole.
⇔space
                     # optional - sage.plot
Graphics3d Object
sage: Polyhedron(vertices=[[1,1,1]], rays=[[1,0,0]],
                # optional - sage.plot
                 lines=[[0,1,0],[0,0,1]]).plot()
                                                                     # half space
. . . . :
Graphics3d Object
sage: Polyhedron(vertices=[[1,1,1]],
                # optional - sage.plot
\hookrightarrow
                 lines=[[0,1,0],[0,0,1]]).plot()
                                                                     # R^2 in R^3
Graphics3d Object
sage: Polyhedron(rays=[[0,1,0],[0,0,1]], lines=[[1,0,0]]).plot()
                                                                     # quadrant_
→wedge in R^2
                  # optional - sage.plot
Graphics3d Object
sage: Polyhedron(rays=[[0,1,0]], lines=[[1,0,0]]).plot()
                                                                     # upper half_
→plane in R^3 # optional - sage.plot
Graphics3d Object
sage: Polyhedron(lines=[[1,0,0]]).plot()
                                                                     # R^1 in R^2
                # optional - sage.plot
Graphics3d Object
sage: Polyhedron(rays=[[0,1,0]]).plot()
                                                                     # Half-line_
→in R^3
                 # optional - sage.plot
Graphics3d Object
sage: Polyhedron(vertices=[[1,1,1]]).plot()
                                                                     # point in R^
→3
                # optional - sage.plot
Graphics3d Object
```

The origin is not included, if it is not in the polyhedron (trac ticket #23555):

Plot 3d polytope with rainbow colors:

## render\_fill\_2d(\*\*kwds)

Return the filled interior (a polygon) of a polyhedron in 2d.

**EXAMPLES**:

```
sage: cps = [i^3 for i in srange(-2,2,1/5)]
sage: p = Polyhedron(vertices = [[(t^2-1)/(t^2+1),2*t/(t^2+1)] for t in cps])
sage: proj = p.projection()
sage: filled_poly = proj.render_fill_2d()  # optional - sage.plot
sage: filled_poly.axes_width()  # optional - sage.plot
0.8
```

## render\_line\_1d(\*\*kwds)

Return the line of a polyhedron in 1d.

INPUT:

• \*\*kwds – options passed through to line2d().

**OUTPUT**:

A 2-d graphics object.

**EXAMPLES:** 

## render\_outline\_2d(\*\*kwds)

Return the outline (edges) of a polyhedron in 2d.

**EXAMPLES:** 

## render\_points\_1d(\*\*kwds)

Return the points of a polyhedron in 1d.

## INPUT:

• \*\*kwds – options passed through to point2d().

### **OUTPUT**:

A 2-d graphics object.

### **EXAMPLES:**

```
sage: cube1 = polytopes.hypercube(1)
sage: proj = cube1.projection()
sage: points = proj.render_points_1d()  # optional - sage.plot
sage: points._objects  # optional - sage.plot
[Point set defined by 2 point(s)]
```

## render\_points\_2d(\*\*kwds)

Return the points of a polyhedron in 2d.

### **EXAMPLES:**

```
sage: hex = polytopes.regular_polygon(6)
sage: proj = hex.projection()
sage: hex_points = proj.render_points_2d()  # optional - sage.plot
sage: hex_points._objects  # optional - sage.plot
[Point set defined by 6 point(s)]
```

#### render\_solid\_3d(\*\*kwds)

Return solid 3d rendering of a 3d polytope.

#### **EXAMPLES:**

```
sage: p = polytopes.hypercube(3).projection()
sage: p_solid = p.render_solid_3d(opacity=.7) # optional - sage.plot
sage: type(p_solid) # optional - sage.plot
<class 'sage.plot.plot3d.index_face_set.IndexFaceSet'>
```

## render\_vertices\_3d(\*\*kwds)

Return the 3d rendering of the vertices.

### **EXAMPLES:**

```
sage: p = polytopes.cross_polytope(3)
sage: proj = p.projection()
sage: verts = proj.render_vertices_3d() # optional - sage.plot
sage: verts.bounding_box() # optional - sage.plot
((-1.0, -1.0, -1.0), (1.0, 1.0, 1.0))
```

## render\_wireframe\_3d(\*\*kwds)

Return the 3d wireframe rendering.

### **EXAMPLES:**

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```
sage: print(wire.tachyon().split('\n')[77]) # for testing # optional - sage. \rightarrow plot
FCylinder base 1.0 1.0 -1.0 apex -1.0 1.0 -1.0 rad 0.005 texture...
```

## schlegel(facet=None, position=None)

Return the Schlegel projection.

- The facet is orthonormally transformed into its affine hull.
- The position specifies a point coming out of the barycenter of the facet from which the other vertices will be projected into the facet.

#### INPUT:

- facet a PolyhedronFace. The facet into which the Schlegel diagram is created. The default is the first facet.
- position a positive number. Determines a relative distance from the barycenter of facet. A value close to 0 will place the projection point close to the facet and a large value further away. If the given value is too large, an error is returned. If no position is given, it takes the midpoint of the possible point of views along a line spanned by the barycenter of the facet and a valid point outside the facet.

#### **EXAMPLES:**

```
sage: cube4 = polytopes.hypercube(4)
sage: from sage.geometry.polyhedron.plot import Projection
sage: Projection(cube4).schlegel()
The projection of a polyhedron into 3 dimensions
sage: _.plot() # optional - sage.plot
Graphics3d Object
```

The 4-cube with a truncated vertex seen into the resulting tetrahedron facet:

Taking a larger value for the position changes the image:

```
sage: into_tetra_far = Projection(tcube4).schlegel(tcube4.facets()[4],4)
sage: into_tetra_far.plot() # optional - sage.plot
Graphics3d Object
```

A value which is too large or negative give a projection point that sees more than one facet resulting in a error:

```
sage: Projection(tcube4).schlegel(tcube4.facets()[4],5)
Traceback (most recent call last):
...
ValueError: the chosen position is too large
sage: Projection(tcube4).schlegel(tcube4.facets()[4],-1)
Traceback (most recent call last):
```

(continues on next page)

```
...
ValueError: 'position' should be a positive number
```

#### stereographic(projection point=None)

Return the stereographic projection.

#### INPUT:

• projection\_point - The projection point. This must be distinct from the polyhedron's vertices. Default is  $(1,0,\ldots,0)$ 

#### **EXAMPLES**:

tikz(view=[0, 0, 1], angle=0, scale=1, edge\_color='blue!95!black', facet\_color='blue!95!black', opacity=0.8, vertex\_color='green', axis=False)

Return a string tikz\_pic consisting of a tikz picture of self according to a projection view and an angle angle obtained via Jmol through the current state property.

## INPUT:

- view list (default: [0,0,1]) representing the rotation axis (see note below).
- angle integer (default: 0) angle of rotation in degree from 0 to 360 (see note below).
- scale integer (default: 1) specifying the scaling of the tikz picture.
- edge\_color string (default: 'blue!95!black') representing colors which tikz recognize.
- facet\_color string (default: 'blue!95!black') representing colors which tikz recognize.
- vertex\_color string (default: 'green') representing colors which tikz recognize.
- opacity real number (default: 0.8) between 0 and 1 giving the opacity of the front facets.
- axis Boolean (default: False) draw the axes at the origin or not.

### **OUTPUT**:

• LatexExpr – containing the TikZ picture.

**Note:** The inputs view and angle can be obtained by visualizing it using .show(aspect\_ratio=1). This will open an interactive view in your default browser, where you can rotate the polytope. Once the desired view angle is found, click on the information icon in the lower right-hand corner and select *Get Viewpoint*. This will copy a string of the form '[x,y,z],angle' to your local clipboard. Go back to Sage and type Img = P.projection().tikz([x,y,z],angle).

The inputs view and angle can also be obtained from the viewer Jmol:

```
1) Right click on the image
2) Select ``Console``
3) Select the tab ``State``
4) Scroll to the line ``moveto``
```

It reads something like:

```
moveto 0.0 {x y z angle} Scale
```

The view is then [x,y,z] and angle is angle. The following number is the scale.

Jmol performs a rotation of angle degrees along the vector [x,y,z] and show the result from the z-axis.

#### **EXAMPLES:**

```
sage: P1 = polytopes.small_rhombicuboctahedron()
sage: Image1 = P1.projection().tikz([1,3,5], 175, scale=4)
sage: type(Image1)
<class 'sage.misc.latex.LatexExpr'>
sage: print('\n'.join(Image1.splitlines()[:4]))
\begin{tikzpicture}%
    [x={(-0.939161cm, 0.244762cm)},
    y=\{(0.097442cm, -0.482887cm)\},\
    z = \{(0.329367cm, 0.840780cm)\},\
sage: with open('polytope-tikz1.tex', 'w') as f: # not tested
         _ = f.write(Image1)
sage: P2 = Polyhedron(vertices=[[1, 1],[1, 2],[2, 1]])
sage: Image2 = P2.projection().tikz(scale=3, edge_color='blue!95!black', facet_
color='orange!95!black', opacity=0.4, vertex_color='yellow', axis=True)
sage: type(Image2)
<class 'sage.misc.latex.LatexExpr'>
sage: print('\n'.join(Image2.splitlines()[:4]))
\begin{tikzpicture}%
    [scale=3.000000,
    back/.style={loosely dotted, thin},
    edge/.style={color=blue!95!black, thick},
sage: with open('polytope-tikz2.tex', 'w') as f: # not tested
         _ = f.write(Image2)
sage: P3 = Polyhedron(vertices=[[-1, -1, 2],[-1, 2, -1],[2, -1, -1]])
sage: P3
A 2-dimensional polyhedron in ZZ^3 defined as the convex hull of 3 vertices
sage: Image3 = P3.projection().tikz([0.5,-1,-0.1], 55, scale=3, edge\_color=
→'blue!95!black', facet_color='orange!95!black', opacity=0.7, vertex_color=
→'yellow', axis=True)
sage: print('\n'.join(Image3.splitlines()[:4]))
\begin{tikzpicture}%
    [x={(0.658184cm, -0.242192cm)},
    y=\{(-0.096240cm, 0.912008cm)\},\
    z = \{(-0.746680 \text{cm}, -0.331036 \text{cm})\},\
sage: with open('polytope-tikz3.tex', 'w') as f: # not tested
          _ = f.write(Image3)
```

(continues on next page)

**Todo:** Make it possible to draw Schlegel diagram for 4-polytopes.

```
sage: P=Polyhedron(vertices=[[1,1,0,0],[1,2,0,0],[2,1,0,0],[0,0,1,0],[0,0,0,1]])
sage: P
A 4-dimensional polyhedron in ZZ^4 defined as the convex hull of 5 vertices
sage: P.projection().tikz()
Traceback (most recent call last):
...
NotImplementedError: The polytope has to live in 2 or 3 dimensions.
```

Make it possible to draw 3-polytopes living in higher dimension.

# 

The Schlegel projection from the given input point.

# **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.plot import ProjectionFuncSchlegel
sage: fcube = polytopes.hypercube(4)
sage: facet = fcube.facets()[0]
sage: proj = ProjectionFuncSchlegel(facet,[0,-1.5,0,0])
sage: proj([0,0,0,0])[0]
1.0
```

# class sage.geometry.polyhedron.plot.ProjectionFuncStereographic(projection\_point) Bases: object

The stereographic (or perspective) projection onto a codimension-1 linear subspace with respect to a sphere centered at the origin.

#### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.plot import ProjectionFuncStereographic
sage: cube = polytopes.hypercube(3).vertices()
sage: proj = ProjectionFuncStereographic([1.2, 3.4, 5.6])
sage: ppoints = [proj(vector(x)) for x in cube]
sage: ppoints[5]
(-0.0918273..., -0.036375...)
```

sage.geometry.polyhedron.plot.cyclic\_sort\_vertices\_2d(Vlist)

Return the vertices/rays in cyclic order if possible.

**Note:** This works if and only if each vertex/ray is adjacent to exactly two others. For example, any 2-dimensional polyhedron satisfies this.

See vertex\_adjacency\_matrix() for a discussion of "adjacent".

#### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.plot import cyclic_sort_vertices_2d
sage: square = Polyhedron([[1,0],[-1,0],[0,1],[0,-1]])
sage: vertices = [v for v in square.vertex_generator()]
sage: vertices
[A vertex at (-1, 0),
    A vertex at (0, -1),
    A vertex at (0, 1),
    A vertex at (1, 0)]
sage: cyclic_sort_vertices_2d(vertices)
[A vertex at (1, 0),
    A vertex at (0, -1),
    A vertex at (-1, 0),
    A vertex at (0, 1)]
```

Rays are allowed, too:

```
sage: P = Polyhedron(vertices=[(0, 1), (1, 0), (2, 0), (3, 0), (4, 1)], rays=[(0, 1), (1, 0), (2, 0), (3, 0), (4, 1)]
→1)])
sage: P.adjacency_matrix()
[0 1 0 1 0]
[1 0 1 0 0]
[0 1 0 0 1]
[1 0 0 0 1]
[0 \ 0 \ 1 \ 1 \ 0]
sage: cyclic_sort_vertices_2d(P.Vrepresentation())
[A vertex at (3, 0),
A vertex at (1, 0),
A vertex at (0, 1),
A ray in the direction (0, 1),
A vertex at (4, 1)
sage: P = Polyhedron(vertices=[(0, 1), (1, 0), (2, 0), (3, 0), (4, 1)], rays=[(0, 1), (1, 0), (2, 0), (3, 0), (4, 1)]
\rightarrow (1,1)])
sage: P.adjacency_matrix()
[0 1 0 0 0]
[1 0 1 0 0]
[0 1 0 0 1]
[0 0 0 0 1]
[0 0 1 1 0]
sage: cyclic_sort_vertices_2d(P.Vrepresentation())
[A ray in the direction (1, 1),
A vertex at (3, 0),
A vertex at (1, 0),
A vertex at (0, 1),
A ray in the direction (0, 1)]
```

(continues on next page)

```
sage: P = Polyhedron(vertices=[(1,2)], rays=[(0,1)], lines=[(1,0)])
sage: P.adjacency_matrix()
[0 0 1]
[0 0 0]
[1 0 0]
sage: cyclic_sort_vertices_2d(P.Vrepresentation())
[A vertex at (0, 2),
    A line in the direction (1, 0),
    A ray in the direction (0, 1)]
```

sage.geometry.polyhedron.plot.projection\_func\_identity(x)
The identity projection.

**EXAMPLES:** 

```
sage: from sage.geometry.polyhedron.plot import projection_func_identity
sage: projection_func_identity((1,2,3))
[1, 2, 3]
```

# 2.1.6 A class to keep information about faces of a polyhedron

This module gives you a tool to work with the faces of a polyhedron and their relative position. First, you need to find the faces. To get the faces in a particular dimension, use the face() method:

```
sage: P = polytopes.cross_polytope(3)
sage: P.faces(3)
(A 3-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 6 vertices,)
sage: [f.ambient_V_indices() for f in P.facets()]
[(3, 4, 5),
(2, 4, 5),
(1, 3, 5),
(1, 2, 5),
(0, 3, 4),
 (0, 2, 4),
(0, 1, 3),
(0, 1, 2)
sage: [f.ambient_V_indices() for f in P.faces(1)]
[(4, 5),
(3, 5),
(2, 5),
(1, 5),
(3, 4),
(2, 4),
 (0, 4),
 (1, 3),
 (0, 3),
 (1, 2),
 (0, 2),
(0, 1)
```

or face\_lattice() to get the whole face lattice as a poset:

The faces are printed in shorthand notation where each integer is the index of a vertex/ray/line in the same order as the containing Polyhedron's Vrepresentation()

```
sage: face = P.faces(1)[8]; face
A 1-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 2 vertices
sage: face.ambient_V_indices()
(0, 3)
sage: P.Vrepresentation(0)
A vertex at (-1, 0, 0)
sage: P.Vrepresentation(3)
A vertex at (0, 0, 1)
sage: face.vertices()
(A vertex at (-1, 0, 0), A vertex at (0, 0, 1))
```

The face itself is not represented by Sage's sage.geometry.polyhedron.constructor.Polyhedron() class, but by an auxiliary class to keep the information. You can get the face as a polyhedron with the PolyhedronFace. as\_polyhedron() method:

```
sage: face.as_polyhedron()
A 1-dimensional polyhedron in ZZ^3 defined as the convex hull of 2 vertices
sage: _.equations()
(An equation (0, 1, 0) \times + 0 == 0,
An equation (1, 0, -1) \times + 1 == 0)
```

**class** sage.geometry.polyhedron.face.**PolyhedronFace**(polyhedron, V\_indices, H\_indices)

Bases: sage.geometry.convex\_set.ConvexSet\_closed

A face of a polyhedron.

This class is for use in face\_lattice().

INPUT:

No checking is performed whether the H/V-representation indices actually determine a face of the polyhedron. You should not manually create *PolyhedronFace* objects unless you know what you are doing.

**OUTPUT**:

A PolyhedronFace.

#### **EXAMPLES:**

(continues on next page)

```
sage: face.dim()
2
sage: face.ambient_V_indices()
(0, 1, 2)
sage: face.ambient_Hrepresentation()
(An inequality (1, 1, 1) x + 1 >= 0,)
sage: face.ambient_Vrepresentation()
(A vertex at (-1, 0, 0), A vertex at (0, -1, 0), A vertex at (0, 0, -1))
```

# affine\_tangent\_cone()

Return the affine tangent cone of self as a polyhedron.

It is equal to the sum of self and the cone of feasible directions at any point of the relative interior of self.

#### **OUTPUT:**

A polyhedron.

#### **EXAMPLES:**

```
sage: half_plane_in_space = Polyhedron(ieqs=[(0,1,0,0)], eqns=[(0,0,0,1)])
sage: line = half_plane_in_space.faces(1)[0]; line
A 1-dimensional face
of a Polyhedron in QQ^3 defined as the convex hull of 1 vertex and 1 line
sage: T_line = line.affine_tangent_cone()
sage: T_line == half_plane_in_space
True
sage: c = polytopes.cube()
sage: edge = min(c.faces(1))
sage: edge.vertices()
(A vertex at (1, -1, -1), A vertex at (1, 1, -1))
sage: T_edge = edge.affine_tangent_cone()
sage: T_edge.Vrepresentation()
(A line in the direction (0, 1, 0),
A ray in the direction (0, 0, 1),
A vertex at (1, 0, -1),
A ray in the direction (-1, 0, 0)
```

# ambient()

Return the containing polyhedron.

#### **EXAMPLES:**

```
sage: P = polytopes.cross_polytope(3); P
A 3-dimensional polyhedron in ZZ^3 defined as the convex hull of 6 vertices
sage: face = P.facets()[3]
sage: face
A 2-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 3
overtices
sage: face.polyhedron()
A 3-dimensional polyhedron in ZZ^3 defined as the convex hull of 6 vertices
```

# ambient\_H\_indices()

Return the indices of the H-representation objects of the ambient polyhedron that make up the H-

representation of self.

See also ambient\_Hrepresentation().

#### **OUTPUT**:

Tuple of indices

#### **EXAMPLES:**

```
sage: Q = polytopes.cross_polytope(3)
sage: F = Q.faces(1)
sage: [f.ambient_H_indices() for f in F]
[(4, 5),
    (5, 6),
    (4, 7),
    (6, 7),
    (0, 5),
    (3, 4),
    (0, 3),
    (1, 6),
    (0, 1),
    (2, 7),
    (2, 3),
    (1, 2)]
```

# ambient\_Hrepresentation(index=None)

Return the H-representation objects of the ambient polytope defining the face.

# INPUT:

• index – optional. Either an integer or None (default).

# **OUTPUT**:

If the optional argument is not present, a tuple of H-representation objects. Each entry is either an inequality or an equation.

If the optional integer index is specified, the index-th element of the tuple is returned.

# **EXAMPLES:**

```
sage: square = polytopes.hypercube(2)
sage: for face in square.face_lattice():
                                                                          # optional -
→ sage.combinat
          print(face.ambient_Hrepresentation())
. . . . :
(An inequality (-1, 0) x + 1 >= 0, An inequality (0, -1) x + 1 >= 0,
An inequality (1, 0) \times + 1 \ge 0, An inequality (0, 1) \times + 1 \ge 0
(An inequality (-1, 0) x + 1 \ge 0, An inequality (0, 1) x + 1 \ge 0)
(An inequality (-1, 0) x + 1 \ge 0, An inequality (0, -1) x + 1 \ge 0)
(An inequality (-1, 0) x + 1 \ge 0,)
(An inequality (0, -1) \times + 1 \ge 0, An inequality (1, 0) \times + 1 \ge 0)
(An inequality (0, -1) \times + 1 \ge 0,)
(An inequality (1, 0) \times + 1 \ge 0, An inequality (0, 1) \times + 1 \ge 0)
(An inequality (0, 1) \times + 1 >= 0,)
(An inequality (1, 0) x + 1 >= 0,)
()
```

# ambient\_V\_indices()

Return the indices of the V-representation objects of the ambient polyhedron that make up the V-representation of self.

See also ambient\_Vrepresentation().

# **OUTPUT**:

Tuple of indices

#### **EXAMPLES:**

```
sage: P = polytopes.cube()
sage: F = P.faces(2)
sage: [f.ambient_V_indices() for f in F]
[(0, 3, 4, 5),
  (0, 1, 5, 6),
  (4, 5, 6, 7),
  (2, 3, 4, 7),
  (1, 2, 6, 7),
  (0, 1, 2, 3)]
```

# ambient\_Vrepresentation(index=None)

Return the V-representation objects of the ambient polytope defining the face.

#### INPUT:

• index – optional. Either an integer or None (default).

# OUTPUT:

If the optional argument is not present, a tuple of V-representation objects. Each entry is either a vertex, a ray, or a line.

If the optional integer index is specified, the index-th element of the tuple is returned.

# **EXAMPLES:**

```
sage: square = polytopes.hypercube(2)
sage: for fl in square.face_lattice():
                                                                      # optional -
→ sage.combinat
. . . . :
          print(fl.ambient_Vrepresentation())
()
(A vertex at (1, -1),)
(A vertex at (1, 1),)
(A vertex at (1, -1), A vertex at (1, 1))
(A vertex at (-1, 1),)
(A vertex at (1, 1), A vertex at (-1, 1))
(A vertex at (-1, -1),)
(A vertex at (1, -1), A vertex at (-1, -1))
(A vertex at (-1, 1), A vertex at (-1, -1))
(A vertex at (1, -1), A vertex at (1, 1),
A vertex at (-1, 1), A vertex at (-1, -1))
```

# ambient\_dim()

Return the dimension of the containing polyhedron.

# **EXAMPLES:**

```
sage: P = Polyhedron(vertices = [[1,0,0,0],[0,1,0,0]])
sage: face = P.faces(1)[0]
sage: face.ambient_dim()
4
```

# ambient\_vector\_space(base\_field=None)

Return the ambient vector space.

It is the ambient free module of the containing polyhedron tensored with a field.

#### INPUT:

• base\_field - (default: the fraction field of the base ring) a field.

#### **EXAMPLES:**

#### as\_polyhedron()

Return the face as an independent polyhedron.

#### **OUTPUT**:

A polyhedron.

# **EXAMPLES:**

#### contains(point)

Test whether the polyhedron contains the given point.

#### INPUT:

• point – a point or its coordinates

# **EXAMPLES:**

```
sage: half_plane = Polyhedron(ieqs=[(0,1,0)])
sage: line = half_plane.faces(1)[0]; line
```

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```
A 1-dimensional face of a Polyhedron in QQ^2 defined as the convex hull of 1...

--vertex and 1 line
sage: line.contains([0, 1])
True
```

As a shorthand, one may use the usual in operator:

```
sage: [5, 7] in line
False
```

#### dim()

Return the dimension of the face.

**OUTPUT:** 

Integer.

**EXAMPLES:** 

#### is\_compact()

Return whether self is compact.

OUTPUT:

Boolean.

**EXAMPLES:** 

# is\_relatively\_open()

Return whether self is relatively open.

**OUTPUT**:

Boolean.

**EXAMPLES:** 

# line\_generator()

Return a generator for the lines of the face.

**EXAMPLES:** 

```
sage: pr = Polyhedron(rays = [[1,0],[-1,0],[0,1]], vertices = [[-1,-1]])
sage: face = pr.faces(1)[0]
sage: next(face.line_generator())
A line in the direction (1, 0)
```

#### lines()

Return all lines of the face.

OUTPUT:

A tuple of lines.

**EXAMPLES**:

#### n\_ambient\_Hrepresentation()

Return the number of objects that make up the ambient H-representation of the polyhedron.

See also ambient\_Hrepresentation().

**OUTPUT**:

Integer.

**EXAMPLES:** 

```
sage: p = polytopes.cross_polytope(4)
sage: face = p.face_lattice()[5]
                                                                     # optional -
→ sage.combinat
sage: face
                                                                      # optional -
→ sage.combinat
A 1-dimensional face of a Polyhedron in ZZ^4 defined as the convex hull of 2.
→vertices
sage: face.ambient_Hrepresentation()
                                                                     # optional -
→ sage.combinat
(An inequality (1, -1, 1, -1) \times + 1 >= 0,
An inequality (1, 1, 1, 1) x + 1 >= 0,
An inequality (1, 1, 1, -1) x + 1 >= 0,
An inequality (1, -1, 1, 1) x + 1 >= 0)
sage: face.n_ambient_Hrepresentation()
                                                                      # optional -
→ sage.combinat
```

# n\_ambient\_Vrepresentation()

Return the number of objects that make up the ambient V-representation of the polyhedron.

See also ambient\_Vrepresentation().

**OUTPUT**:

Integer.

#### **EXAMPLES:**

```
sage: p = polytopes.cross_polytope(4)
sage: face = p.face_lattice()[5]
                                                                     # optional -
→ sage.combinat
sage: face
                                                                     # optional -
→ sage.combinat
A 1-dimensional face of a Polyhedron in ZZ^4 defined as the convex hull of 2_
→vertices
sage: face.ambient_Vrepresentation()
                                                                     # optional -
→ sage.combinat
(A vertex at (-1, 0, 0, 0), A vertex at (0, 0, -1, 0))
sage: face.n_ambient_Vrepresentation()
                                                                     # optional -
→ sage.combinat
```

#### n\_lines()

Return the number of lines of the face.

OUTPUT:

Integer.

**EXAMPLES:** 

#### n\_rays()

Return the number of rays of the face.

OUTPUT:

Integer.

**EXAMPLES:** 

```
sage: p = Polyhedron(ieqs = [[0,0,0,1],[0,0,1,0],[1,1,0,0]])
sage: face = p.faces(2)[0]
sage: face.n_rays()
2
```

# n\_vertices()

Return the number of vertices of the face.

**OUTPUT:** 

Integer.

**EXAMPLES:** 

```
sage: Q = polytopes.cross_polytope(3)
sage: face = Q.faces(2)[0]
sage: face.n_vertices()
3
```

#### normal\_cone(direction='outer')

Return the polyhedral cone consisting of normal vectors to hyperplanes supporting self.

#### INPUT:

• direction – string (default: 'outer'), the direction in which to consider the normals. The other allowed option is 'inner'.

#### **OUTPUT:**

A polyhedron.

#### **EXAMPLES:**

```
sage: p = Polyhedron(vertices = [[1,2],[2,1],[-2,2],[-2,-2],[2,-2]])
sage: for v in p.face_generator(0):
        vect = v.vertices()[0].vector()
         nc = v.normal_cone().rays_list()
          print("{} has outer normal cone spanned by {}".format(vect,nc))
(2, 1) has outer normal cone spanned by [[1, 0], [1, 1]]
(1, 2) has outer normal cone spanned by [[0, 1], [1, 1]]
(2, -2) has outer normal cone spanned by [[0, -1], [1, 0]]
(-2, -2) has outer normal cone spanned by [[-1, 0], [0, -1]]
(-2, 2) has outer normal cone spanned by [[-1, 0], [0, 1]]
sage: for v in p.face_generator(0):
          vect = v.vertices()[0].vector()
          nc = v.normal_cone(direction='inner').rays_list()
. . . . .
. . . . :
          print("{} has inner normal cone spanned by {}".format(vect,nc))
. . . . :
(2, 1) has inner normal cone spanned by [[-1, -1], [-1, 0]]
(1, 2) has inner normal cone spanned by [[-1, -1], [0, -1]]
(2, -2) has inner normal cone spanned by [[-1, 0], [0, 1]]
(-2, -2) has inner normal cone spanned by [[0, 1], [1, 0]]
(-2, 2) has inner normal cone spanned by [[0, -1], [1, 0]]
```

The function works for polytopes that are not full-dimensional:

Normal cones are only defined for non-empty faces:

```
sage: f0 = p.faces(-1)[0]
sage: f0.normal_cone()
Traceback (most recent call last):
...
ValueError: the empty face does not have a normal cone
```

## polyhedron()

Return the containing polyhedron.

**EXAMPLES**:

#### ray\_generator()

Return a generator for the rays of the face.

**EXAMPLES:** 

```
sage: pi = Polyhedron(ieqs = [[1,1,0],[1,0,1]])
sage: face = pi.faces(1)[1]
sage: next(face.ray_generator())
A ray in the direction (1, 0)
```

#### rays()

Return the rays of the face.

OUTPUT:

A tuple of rays.

**EXAMPLES:** 

```
sage: p = Polyhedron(ieqs = [[0,0,0,1],[0,0,1,0],[1,1,0,0]])
sage: face = p.faces(2)[2]
sage: face.rays()
(A ray in the direction (1, 0, 0), A ray in the direction (0, 1, 0))
```

# stacking\_locus()

Return the polyhedron containing the points that sees every facet containing self.

**OUTPUT**:

A polyhedron.

**EXAMPLES:** 

```
sage: cp = polytopes.cross_polytope(4)
sage: facet = cp.facets()[0]
sage: facet.stacking_locus().vertices()
(A vertex at (1/2, 1/2, 1/2, 1/2),
```

(continues on next page)

```
A vertex at (1, 0, 0, 0),
A vertex at (0, 0, 0, 1),
A vertex at (0, 0, 1, 0),
A vertex at (0, 1, 0, 0)
sage: face = cp.faces(2)[0]
sage: face.stacking_locus().vertices()
(A vertex at (0, 1, 0, 0),
A vertex at (0, 0, 1, 0),
A vertex at (1, 0, 0, 0),
A vertex at (1, 1, 1, 0),
A vertex at (1/2, 1/2, 1/2, 1/2),
A vertex at (1/2, 1/2, 1/2, -1/2)
```

# vertex\_generator()

Return a generator for the vertices of the face.

**EXAMPLES:** 

```
sage: triangle = Polyhedron(vertices=[[1,0],[0,1],[1,1]])
sage: face = triangle.facets()[0]
sage: for v in face.vertex_generator(): print(v)
A vertex at (1, 0)
A vertex at (1, 1)
sage: type(face.vertex_generator())
<... 'generator'>
```

# vertices()

Return all vertices of the face.

**OUTPUT:** 

A tuple of vertices.

**EXAMPLES**:

```
sage: triangle = Polyhedron(vertices=[[1,0],[0,1],[1,1]])
sage: face = triangle.faces(1)[2]
sage: face.vertices()
(A vertex at (0, 1), A vertex at (1, 0))
```

sage.geometry.polyhedron.face.combinatorial\_face\_to\_polyhedral\_face(polyhedron,

combinatorial\_face)

Convert a combinatorial face to a face of a polyhedron.

INPUT:

- polyhedron a polyhedron containing combinatorial\_face
- combinatorial\_face a CombinatorialFace

OUTPUT: a PolyhedronFace.

**EXAMPLES:** 

2.1. Polyhedra

```
sage: from sage.geometry.polyhedron.face import combinatorial_face_to_polyhedral_
<u></u>face
sage: P = polytopes.simplex()
```

(continues on next page)

155

# 2.1.7 Generate cdd .ext / .ine file format

Return a string containing the H-representation in cddlib's ine format.

#### INPUT:

• file\_output (string; optional) – a filename to which the representation should be written. If set to None (default), representation is returned as a string.

# **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.cdd_file_format import cdd_Hrepresentation
sage: cdd_Hrepresentation('rational', None, [[0,1]])
'H-representation\nlinearity 1 \lambda\negin\n 1 2 rational\n 0 1\nend\n'
```

Return a string containing the V-representation in cddlib's ext format.

# INPUT:

• file\_output (string; optional) – a filename to which the representation should be written. If set to None (default), representation is returned as a string.

**Note:** If there is no vertex given, then the origin will be implicitly added. You cannot write the empty V-representation (which cdd would refuse to process).

# **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.cdd_file_format import cdd_Vrepresentation
sage: print(cdd_Vrepresentation('rational', [[0,0]], [[1,0]], [[0,1]]))
V-representation
linearity 1 1
begin
   3 3 rational
   0 0 1
   0 1 0
   1 0 0
end
```

# 2.1.8 Formal modules generated by polyhedra

class sage.geometry.polyhedron.modules.formal\_polyhedra\_module.FormalPolyhedraModule(base\_ring,

mension, basis, category)

Bases: sage.combinat.free\_module.CombinatorialFreeModule

Class for formal modules generated by polyhedra.

It is formal because it is free – it does not know about linear relations of polyhedra.

A formal polyhedral module is graded by dimension.

# INPUT:

- base\_ring base ring of the module; unrelated to the base ring of the polyhedra
- dimension the ambient dimension of the polyhedra
- basis the basis

#### **EXAMPLES:**

A three-dimensional vector space of polyhedra:

```
sage: I01 = closed_interval(0, 1); I01.rename("conv([0], [1])")
sage: I11 = closed_interval(1, 1); I11.rename("{[1]}")
sage: I12 = closed_interval(1, 2); I12.rename("conv([1], [2])")
sage: basis = [I01, I11, I12]
sage: M = FormalPolyhedraModule(QQ, 1, basis=basis); M
Free module generated by {conv([0], [1]), {[1]}, conv([1], [2])} over Rational Field
sage: M.get_order()
[conv([0], [1]), {[1]}, conv([1], [2])]
```

A one-dimensional subspace; bases of subspaces just use the indexing set  $0, \dots, d-1$ , where d is the dimension:

```
sage: M_lower = M.submodule([M(I11)]); M_lower
Free module generated by {0} over Rational Field
sage: M_lower.print_options(prefix='S')
sage: M_lower.is_submodule(M)
True
sage: x = M(I01) - 2*M(I11) + M(I12)
sage: M_lower.reduce(x)
[conv([0], [1])] + [conv([1], [2])]
sage: M_lower.retract.domain() is M
True
sage: y = M_lower.retract(M(I11)); y
S[0]
sage: M_lower.lift(y)
[{[1]}]
```

Quotient space; bases of quotient space are families indexed by elements of the ambient space:

# degree\_on\_basis(m)

The degree of an element of the basis is defined as the dimension of the polyhedron.

#### INPUT:

• m – an element of the basis (a polyhedron)

#### **EXAMPLES:**

We can extract homogeneous components:

```
sage: 0 = M(I01) + M(I11) + M(I12)
sage: 0.homogeneous_component(0)
[{[1]}]
sage: 0.homogeneous_component(1)
[conv([0], [1])] + [conv([1], [2])]
```

We note that modulo the linear relations of polyhedra, this would only be a filtration, not a grading, as the following example shows:

```
sage: X = M(I01) + M(I12) - M(I02)
sage: X.degree()
1
sage: Y = M(I11)
sage: Y.degree()
0
```

# 2.2 Lattice polyhedra

# 2.2.1 Lattice and reflexive polytopes

This module provides tools for work with lattice and reflexive polytopes. A *convex polytope* is the convex hull of finitely many points in  $\mathbb{R}^n$ . The dimension n of a polytope is the smallest n such that the polytope can be embedded in  $\mathbb{R}^n$ .

A *lattice polytope* is a polytope whose vertices all have integer coordinates.

If L is a lattice polytope, the dual polytope of L is

$$\{y \in \mathbf{Z}^n : x \cdot y \ge -1 \text{ all } x \in L\}$$

A *reflexive polytope* is a lattice polytope, such that its polar is also a lattice polytope, i.e. it is bounded and has vertices with integer coordinates.

This Sage module uses Package for Analyzing Lattice Polytopes (PALP), which is a program written in C by Maximilian Kreuzer and Harald Skarke, which is freely available under the GNU license terms at http://hep.itp.tuwien.ac.at/~kreuzer/CY/. Moreover, PALP is included standard with Sage.

PALP is described in the paper arXiv math.SC/0204356. Its distribution also contains the application nef.x, which was created by Erwin Riegler and computes nef-partitions and Hodge data for toric complete intersections.

ACKNOWLEDGMENT: polytope.py module written by William Stein was used as an example of organizing an interface between an external program and Sage. William Stein also helped Andrey Novoseltsev with debugging and tuning of this module.

Robert Bradshaw helped Andrey Novoseltsev to realize plot3d function.

**Note:** IMPORTANT: PALP requires some parameters to be determined during compilation time, i.e., the maximum dimension of polytopes, the maximum number of points, etc. These limitations may lead to errors during calls to different functions of these module. Currently, a ValueError exception will be raised if the output of poly.x or nef.x is empty or contains the exclamation mark. The error message will contain the exact command that caused an error, the description and vertices of the polytope, and the obtained output.

Data obtained from PALP and some other data is cached and most returned values are immutable. In particular, you cannot change the vertices of the polytope or their order after creation of the polytope.

If you are going to work with large sets of data, take a look at all\_\* functions in this module. They precompute different data for sequences of polynomials with a few runs of external programs. This can significantly affect the time of future computations. You can also use dump/load, but not all data will be stored (currently only faces and the number of their internal and boundary points are stored, in addition to polytope vertices and its polar).

#### **AUTHORS:**

- Andrey Novoseltsev (2007-01-11): initial version
- Andrey Novoseltsev (2007-01-15): all\_\* functions
- Andrey Novoseltsev (2008-04-01): second version, including:
  - dual nef-partitions and necessary convex\_hull and minkowski\_sum
  - built-in sequences of 2- and 3-dimensional reflexive polytopes
  - plot3d, skeleton\_show
- Andrey Novoseltsev (2009-08-26): dropped maximal dimension requirement
- Andrey Novoseltsev (2010-12-15): new version of nef-partitions

- Andrey Novoseltsev (2013-09-30): switch to PointCollection.
- Maximilian Kreuzer and Harald Skarke: authors of PALP (which was also used to obtain the list of 3-dimensional reflexive polytopes)
- Erwin Riegler: the author of nef.x

sage.geometry.lattice\_polytope.LatticePolytope(data, compute\_vertices=True, n=0, lattice=None) Construct a lattice polytope.

#### INPUT:

- data points spanning the lattice polytope, specified as one of:
  - a point collection (this is the preferred input and it is the quickest and the most memory efficient one);
  - an iterable of iterables (for example, a list of vectors) defining the point coordinates;
  - a file with matrix data, opened for reading, or
  - a filename of such a file, see read\_palp\_point\_collection() for the file format;
- **compute\_vertices boolean (default: True). If True, the** convex hull of the given points will be computed for determining vertices. Otherwise, the given points must be vertices;
- n an integer (default: 0) if data is a name of a file, that contains data blocks for several polytopes, the n-th block will be used;
- lattice the ambient lattice of the polytope. If not given, a suitable lattice will be determined automatically, most likely the *toric lattice M* of the appropriate dimension.

# **OUTPUT**:

• a lattice polytope.

# **EXAMPLES:**

```
sage: points = [(1,0,0), (0,1,0), (0,0,1), (-1,0,0), (0,-1,0), (0,0,-1)]
sage: p = LatticePolytope(points)
sage: p
3-d reflexive polytope in 3-d lattice M
sage: p.vertices()
M( 1,  0,  0),
M( 0,  1,  0),
M( 0,  0,  1),
M(-1,  0,  0),
M( 0,  -1,  0),
M( 0,  0, -1)
in 3-d lattice M
```

We draw a pretty picture of the polytope in 3-dimensional space:

Now we add an extra point, which is in the interior of the polytope...

```
sage: points.append((0,0,0))
sage: p = LatticePolytope(points)
sage: p.nvertices()
6
```

You can suppress vertex computation for speed but this can lead to mistakes:

```
sage: p = LatticePolytope(points, compute_vertices=False)
...
sage: p.nvertices()
7
```

Given points must be in the lattice:

```
sage: LatticePolytope([[1/2], [3/2]])
Traceback (most recent call last):
...
ValueError: points
[[1/2], [3/2]]
are not in 1-d lattice M!
```

But it is OK to create polytopes of non-maximal dimension:

An empty lattice polytope can be considered as well:

```
sage: p = LatticePolytope([], lattice=ToricLattice(3).dual()); p
-1-d lattice polytope in 3-d lattice M
sage: p.lattice_dim()
3
sage: p.npoints()
0
sage: p.nfacets()
0
sage: p.points()
Empty collection
in 3-d lattice M
sage: p.faces()
((-1-d lattice polytope in 3-d lattice M,),)
```

```
\begin{tabular}{ll} \textbf{class} & sage.geometry.lattice\_polytope.LatticePolytopeClass(points=None, compute\_vertices=None, ambient=None, ambient\_vertex\_indices=None, ambient\_vertex\_indices=Non
```

ambient\_facet\_indices=None)

collections.abc.Hashable.se

 $Bases: sage.geometry.convex\_set.ConvexSet\_compact, collections.abc. Hashable, sage.geometry.abc. LatticePolytope$ 

Create a lattice polytope.

**Warning:** This class does not perform any checks of correctness of input nor does it convert input into the standard representation. Use *LatticePolytope()* to construct lattice polytopes.

Lattice polytopes are immutable, but they cache most of the returned values.

# INPUT:

The input can be either:

- points PointCollection;
- compute\_vertices boolean.

or (these parameters must be given as keywords):

- ambient ambient structure, this polytope *must be a face of* ambient;
- ambient\_vertex\_indices increasing list or tuple of integers, indices of vertices of ambient generating this polytope;
- ambient\_facet\_indices increasing list or tuple of integers, indices of facets of ambient generating this polytope.

#### **OUTPUT**:

• lattice polytope.

Note: Every polytope has an ambient structure. If it was not specified, it is this polytope itself.

# adjacent()

Return faces adjacent to self in the ambient face lattice.

Two distinct faces  $F_1$  and  $F_2$  of the same face lattice are **adjacent** if all of the following conditions hold:

- $F_1$  and  $F_2$  have the same dimension d;
- $F_1$  and  $F_2$  share a facet of dimension d-1;
- $F_1$  and  $F_2$  are facets of some face of dimension d+1, unless d is the dimension of the ambient structure.

# **OUTPUT**:

• tuple of lattice polytopes.

#### **EXAMPLES:**

```
sage: o = lattice_polytope.cross_polytope(3)
sage: o.adjacent()
()
sage: face = o.faces(1)[0]
sage: face.adjacent()
(1-d face of 3-d reflexive polytope in 3-d lattice M,
1-d face of 3-d reflexive polytope in 3-d lattice M,
1-d face of 3-d reflexive polytope in 3-d lattice M,
1-d face of 3-d reflexive polytope in 3-d lattice M,
```

# $affine_transform(a=1, b=0)$

Return a\*P+b, where P is this lattice polytope.

Note:

- 1. While a and b may be rational, the final result must be a lattice polytope, i.e. all vertices must be integral.
- 2. If the transform (restricted to this polytope) is bijective, facial structure will be preserved, e.g. the first facet of the image will be spanned by the images of vertices which span the first facet of the original polytope.

#### INPUT:

- a (default: 1) rational scalar or matrix
- b (default: 0) rational scalar or vector, scalars are interpreted as vectors with the same components

#### **EXAMPLES:**

```
sage: o = lattice_polytope.cross_polytope(2)
sage: o.vertices()
M(1, 0),
M(0, 1),
M(-1, 0),
M(0, -1)
in 2-d lattice M
sage: o.affine_transform(2).vertices()
M(2, 0),
M(0, 2),
M(-2, 0),
M(0, -2)
in 2-d lattice M
sage: o.affine_transform(1,1).vertices()
M(2, 1),
M(1, 2),
M(0, 1),
M(1, 0)
in 2-d lattice M
sage: o.affine_transform(b=1).vertices()
M(2, 1),
M(1, 2),
M(0, 1),
M(1, 0)
in 2-d lattice M
sage: o.affine_transform(b=(1, 0)).vertices()
M(2, 0),
M(1, 1),
M(0, 0),
M(1, -1)
in 2-d lattice M
sage: a = matrix(QQ, 2, [1/2, 0, 0, 3/2])
sage: o.polar().vertices()
N(1, 1),
N(1, -1),
N(-1, -1),
N(-1, 1)
in 2-d lattice N
sage: o.polar().affine_transform(a, (1/2, -1/2)).vertices()
M(1, 1),
```

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```
M(1, -2),
M(0, -2),
M(0, 1)
in 2-d lattice M
```

While you can use rational transformation, the result must be integer:

```
sage: o.affine_transform(a)
Traceback (most recent call last):
...
ValueError: points
[(1/2, 0), (0, 3/2), (-1/2, 0), (0, -3/2)]
are not in 2-d lattice M!
```

# ambient()

Return the ambient structure of self.

#### **OUTPUT**:

• lattice polytope containing self as a face.

#### **EXAMPLES:**

```
sage: o = lattice_polytope.cross_polytope(3)
sage: o.ambient()
3-d reflexive polytope in 3-d lattice M
sage: o.ambient() is o
True
sage: face = o.faces(1)[0]
sage: face
1-d face of 3-d reflexive polytope in 3-d lattice M
sage: face.ambient()
3-d reflexive polytope in 3-d lattice M
sage: face.ambient() is o
True
```

#### ambient\_dim()

Return the dimension of the ambient lattice of self.

An alias is ambient\_dim().

# **OUTPUT**:

• integer.

#### **EXAMPLES:**

```
sage: p = LatticePolytope([(1,0)])
sage: p.lattice_dim()
2
sage: p.dim()
0
```

# ambient\_facet\_indices()

Return indices of facets of the ambient polytope containing self.

**OUTPUT**:

• increasing tuple of integers.

# **EXAMPLES:**

The polytope itself is not contained in any of its facets:

```
sage: o = lattice_polytope.cross_polytope(3)
sage: o.ambient_facet_indices()
()
```

But each of its other faces is contained in one or more facets:

```
sage: face = o.faces(1)[0]
sage: face.ambient_facet_indices()
(4, 5)
sage: face.vertices()
M(1, 0, 0),
M(0, 1, 0)
in 3-d lattice M
sage: o.facets()[face.ambient_facet_indices()[0]].vertices()
M(1, 0, 0),
M(0, 1, 0),
M(0, 0, -1)
in 3-d lattice M
```

#### ambient\_ordered\_point\_indices()

Return indices of points of the ambient polytope contained in this one.

#### **OUTPUT**:

• tuple of integers such that ambient points in this order are geometrically ordered, e.g. for an edge points will appear from one end point to the other.

# **EXAMPLES:**

```
sage: cube = lattice_polytope.cross_polytope(3).polar()
sage: face = cube.facets()[0]
sage: face.ambient_ordered_point_indices()
                                                                    # optional -
→ palp
(5, 8, 4, 9, 10, 11, 6, 12, 7)
sage: cube.points(face.ambient_ordered_point_indices())
                                                                    # optional -
→ palp
N(-1, -1, -1),
N(-1, -1, 0),
N(-1, -1, 1),
N(-1, 0, -1),
N(-1, 0, 0),
N(-1, 0, 1),
N(-1, 1, -1),
N(-1, 1, 0),
N(-1, 1, 1)
in 3-d lattice N
```

# ambient\_point\_indices()

Return indices of points of the ambient polytope contained in this one.

**OUTPUT**:

• tuple of integers, the order corresponds to the order of points of this polytope.

#### **EXAMPLES:**

# ambient\_vector\_space(base\_field=None)

Return the ambient vector space.

It is the ambient lattice (lattice()) tensored with a field.

#### INPUT:

• base\_field - (default: the rationals) a field.

#### **EXAMPLES:**

```
sage: p = LatticePolytope([(1,0)])
sage: p.ambient_vector_space()
Vector space of dimension 2 over Rational Field
sage: p.ambient_vector_space(AA)
Vector space of dimension 2 over Algebraic Real Field
```

#### ambient\_vertex\_indices()

Return indices of vertices of the ambient structure generating self.

# **OUTPUT**:

• increasing tuple of integers.

# **EXAMPLES:**

```
sage: o = lattice_polytope.cross_polytope(3)
sage: o.ambient_vertex_indices()
(0, 1, 2, 3, 4, 5)
sage: face = o.faces(1)[0]
sage: face.ambient_vertex_indices()
(0, 1)
```

# boundary\_point\_indices()

Return indices of (relative) boundary lattice points of this polytope.

#### **OUTPUT**:

• increasing tuple of integers.

# **EXAMPLES:**

All points but the origin are on the boundary of this square:

```
sage: square = lattice_polytope.cross_polytope(2).polar()
sage: square.points() # optional -
    palp
```

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```
N(1, 1),
N(1, -1),
N(-1, -1),
N(-1, 1),
N(-1, 0),
N(0, -1),
N(0, 0),
N(0, 1),
N(1, 0)
in 2-d lattice N

sage: square.boundary_point_indices()
palp
(0, 1, 2, 3, 4, 5, 7, 8)
```

For an edge the boundary is formed by the end points:

```
sage: face = square.edges()[0]
sage: face.points()
N(-1, -1),
N(-1, 1),
N(-1, 0)
in 2-d lattice N
sage: face.boundary_point_indices()
(0, 1)
```

# boundary\_points()

Return (relative) boundary lattice points of this polytope.

# **OUTPUT**:

• a point collection.

# **EXAMPLES**:

All points but the origin are on the boundary of this square:

For an edge the boundary is formed by the end points:

```
sage: face = square.edges()[0]
sage: face.boundary_points()
N(-1, -1),
```

(continues on next page)

```
N(-1, 1) in 2-d lattice N
```

#### contains(\*args)

Check if a given point is contained in self.

# INPUT:

• an attempt will be made to convert all arguments into a single element of the ambient space of self; if it fails, False will be returned

#### **OUTPUT**:

• True if the given point is contained in self, False otherwise

#### **EXAMPLES:**

```
sage: p = lattice_polytope.cross_polytope(2)
sage: p.contains(p.lattice()(1,0))
True
sage: p.contains((1,0))
True
sage: p.contains(1,0)
True
sage: p.contains((2,0))
False
```

# dim()

Return the dimension of this polytope.

# **EXAMPLES:**

We create a 3-dimensional octahedron and check its dimension:

```
sage: o = lattice_polytope.cross_polytope(3)
sage: o.dim()
3
```

Now we create a 2-dimensional diamond in a 3-dimensional space:

```
sage: p = LatticePolytope([(1,0,0), (0,1,0), (-1,0,0), (0,-1,0)])
sage: p.dim()
2
sage: p.lattice_dim()
3
```

# distances(point=None)

Return the matrix of distances for this polytope or distances for the given point.

The matrix of distances m gives distances m[i,j] between the i-th facet (which is also the i-th vertex of the polar polytope in the reflexive case) and j-th point of this polytope.

If point is specified, integral distances from the point to all facets of this polytope will be computed.

EXAMPLES: The matrix of distances for a 3-dimensional octahedron:

```
sage: o = lattice_polytope.cross_polytope(3)
sage: o.distances() # optional -
    palp
[2 0 0 0 0 2 2 1]
[2 2 0 0 0 0 2 1]
[2 2 2 0 0 0 1]
[2 0 2 0 2 0 2 0 1]
[0 0 0 2 2 2 2 0 1]
[0 0 0 2 2 2 2 1]
[0 2 0 2 0 2 0 2 1]
[0 2 0 2 0 2 0 2 1]
```

Distances from facets to the point (1,2,3):

```
sage: o.distances([1,2,3])
(-3, 1, 7, 3, 1, -5, -1, 5)
```

It is OK to use RATIONAL coordinates:

```
sage: o.distances([1,2,3/2])
(-3/2, 5/2, 11/2, 3/2, -1/2, -7/2, 1/2, 7/2)
sage: o.distances([1,2,sqrt(2)])
Traceback (most recent call last):
...
TypeError: unable to convert sqrt(2) to an element of Rational Field
```

Now we create a non-spanning polytope:

This point is not even in the affine subspace of the polytope:

```
sage: p.distances((1, 1, 1)) # optional - palp (3, 1, -1, 1)
```

# dual()

Return the dual face under face duality of polar reflexive polytopes.

This duality extends the correspondence between vertices and facets.

OUTPUT:

• a lattice polytope.

**EXAMPLES:** 

```
sage: o = lattice_polytope.cross_polytope(4)
sage: e = o.edges()[0]; e
1-d face of 4-d reflexive polytope in 4-d lattice M
sage: ed = e.dual(); ed
2-d face of 4-d reflexive polytope in 4-d lattice N
sage: ed.ambient() is e.ambient().polar()
True
sage: e.ambient_vertex_indices() == ed.ambient_facet_indices()
True
sage: e.ambient_facet_indices() == ed.ambient_vertex_indices()
True
```

# dual\_lattice()

Return the dual of the ambient lattice of self.

#### **OUTPUT**:

• a lattice. If possible (that is, if *lattice()* has a dual() method), the dual lattice is returned. Otherwise, **Z**<sup>n</sup> is returned, where n is the dimension of self.

#### **EXAMPLES:**

```
sage: LatticePolytope([(1,0)]).dual_lattice()
2-d lattice N
sage: LatticePolytope([], lattice=ZZ^3).dual_lattice()
Ambient free module of rank 3
over the principal ideal domain Integer Ring
```

# edges()

Return edges (faces of dimension 1) of self.

# **OUTPUT**:

• tuple of lattice polytopes.

# **EXAMPLES:**

```
sage: o = lattice_polytope.cross_polytope(3)
sage: o.edges()
(1-d face of 3-d reflexive polytope in 3-d lattice M,
...
1-d face of 3-d reflexive polytope in 3-d lattice M)
sage: len(o.edges())
12
```

# face\_lattice()

Return the face lattice of self.

This lattice will have the empty polytope as the bottom and this polytope itself as the top.

#### **OUTPUT**:

• finite poset of lattice polytopes.

# EXAMPLES:

Let's take a look at the face lattice of a square:

```
sage: square = LatticePolytope([(0,0), (1,0), (1,1), (0,1)])
sage: L = square.face_lattice()
sage: L
Finite lattice containing 10 elements with distinguished linear extension
```

To see all faces arranged by dimension, you can do this:

```
sage: for level in L.level_sets(): print(level)
[-1-d face of 2-d lattice polytope in 2-d lattice M]
[0-d face of 2-d lattice polytope in 2-d lattice M,
  0-d face of 2-d lattice polytope in 2-d lattice M,
  0-d face of 2-d lattice polytope in 2-d lattice M,
  0-d face of 2-d lattice polytope in 2-d lattice M]
[1-d face of 2-d lattice polytope in 2-d lattice M,
  1-d face of 2-d lattice polytope in 2-d lattice M,
  1-d face of 2-d lattice polytope in 2-d lattice M,
  1-d face of 2-d lattice polytope in 2-d lattice M]
[2-d lattice polytope in 2-d lattice M]
```

For a particular face you can look at its actual vertices...

```
sage: face = L.level_sets()[1][0]
sage: face.vertices()
M(0, 0)
in 2-d lattice M
```

... or you can see the index of the vertex of the original polytope that corresponds to the above one:

```
sage: face.ambient_vertex_indices()
(0,)
sage: square.vertex(0)
M(0, 0)
```

An alternative to extracting faces from the face lattice is to use faces() method:

```
sage: face is square.faces(dim=0)[0]
True
```

The advantage of working with the face lattice directly is that you can (relatively easily) get faces that are related to the given one:

```
sage: face = L.level_sets()[1][0]
sage: D = L.hasse_diagram()
sage: sorted(D.neighbors(face))
[-1-d face of 2-d lattice polytope in 2-d lattice M,
   1-d face of 2-d lattice polytope in 2-d lattice M,
   1-d face of 2-d lattice polytope in 2-d lattice M]
```

However, you can achieve some of this functionality using facets(), facet\_of(), and adjacent() methods:

```
sage: face = square.faces(0)[0]
sage: face
0-d face of 2-d lattice polytope in 2-d lattice M
```

(continues on next page)

```
sage: face.vertices()
M(0, 0)
in 2-d lattice M
sage: face.facets()
(-1-d face of 2-d lattice polytope in 2-d lattice M,)
sage: face.facet_of()
(1-d face of 2-d lattice polytope in 2-d lattice M,
    1-d face of 2-d lattice polytope in 2-d lattice M)
sage: face.adjacent()
(0-d face of 2-d lattice polytope in 2-d lattice M,
    0-d face of 2-d lattice polytope in 2-d lattice M)
sage: face.adjacent()[0].vertices()
M(1, 0)
in 2-d lattice M
```

Note that if p is a face of superp, then the face lattice of p consists of (appropriate) faces of superp:

```
sage: superp = LatticePolytope([(1,2,3,4), (5,6,7,8),
                                (1,2,4,8), (1,3,9,7)])
sage: superp.face_lattice()
Finite lattice containing 16 elements with distinguished linear extension
sage: superp.face_lattice().top()
3-d lattice polytope in 4-d lattice M
sage: p = superp.facets()[0]
sage: p
2-d face of 3-d lattice polytope in 4-d lattice M
sage: p.face_lattice()
Finite poset containing 8 elements with distinguished linear extension
sage: p.face_lattice().bottom()
-1-d face of 3-d lattice polytope in 4-d lattice M
sage: p.face_lattice().top()
2-d face of 3-d lattice polytope in 4-d lattice M
sage: p.face_lattice().top() is p
True
```

# faces(dim=None, codim=None)

Return faces of self of specified (co)dimension.

#### INPUT:

- dim integer, dimension of the requested faces;
- codim integer, codimension of the requested faces.

Note: You can specify at most one parameter. If you don't give any, then all faces will be returned.

#### **OUTPUT**:

- if either dim or codim is given, the output will be a tuple of lattice polytopes;
- if neither dim nor codim is given, the output will be the tuple of tuples as above, giving faces of all existing dimensions. If you care about inclusion relations between faces, consider using face\_lattice() or adjacent(), facet\_of(), and facets().

**EXAMPLES:** 

Let's take a look at the faces of a square:

```
sage: square = LatticePolytope([(0,0), (1,0), (1,1), (0,1)])
sage: square.faces()
((-1-d face of 2-d lattice polytope in 2-d lattice M,),
  (0-d face of 2-d lattice polytope in 2-d lattice M,
    0-d face of 2-d lattice polytope in 2-d lattice M,
    0-d face of 2-d lattice polytope in 2-d lattice M,
    0-d face of 2-d lattice polytope in 2-d lattice M),
    (1-d face of 2-d lattice polytope in 2-d lattice M,
    1-d face of 2-d lattice polytope in 2-d lattice M,
    1-d face of 2-d lattice polytope in 2-d lattice M,
    1-d face of 2-d lattice polytope in 2-d lattice M,
    1-d face of 2-d lattice polytope in 2-d lattice M),
    (2-d lattice polytope in 2-d lattice M,))
```

Its faces of dimension one (i.e., edges):

```
sage: square.faces(dim=1)
(1-d face of 2-d lattice polytope in 2-d lattice M,
1-d face of 2-d lattice polytope in 2-d lattice M,
1-d face of 2-d lattice polytope in 2-d lattice M,
1-d face of 2-d lattice polytope in 2-d lattice M)
```

Its faces of codimension one are the same (also edges):

```
sage: square.faces(codim=1) is square.faces(dim=1)
True
```

Let's pick a particular face:

```
sage: face = square.faces(dim=1)[0]
```

Now you can look at the actual vertices of this face...

```
sage: face.vertices()
M(0, 0),
M(0, 1)
in 2-d lattice M
```

... or you can see indices of the vertices of the original polytope that correspond to the above ones:

```
sage: face.ambient_vertex_indices()
(0, 3)
sage: square.vertices(face.ambient_vertex_indices())
M(0, 0),
M(0, 1)
in 2-d lattice M
```

# facet\_constant(i)

Return the constant in the i-th facet inequality of this polytope.

This is equivalent to facet\_constants()[i].

INPUT:

• i – integer; the index of the facet

#### **OUTPUT**:

• integer – the constant in the i-th facet inequality.

#### See also:

```
facet_constants(), facet_normal(), facet_normals(), facets().
```

#### **EXAMPLES:**

```
sage: o = lattice_polytope.cross_polytope(3)
sage: o.facet_constant(0)
1
sage: o.facet_constant(0) == o.facet_constants()[0]
True
```

# facet\_constants()

Return facet constants of self.

Facet inequalities have form  $n \cdot x + c \ge 0$  where n is the inner normal and c is a constant.

# OUTPUT:

· an integer vector

#### See also:

```
facet_constant(), facet_normal(), facet_normals(), facets().
```

# **EXAMPLES:**

For reflexive polytopes all constants are 1:

```
sage: o = lattice_polytope.cross_polytope(3)
sage: o.vertices()
M( 1,  0,  0),
M( 0,  1,  0),
M( 0,  0,  1),
M(-1,  0,  0),
M( 0,  -1,  0),
M( 0,  0,  -1)
in 3-d lattice M
sage: o.facet_constants()
(1, 1, 1, 1, 1, 1, 1, 1)
```

Here is an example of a 3-dimensional polytope in a 4-dimensional space with 3 facets containing the origin:

# facet\_normal(i)

Return the inner normal to the i-th facet of this polytope.

This is equivalent to facet\_normals()[i].

#### INPUT:

• i – integer; the index of the facet

#### **OUTPUT:**

a vector

#### See also:

```
facet_constant(), facet_constants(), facet_normals(), facets().
```

#### **EXAMPLES:**

```
sage: o = lattice_polytope.cross_polytope(3)
sage: o.facet_normal(0)
N(1, -1, -1)
sage: o.facet_normal(0) is o.facet_normals()[0]
True
```

#### facet normals()

Return inner normals to the facets of self.

If this polytope is not full-dimensional, facet normals will define this polytope in the affine subspace spanned by it.

#### OUTPUT:

• a point collection in the dual\_lattice() of self.

# See also:

```
facet_constant(), facet_constants(), facet_normal(), facets().
```

#### **EXAMPLES:**

Normals to facets of an octahedron are vertices of a cube:

```
sage: o = lattice_polytope.cross_polytope(3)
sage: o.vertices()
M(1, 0, 0),
M(0, 1, 0),
M(0, 0, 1),
M(-1, 0, 0),
M(0, -1, 0),
M(0, 0, -1)
in 3-d lattice M
sage: o.facet_normals()
N(1, -1, -1),
N(1, 1, -1),
N(1, 1, 1),
N(1, -1, 1),
N(-1, -1, 1),
N(-1, -1, -1),
N(-1, 1, -1),
```

(continues on next page)

```
N(-1, 1, 1)
in 3-d lattice N
```

Here is an example of a 3-dimensional polytope in a 4-dimensional space:

```
sage: p = LatticePolytope([(0,0,0,0), (1,1,1,3),
                           (1,-1,1,3), (-1,-1,1,3)]
. . . . . .
sage: p.vertices()
M(0, 0, 0, 0),
M(1, 1, 1, 3),
M(1, -1, 1, 3),
M(-1, -1, 1, 3)
in 4-d lattice M
sage: p.facet_normals()
N(0, 3, 0, 1),
N(1, -1, 0, 0),
N(0, 0, 0, -1),
N(-3, 0, 0, 1)
in 4-d lattice N
sage: p.facet_constants()
(0, 0, 3, 0)
```

Now we manually compute the distance matrix of this polytope. Since it is a simplex, each line (corresponding to a facet) should consist of zeros (indicating generating vertices of the corresponding facet) and a single positive number (since our normals are inner):

```
sage: matrix([[n * v + c for v in p.vertices()]
....:     for n, c in zip(p.facet_normals(), p.facet_constants())])
[0 6 0 0]
[0 0 2 0]
[3 0 0 0]
[0 0 0 6]
```

# facet\_of()

Return elements of the ambient face lattice having self as a facet.

# **OUTPUT**:

• tuple of lattice polytopes.

# **EXAMPLES:**

```
sage: square = LatticePolytope([(0,0), (1,0), (1,1), (0,1)])
sage: square.facet_of()
()
sage: face = square.faces(0)[0]
sage: len(face.facet_of())
2
sage: face.facet_of()[1]
1-d face of 2-d lattice polytope in 2-d lattice M
```

#### facets()

Return facets (faces of codimension 1) of self.

**OUTPUT**:

• tuple of lattice polytopes.

#### **EXAMPLES:**

```
sage: o = lattice_polytope.cross_polytope(3)
sage: o.facets()
(2-d face of 3-d reflexive polytope in 3-d lattice M,
...
2-d face of 3-d reflexive polytope in 3-d lattice M)
sage: len(o.facets())
8
```

## incidence\_matrix()

Return the incidence matrix.

**Note:** The columns correspond to facets/facet normals in the order of facet\_normals(), the rows correspond to the vertices in the order of vertices().

## **EXAMPLES:**

```
sage: o = lattice_polytope.cross_polytope(2)
sage: o.incidence_matrix()
[0 0 1 1]
[0 1 1 0]
[1 1 0 0]
[1 0 0 1]
sage: o.faces(1)[0].incidence_matrix()
[1 0]
[0 1]

sage: o = lattice_polytope.cross_polytope(4)
sage: o.incidence_matrix().column(3).nonzero_positions()
[3, 4, 5, 6]
sage: o.facets()[3].ambient_vertex_indices()
(3, 4, 5, 6)
```

## index()

Return the index of this polytope in the internal database of 2- or 3-dimensional reflexive polytopes. Databases are stored in the directory of the package.

**Note:** The first call to this function for each dimension can take a few seconds while the dictionary of all polytopes is constructed, but after that it is cached and fast.

## Return type integer

EXAMPLES: We check what is the index of the "diamond" in the database:

```
sage: d = lattice_polytope.cross_polytope(2)
sage: d.index() # optional -
    palp
3
```

Note that polytopes with the same index are not necessarily the same:

```
sage: d.vertices()
M( 1,  0),
M( 0,  1),
M(-1,  0),
M( 0, -1)
in 2-d lattice M
sage: lattice_polytope.ReflexivePolytope(2,3).vertices()
M( 1,  0),
M( 0,  1),
M( 0,  -1),
M( -1,  0)
in 2-d lattice M
```

But they are in the same  $GL(\mathbb{Z}^n)$  orbit and have the same normal form:

```
sage: d.normal_form()  # optional -
    palp
M( 1,  0),
M( 0,  1),
M( 0,  -1),
M(-1,  0)
in 2-d lattice M
sage: lattice_polytope.ReflexivePolytope(2,3).normal_form()
M( 1,  0),
M( 0,  1),
M( 0,  -1),
M( 0,  -1),
M(-1,  0)
in 2-d lattice M
```

## interior\_point\_indices()

Return indices of (relative) interior lattice points of this polytope.

## **OUTPUT**:

• increasing tuple of integers.

## **EXAMPLES**:

The origin is the only interior point of this square:

```
sage: square = lattice_polytope.cross_polytope(2).polar()
sage: square.points()
                                                               # optional -_
→palp
N(1, 1),
N(1, -1),
N(-1, -1),
N(-1, 1),
N(-1, 0),
N(0, -1),
N(0, 0),
N(0, 1),
N(1, 0)
in 2-d lattice N
sage: square.interior_point_indices()
                                                               # optional -_
→palp
```

```
(6,)
```

Its edges also have a single interior point each:

```
sage: face = square.edges()[0]
sage: face.points()
N(-1, -1),
N(-1, 1),
N(-1, 0)
in 2-d lattice N
sage: face.interior_point_indices()
(2,)
```

## interior\_points()

Return (relative) boundary lattice points of this polytope.

**OUTPUT**:

• a point collection.

#### **EXAMPLES:**

The origin is the only interior point of this square:

Its edges also have a single interior point each:

```
sage: face = square.edges()[0]
sage: face.interior_points()
N(-1, 0)
in 2-d lattice N
```

## is\_reflexive()

Return True if this polytope is reflexive.

EXAMPLES: The 3-dimensional octahedron is reflexive (and 4319 other 3-polytopes):

```
sage: o = lattice_polytope.cross_polytope(3)
sage: o.is_reflexive()
True
```

But not all polytopes are reflexive:

```
sage: p = LatticePolytope([(1,0,0), (0,1,17), (-1,0,0), (0,-1,0)])
sage: p.is_reflexive()
False
```

Only full-dimensional polytopes can be reflexive (otherwise the polar set is not a polytope at all, since it is unbounded):

```
sage: p = LatticePolytope([(1,0,0), (0,1,0), (-1,0,0), (0,-1,0)])
sage: p.is_reflexive()
False
```

## lattice()

Return the ambient lattice of self.

**OUTPUT**:

· a lattice.

**EXAMPLES:** 

```
sage: lattice_polytope.cross_polytope(3).lattice()
3-d lattice M
```

## lattice\_dim()

Return the dimension of the ambient lattice of self.

An alias is ambient\_dim().

OUTPUT:

• integer.

**EXAMPLES:** 

```
sage: p = LatticePolytope([(1,0)])
sage: p.lattice_dim()
2
sage: p.dim()
0
```

## linearly\_independent\_vertices()

Return a maximal set of linearly independent vertices.

**OUTPUT**:

A tuple of vertex indices.

**EXAMPLES:** 

```
sage: L = LatticePolytope([[0, 0], [-1, 1], [-1, -1]])
sage: L.linearly_independent_vertices()
(1, 2)
sage: L = LatticePolytope([[0, 0, 0]])
sage: L.linearly_independent_vertices()
()
sage: L = LatticePolytope([[0, 1, 0]])
sage: L.linearly_independent_vertices()
(0,)
```

**nef\_partitions**(keep\_symmetric=False, keep\_products=True, keep\_projections=True,

hodge\_numbers=False)

Return 2-part nef-partitions of self.

INPUT:

• keep\_symmetric - (default: False) if True, "-s" option will be passed to nef.x in order to keep symmetric partitions, i.e. partitions related by lattice automorphisms preserving self;

- keep\_products (default: True) if True, "-D" option will be passed to nef.x in order to keep product partitions, with corresponding complete intersections being direct products;
- keep\_projections (default: True) if True, "-P" option will be passed to nef.x in order to keep projection partitions, i.e. partitions with one of the parts consisting of a single vertex;
- hodge\_numbers (default: False) if False, "-p" option will be passed to nef.x in order to skip Hodge numbers computation, which takes a lot of time.

#### **OUTPUT:**

• a sequence of nef-partitions.

Type NefPartition? for definitions and notation.

#### **EXAMPLES:**

Nef-partitions of the 4-dimensional cross-polytope:

```
sage: p = lattice_polytope.cross_polytope(4)
sage: p.nef_partitions()  # optional -
    palp
[
Nef-partition {0, 1, 4, 5} □ {2, 3, 6, 7} (direct product),
Nef-partition {0, 1, 2, 4} □ {3, 5, 6, 7},
Nef-partition {0, 1, 2, 4, 5} □ {3, 6, 7},
Nef-partition {0, 1, 2, 4, 5, 6} □ {3, 7} (direct product),
Nef-partition {0, 1, 2, 3, □ {4, 5, 6, 7},
Nef-partition {0, 1, 2, 3, 4} □ {5, 6, 7},
Nef-partition {0, 1, 2, 3, 4, 5} □ {6, 7},
Nef-partition {0, 1, 2, 3, 4, 5, 6} □ {7} (projection)
]
```

Now we omit projections:

```
sage: p.nef_partitions(keep_projections=False) # optional -
    palp
[
Nef-partition {0, 1, 4, 5} □ {2, 3, 6, 7} (direct product),
Nef-partition {0, 1, 2, 4} □ {3, 5, 6, 7},
Nef-partition {0, 1, 2, 4, 5} □ {3, 6, 7},
Nef-partition {0, 1, 2, 4, 5, 6} □ {3, 7} (direct product),
Nef-partition {0, 1, 2, 3} □ {4, 5, 6, 7},
Nef-partition {0, 1, 2, 3, 4} □ {5, 6, 7},
Nef-partition {0, 1, 2, 3, 4, 5} □ {6, 7}
]
```

Currently Hodge numbers cannot be computed for a given nef-partition:

```
sage: p.nef_partitions()[1].hodge_numbers() # optional -
    palp
Traceback (most recent call last):
...
NotImplementedError: use nef_partitions(hodge_numbers=True)!
```

But they can be obtained from nef.x for all nef-partitions at once. Partitions will be exactly the same:

```
sage: p.nef_partitions(hodge_numbers=True) # long time (2s on sage.math, 2011)

# optional - palp
[
Nef-partition {0, 1, 4, 5} □ {2, 3, 6, 7} (direct product),
Nef-partition {0, 1, 2, 4} □ {3, 5, 6, 7},
Nef-partition {0, 1, 2, 4, 5} □ {3, 6, 7},
Nef-partition {0, 1, 2, 4, 5, 6} □ {3, 7} (direct product),
Nef-partition {0, 1, 2, 3} □ {4, 5, 6, 7},
Nef-partition {0, 1, 2, 3, 4} □ {5, 6, 7},
Nef-partition {0, 1, 2, 3, 4, 5} □ {6, 7},
Nef-partition {0, 1, 2, 3, 4, 5, 6} □ {7} (projection)
]
```

Now it is possible to get Hodge numbers:

Since nef-partitions are cached, their Hodge numbers are accessible after the first request, even if you do not specify hodge\_numbers=True anymore:

```
sage: p.nef_partitions()[1].hodge_numbers() # optional -
    palp
(20,)
```

We illustrate removal of symmetric partitions on a diamond:

```
sage: p = lattice_polytope.cross_polytope(2)
sage: p.nef_partitions()
                                                                                # optional -
→ palp
Nef-partition \{0, 2\} \sqcup \{1, 3\} (direct product),
Nef-partition \{0, 1\} \sqcup \{2, 3\},\
Nef-partition \{0, 1, 2\} \sqcup \{3\} (projection)
sage: p.nef_partitions(keep_symmetric=True)
                                                                                # optional -
→ palp
Nef-partition \{0, 1, 3\} \sqcup \{2\} (projection),
Nef-partition \{0, 2, 3\} \sqcup \{1\} (projection),
Nef-partition \{0, 3\} \sqcup \{1, 2\},\
Nef-partition \{1, 2, 3\} \sqcup \{0\} (projection),
Nef-partition \{1, 3\} \sqcup \{0, 2\} (direct product),
Nef-partition \{2, 3\} \sqcup \{0, 1\},\
Nef-partition \{0, 1, 2\} \sqcup \{3\} (projection)
```

Nef-partitions can be computed only for reflexive polytopes:

```
Traceback (most recent call last):
...
ValueError: The given polytope is not reflexive!
Polytope: 3-d lattice polytope in 3-d lattice M
```

## nef\_x(keys)

Run nef.x with given keys on vertices of this polytope.

#### INPUT:

• keys - a string of options passed to nef.x. The key "-f" is added automatically.

OUTPUT: the output of nef.x as a string.

EXAMPLES: This call is used internally for computing nef-partitions:

```
sage: o = lattice_polytope.cross_polytope(3)
sage: s = o.nef_x("-N -V -p")
                                                                    # optional -
→ palp
                             # output contains random time
sage: s
                                                                    # optional -
→ palp
M:27 8 N:7 6 codim=2 #part=5
3 6 Vertices of P:
   1
        0
             0
                -1
             0
                  0
   0
        1
                      -1
                            0
        0
             1
                  0
                       0
   0
P:0 V:2 4 5
                  0sec 0cpu
P:2 V:3 4 5
                  0sec 0cpu
P:3 V:4 5
                0sec 0cpu
np=3 d:1 p:1
               0sec
                         0cpu
```

## nfacets()

Return the number of facets of this polytope.

EXAMPLES: The number of facets of the 3-dimensional octahedron:

```
sage: o = lattice_polytope.cross_polytope(3)
sage: o.nfacets()
8
```

The number of facets of an interval is 2:

```
sage: LatticePolytope(([1],[2])).nfacets()
2
```

Now consider a 2-dimensional diamond in a 3-dimensional space:

```
sage: p = LatticePolytope([(1,0,0), (0,1,0), (-1,0,0), (0,-1,0)])
sage: p.nfacets()
4
```

## normal\_form(algorithm='palp', permutation=False)

Return the normal form of vertices of self.

Two full-dimensional lattice polytopes are in the same GL(\ZZ)-orbit if and only if their normal forms are the same. Normal form is not defined and thus cannot be used for polytopes whose dimension is smaller than the dimension of the ambient space.

The original algorithm was presented in [KS1998] and implemented in PALP. A modified version of the PALP algorithm is discussed in [GK2013] and available here as "palp\_modified".

#### INPUT:

- algorithm (default: "palp") The algorithm which is used to compute the normal form. Options are:
  - "palp" Run external PALP code, usually the fastest option.
  - "palp\_native" The original PALP algorithm implemented in sage. Currently considerably slower than PALP.
  - "palp\_modified" A modified version of the PALP algorithm which determines the maximal vertex-facet pairing matrix first and then computes its automorphisms, while the PALP algorithm does both things concurrently.
- permutation (default: False) If True the permutation applied to vertices to obtain the normal form is returned as well. Note that the different algorithms may return different results that nevertheless lead to the same normal form.

## **OUTPUT**:

• a point collection in the lattice() of self or a tuple of it and a permutation.

#### **EXAMPLES:**

We compute the normal form of the "diamond":

The diamond is the 3rd polytope in the internal database:

```
sage: d.index() # optional -
    palp
3
sage: d # optional -
    palp
2-d reflexive polytope #3 in 2-d lattice M
```

You can get it in its normal form (in the default lattice) as

```
sage: lattice_polytope.ReflexivePolytope(2, 3).vertices()
M( 1,  0),
M( 0,  1),
M( 0, -1),
(continues on next page)
```

```
M(-1, 0)
in 2-d lattice M
```

It is not possible to compute normal forms for polytopes which do not span the space:

```
sage: p = LatticePolytope([(1,0,0), (0,1,0), (-1,0,0), (0,-1,0)])
sage: p.normal_form()
Traceback (most recent call last):
...
ValueError: normal form is not defined for
2-d lattice polytope in 3-d lattice M
```

We can perform the same examples using other algorithms:

```
sage: o = lattice_polytope.cross_polytope(2)
sage: o.normal_form(algorithm="palp_native")
M( 1,  0),
M( 0,  1),
M( 0,  -1),
M(-1,  0)
in 2-d lattice M

sage: o = lattice_polytope.cross_polytope(2)
sage: o.normal_form(algorithm="palp_modified")
M( 1,  0),
M( 0,  1),
M( 0,  -1),
M( 0,  -1),
M(-1,  0)
in 2-d lattice M
```

## npoints()

Return the number of lattice points of this polytope.

EXAMPLES: The number of lattice points of the 3-dimensional octahedron and its polar cube:

#### nvertices()

Return the number of vertices of this polytope.

EXAMPLES: The number of vertices of the 3-dimensional octahedron and its polar cube:

```
sage: o = lattice_polytope.cross_polytope(3)
sage: o.nvertices()
6
sage: cube = o.polar()
```

```
sage: cube.nvertices()
8
```

#### origin()

Return the index of the origin in the list of points of self.

## **OUTPUT**:

• integer if the origin belongs to this polytope, None otherwise.

#### **EXAMPLES:**

Now we make sure that the origin of non-full-dimensional polytopes can be identified correctly (trac ticket #10661):

```
sage: LatticePolytope([(1,0,0), (-1,0,0)]).origin()
2
```

# parent()

Return the set of all lattice polytopes.

## **EXAMPLES:**

```
sage: o = lattice_polytope.cross_polytope(3)
sage: o.parent()
Set of all Lattice Polytopes
```

Return a 3d-plot of this polytope.

Polytopes with ambient dimension 1 and 2 will be plotted along x-axis or in xy-plane respectively. Polytopes of dimension 3 and less with ambient dimension 4 and greater will be plotted in some basis of the spanned space.

By default, everything is shown with more or less pretty combination of size and color parameters.

INPUT: Most of the parameters are self-explanatory:

- show\_facets (default:True)
- facet\_opacity (default:0.5)
- facet\_color (default:(0,1,0))
- facet\_colors (default:None) if specified, must be a list of colors for each facet separately, used instead of facet\_color
- show\_edges (default:True) whether to draw edges as lines
- edge\_thickness (default:3)
- edge\_color (default:(0.5,0.5,0.5))
- show\_vertices (default:True) whether to draw vertices as balls
- vertex\_size (default:10)
- vertex\_color (default:(1,0,0))
- show\_points (default:True) whether to draw other points as balls
- point\_size (default:10)
- point\_color (default:(0,0,1))
- show\_vindices (default:same as show\_vertices) whether to show indices of vertices
- vindex\_color (default:(0,0,0)) color for vertex labels
- vlabels (default:None) if specified, must be a list of labels for each vertex, default labels are vertex indices
- show\_pindices (default:same as show\_points) whether to show indices of other points
- pindex\_color (default:(0,0,0)) color for point labels
- index\_shift (default:1.1)) if 1, labels are placed exactly at the corresponding points. Otherwise the label position is computed as a multiple of the point position vector.

EXAMPLES: The default plot of a cube:

Plot without facets and points, shown without the frame:

```
sage: c.plot3d(show_facets=false, show_points=false).show(frame=False)

→# optional - palp sage.plot
```

Plot with facets of different colors:

It is also possible to plot lower dimensional polytops in 3D (let's also change labels of vertices):

#### point(i)

Return the i-th point of this polytope, i.e. the i-th column of the matrix returned by points().

EXAMPLES: First few points are actually vertices:

The only other point in the octahedron is the origin:

```
sage: o.point(6)
                                                                 # optional -
→ palp
M(0, 0, 0)
                                                                 # optional -
sage: o.points()
→ palp
M(1, 0,
          0),
M(0, 1,
          0),
M(0,0,
          1),
M(-1, 0, 0),
M(0, -1, 0),
M(0, 0, -1),
M(0, 0, 0)
in 3-d lattice M
```

# points(\*args, \*\*kwds)

Return all lattice points of self.

#### INPUT:

• any arguments given will be passed on to the returned object.

## OUTPUT:

• a point collection.

## **EXAMPLES:**

Lattice points of the octahedron and its polar cube:

```
M(0, 0, -1),
M(0, 0, 0)
in 3-d lattice M
sage: cube = o.polar()
                                                                  # optional -
sage: cube.points()
→ palp
N(1, -1, -1),
N(1, 1, -1),
N(1, 1, 1),
N(1, -1,
          1),
N(-1, -1, 1),
N(-1, -1, -1),
N(-1, 1, -1),
N(-1, 1,
         1),
N(-1, -1,
          0),
N(-1, 0, -1),
N(-1,
      0,
          0),
N(-1, 0,
          1),
N(-1, 1,
          0),
N(0, -1, -1),
N(0, -1,
          0),
N(0, -1,
          1),
N( 0,
      0, -1),
N( 0,
      0,
          0),
N( 0,
      0,
          1),
N( 0,
      1, -1),
N( 0.
      1, 0),
N(0, 1,
          1),
N(1, -1,
          0),
     0, -1),
N( 1,
N( 1,
      0, 0),
N(1, 0, 1),
N(1, 1, 0)
in 3-d lattice N
```

Lattice points of a 2-dimensional diamond in a 3-dimensional space:

```
sage: p = LatticePolytope([(1,0,0), (0,1,0), (-1,0,0), (0,-1,0)])
sage: p.points() # optional -
    palp
M( 1,  0,  0),
M( 0,  1,  0),
M(-1,  0,  0),
M( 0,  -1,  0),
M( 0,  0,  0)
in 3-d lattice M
```

Only two of the above points:

```
sage: p.points(1, 3) # optional - palp M(0, 1, 0), M(0, -1, 0) in 3-d lattice M
```

We check that points of a zero-dimensional polytope can be computed:

```
sage: p = LatticePolytope([[1]])
sage: p.points()
M(1)
in 1-d lattice M
```

#### polar()

Return the polar polytope, if this polytope is reflexive.

EXAMPLES: The polar polytope to the 3-dimensional octahedron:

```
sage: o = lattice_polytope.cross_polytope(3)
sage: cube = o.polar()
sage: cube
3-d reflexive polytope in 3-d lattice N
```

The polar polytope "remembers" the original one:

```
sage: cube.polar()
3-d reflexive polytope in 3-d lattice M
sage: cube.polar().polar() is cube
True
```

Only reflexive polytopes have polars:

## poly\_x(keys, reduce\_dimension=False)

Run poly.x with given keys on vertices of this polytope.

## INPUT:

- keys a string of options passed to poly.x. The key "f" is added automatically.
- reduce\_dimension (default: False) if True and this polytope is not full-dimensional, poly.x will be called for the vertices of this polytope in some basis of the spanned affine space.

OUTPUT: the output of poly.x as a string.

EXAMPLES: This call is used for determining if a polytope is reflexive or not:

```
sage: o = lattice_polytope.cross_polytope(3)
sage: print(o.poly_x("e"))
                                                                 # optional -
→ palp
8 3 Vertices of P-dual <-> Equations of P
 -1 -1
          1
  1 -1
          1
     1
         1
 -1
    1
  1
         1
 -1 -1 -1
  1 - 1 - 1
```

```
-1 1 -1
1 1 -1
```

Since PALP has limits on different parameters determined during compilation, the following code is likely to fail, unless you change default settings of PALP:

You cannot call poly.x for polytopes that don't span the space (if you could, it would crush anyway):

But if you know what you are doing, you can call it for the polytope in some basis of the spanned space:

#### polyhedron()

Return the Polyhedron object determined by this polytope's vertices.

**EXAMPLES:** 

```
sage: o = lattice_polytope.cross_polytope(2)
sage: o.polyhedron()
A 2-dimensional polyhedron in ZZ^2 defined as the convex hull of 4 vertices
```

#### show3d()

Show a 3d picture of the polytope with default settings and without axes or frame.

See self.plot3d? for more details.

**EXAMPLES:** 

```
sage: o = lattice_polytope.cross_polytope(3)
sage: o.show3d() # optional -
    palp sage.plot (continues on next page)
```

#### skeleton()

Return the graph of the one-skeleton of this polytope.

**EXAMPLES:** 

## $skeleton_points(k=1)$

Return the increasing list of indices of lattice points in k-skeleton of the polytope (k is 1 by default).

EXAMPLES: We compute all skeleton points for the cube:

The default was 1-skeleton:

```
sage: c.skeleton_points(k=1) # optional -
    palp
[0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 11, 12, 13, 15, 19, 21, 22, 23, 25, 26]
```

0-skeleton just lists all vertices:

```
sage: c.skeleton_points(k=0) # optional - \rightarrow palp [0, 1, 2, 3, 4, 5, 6, 7]
```

2-skeleton lists all points except for the origin (point #17):

3-skeleton includes all points:

It is OK to compute higher dimensional skeletons - you will get the list of all points:

#### skeleton\_show(normal=None)

Show the graph of one-skeleton of this polytope. Works only for polytopes in a 3-dimensional space.

#### INPUT:

• normal - a 3-dimensional vector (can be given as a list), which should be perpendicular to the screen. If not given, will be selected randomly (new each time and it may be far from "nice").

EXAMPLES: Show a pretty picture of the octahedron:

```
sage: o = lattice_polytope.cross_polytope(3)
sage: o.skeleton_show([1,2,4]) # optional -
    palp sage.plot
```

Does not work for a diamond at the moment:

```
sage: d = lattice_polytope.cross_polytope(2)
sage: d.skeleton_show()
Traceback (most recent call last):
...
NotImplementedError: skeleton view is implemented only in 3-d space
```

#### traverse\_boundary()

Return a list of indices of vertices of a 2-dimensional polytope in their boundary order.

Needed for plot3d function of polytopes.

**EXAMPLES:** 

```
sage: p = lattice_polytope.cross_polytope(2).polar()
sage: p.traverse_boundary()
[3, 0, 1, 2]
```

#### vertex(i)

Return the i-th vertex of this polytope, i.e. the i-th column of the matrix returned by vertices().

EXAMPLES: Note that numeration starts with zero:

```
sage: o = lattice_polytope.cross_polytope(3)
sage: o.vertices()
M( 1,  0,  0),
M( 0,  1,  0),
M( 0,  0,  1),
M(-1,  0,  0),
M( 0,  -1,  0),
M( 0,  0,  -1)
in 3-d lattice M
sage: o.vertex(3)
M(-1,  0,  0)
```

## vertex\_facet\_pairing\_matrix()

Return the vertex facet pairing matrix PM.

Return a matrix whose the  $i, j^{th}$  entry is the height of the  $j^{th}$  vertex over the  $i^{th}$  facet. The ordering of the vertices and facets is as in vertices() and facets().

#### **EXAMPLES:**

```
sage: L = lattice_polytope.cross_polytope(3)
sage: L.vertex_facet_pairing_matrix()
[2 0 0 0 2 2]
[2 2 0 0 0 0 2]
[2 2 2 0 0 0]
[2 0 2 0 2 0]
[0 0 0 2 2 2 0]
[0 0 0 2 2 2 2]
[0 2 0 2 0 2 0]
```

## vertices(\*args, \*\*kwds)

Return vertices of self.

## INPUT:

• any arguments given will be passed on to the returned object.

#### **OUTPUT:**

• a point collection.

## **EXAMPLES:**

Vertices of the octahedron and its polar cube are in dual lattices:

```
sage: o = lattice_polytope.cross_polytope(3)
sage: o.vertices()
M(1, 0, 0),
M(0, 1, 0),
M(0, 0, 1),
M(-1, 0, 0),
M(0, -1, 0),
M(0, 0, -1)
in 3-d lattice M
sage: cube = o.polar()
sage: cube.vertices()
N(1, -1, -1),
N(1, 1, -1),
N(1, 1, 1),
N(1, -1, 1),
N(-1, -1, 1),
N(-1, -1, -1),
N(-1, 1, -1),
N(-1, 1, 1)
in 3-d lattice N
```

## class sage.geometry.lattice\_polytope.NefPartition(data, Delta\_polar, check=True)

Bases: sage.structure.sage\_object.SageObject,collections.abc.Hashable

Create a nef-partition.

INPUT:

- data a list of integers, the i-th element of this list must be the part of the i-th vertex of Delta\_polar in
  this nef-partition;
- Delta\_polar a lattice polytope;
- check by default the input will be checked for correctness, i.e. that data indeed specify a nef-partition. If you are sure that the input is correct, you can speed up construction via check=False option.

#### **OUTPUT:**

• a nef-partition of Delta\_polar.

Let M and N be dual lattices. Let  $\Delta \subset M_{\mathbf{R}}$  be a reflexive polytope with polar  $\Delta^{\circ} \subset N_{\mathbf{R}}$ . Let  $X_{\Delta}$  be the toric variety associated to the normal fan of  $\Delta$ . A **nef-partition** is a decomposition of the vertex set V of  $\Delta^{\circ}$  into a disjoint union  $V = V_0 \sqcup V_1 \sqcup \cdots \sqcup V_{k-1}$  such that divisors  $E_i = \sum_{v \in V_i} D_v$  are Cartier (here  $D_v$  are prime torus-invariant Weil divisors corresponding to vertices of  $\Delta^{\circ}$ ). Equivalently, let  $\nabla_i \subset N_{\mathbf{R}}$  be the convex hull of vertices from  $V_i$  and the origin. These polytopes form a nef-partition if their Minkowski sum  $\nabla \subset N_{\mathbf{R}}$  is a reflexive polytope.

The **dual nef-partition** is formed by polytopes  $\Delta_i \subset M_{\mathbf{R}}$  of  $E_i$ , which give a decomposition of the vertex set of  $\nabla^{\circ} \subset M_{\mathbf{R}}$  and their Minkowski sum is  $\Delta$ , i.e. the polar duality of reflexive polytopes switches convex hull and Minkowski sum for dual nef-partitions:

$$\Delta^{\circ} = \operatorname{Conv} (\nabla_{0}, \nabla_{1}, \dots, \nabla_{k-1}),$$

$$\nabla = \nabla_{0} + \nabla_{1} + \dots + \nabla_{k-1},$$

$$\Delta = \Delta_{0} + \Delta_{1} + \dots + \Delta_{k-1},$$

$$\nabla^{\circ} = \operatorname{Conv} (\Delta_{0}, \Delta_{1}, \dots, \Delta_{k-1}).$$

One can also interpret the duality of nef-partitions as the duality of the associated cones. Below  $\overline{M} = M \times \mathbf{Z}^k$  and  $\overline{N} = N \times \mathbf{Z}^k$  are dual lattices.

The Cayley polytope  $P \subset \overline{M}_{\mathbf{R}}$  of a nef-partition is given by  $P = \operatorname{Conv}(\Delta_0 \times e_0, \Delta_1 \times e_1, \dots, \Delta_{k-1} \times e_{k-1})$ , where  $\{e_i\}_{i=0}^{k-1}$  is the standard basis of  $\mathbf{Z}^k$ . The dual Cayley polytope  $P^* \subset \overline{N}_{\mathbf{R}}$  is the Cayley polytope of the dual nef-partition.

The Cayley cone  $C \subset \overline{M}_{\mathbf{R}}$  of a nef-partition is the cone spanned by its Cayley polytope. The dual Cayley cone  $C^{\vee} \subset \overline{M}_{\mathbf{R}}$  is the usual dual cone of C. It turns out, that  $C^{\vee}$  is spanned by  $P^*$ .

It is also possible to go back from the Cayley cone to the Cayley polytope, since C is a reflexive Gorenstein cone supported by P: primitive integral ray generators of C are contained in an affine hyperplane and coincide with vertices of P.

See Section 4.3.1 in [CK1999] and references therein for further details, or [BN2008] for a purely combinatorial approach.

## **EXAMPLES:**

It is very easy to create a nef-partition for the octahedron, since for this polytope any decomposition of vertices is a nef-partition. We create a 3-part nef-partition with the 0-th and 1-st vertices belonging to the 0-th part (recall that numeration in Sage starts with 0), the 2-nd and 5-th vertices belonging to the 1-st part, and 3-rd and 4-th vertices belonging to the 2-nd part:

```
sage: o = lattice_polytope.cross_polytope(3)
sage: np = NefPartition([0,0,1,2,2,1], o)
sage: np
Nef-partition {0, 1} \( \preceq \) {2, 5} \( \preceq \) {3, 4}
```

The octahedron plays the role of  $\Delta^{\circ}$  in the above description:

```
sage: np.Delta_polar() is o
True
```

The dual nef-partition (corresponding to the "mirror complete intersection") gives decomposition of the vertex set of  $\nabla^{\circ}$ :

```
sage: np.dual()
Nef-partition \{0, 1, 2\} \sqcup \{3, 4\} \sqcup \{5, 6, 7\}
sage: np.nabla_polar().vertices()
N(-1, -1,
          0).
N(-1, 0,
           0),
N(0, -1,
           0),
N(0, 0, -1),
N(0, 0,
          1).
N(1, 0, 0),
N(0, 1, 0),
N(1, 1,
           0)
in 3-d lattice N
```

Of course,  $\nabla^{\circ}$  is  $\Delta^{\circ}$  from the point of view of the dual nef-partition:

```
sage: np.dual().Delta_polar() is np.nabla_polar()
True
sage: np.Delta(1).vertices()
N(0, 0, -1),
N(0, 0, 1)
in 3-d lattice N
sage: np.dual().nabla(1).vertices()
N(0, 0, -1),
N(0, 0, 1)
in 3-d lattice N
```

Instead of constructing nef-partitions directly, you can request all 2-part nef-partitions of a given reflexive polytope (they will be computed using nef.x program from PALP):

## Delta(i=None)

Return the polytope  $\Delta$  or  $\Delta_i$  corresponding to self.

#### INPUT

• i – an integer. If not given,  $\Delta$  will be returned.

# OUTPUT:

• a lattice polytope.

See *nef-partition* class documentation for definitions and notation.

#### **EXAMPLES:**

```
sage: o = lattice_polytope.cross_polytope(3)
sage: np = NefPartition([0, 0, 1, 0, 1, 1], o); np
Nef-partition \{0, 1, 3\} \sqcup \{2, 4, 5\}
sage: np.Delta().polar() is o
True
sage: np.Delta().vertices()
N(1, -1, -1),
N(1, 1, -1),
N(1, 1, 1),
N(1, -1, 1),
N(-1, -1, 1),
N(-1, -1, -1),
N(-1, 1, -1),
N(-1, 1, 1)
in 3-d lattice N
sage: np.Delta(0).vertices()
N(-1, -1, 0),
N(-1, 0, 0),
N(1, 0, 0),
N(1, -1, 0)
in 3-d lattice N
```

## Delta\_polar()

Return the polytope  $\Delta^{\circ}$  corresponding to self.

## OUTPUT:

• a lattice polytope.

See nef-partition class documentation for definitions and notation.

#### **EXAMPLES:**

```
sage: o = lattice_polytope.cross_polytope(3)
sage: np = NefPartition([0, 0, 1, 0, 1, 1], o); np
Nef-partition {0, 1, 3} \( \preceq \) {2, 4, 5}
sage: np.Delta_polar() is o
True
```

#### Deltas()

Return the polytopes  $\Delta_i$  corresponding to self.

## **OUTPUT**:

• a tuple of lattice polytopes.

See nef-partition class documentation for definitions and notation.

## **EXAMPLES:**

```
sage: o = lattice_polytope.cross_polytope(3)
sage: np = NefPartition([0, 0, 1, 0, 1, 1], o); np
Nef-partition {0, 1, 3} \( \preceq \) {2, 4, 5}
sage: np.Delta().vertices()
```

```
N(1, -1, -1),
N(1, 1, -1),
N(1, 1, 1),
N(1, -1, 1),
N(-1, -1, 1),
N(-1, -1, -1),
N(-1, 1, -1),
N(-1, 1, 1)
in 3-d lattice N
sage: [Delta_i.vertices() for Delta_i in np.Deltas()]
[N(-1, -1, 0),
N(-1, 0, 0),
N(1, 0, 0),
N(1, -1, 0)
in 3-d lattice N,
N(0, 0, -1),
N(0, 1, 1),
N(0, 0, 1),
N(0, 1, -1)
in 3-d lattice N]
sage: np.nabla_polar().vertices()
N(-1, -1, 0),
N(1, -1, 0),
N(1, 0, 0),
N(-1, 0, 0),
N(0, 1, -1),
N(0, 1, 1),
N(0, 0, 1),
N(0, 0, -1)
in 3-d lattice N
```

#### dual()

Return the dual nef-partition.

## **OUTPUT**:

• a nef-partition.

See the class documentation for the definition.

#### ALGORITHM:

See Proposition 3.19 in [BN2008].

**Note:** Automatically constructed dual nef-partitions will be ordered, i.e. vertex partition of  $\nabla$  will look like  $\{0,1,2\} \sqcup \{3,4,5,6\} \sqcup \{7,8\}$ .

## **EXAMPLES:**

```
sage: o = lattice_polytope.cross_polytope(3)
sage: np = NefPartition([0, 0, 1, 0, 1, 1], o); np
Nef-partition {0, 1, 3} □ {2, 4, 5}
sage: np.dual()
Nef-partition {0, 1, 2, 3} □ {4, 5, 6, 7}
```

```
sage: np.dual().Delta() is np.nabla()
True
sage: np.dual().nabla(0) is np.Delta(0)
True
```

# hodge\_numbers()

Return Hodge numbers corresponding to self.

#### **OUTPUT**:

• a tuple of integers (produced by nef.x program from PALP).

#### **EXAMPLES:**

Currently, you need to request Hodge numbers when you compute nef-partitions:

## nabla(i=None)

Return the polytope  $\nabla$  or  $\nabla_i$  corresponding to self.

#### INPUT:

• i – an integer. If not given,  $\nabla$  will be returned.

## **OUTPUT**:

• a lattice polytope.

See *nef-partition* class documentation for definitions and notation.

## **EXAMPLES:**

```
sage: o = lattice_polytope.cross_polytope(3)
sage: np = NefPartition([0, 0, 1, 0, 1, 1], o); np
Nef-partition {0, 1, 3} \( \preceq \) {2, 4, 5}
sage: np.Delta_polar().vertices()
M( 1, 0, 0),
M( 0, 1, 0),
M( 0, 0, 1),
M(-1, 0, 0),
M( 0, -1, 0),
M( 0, 0, -1)
in 3-d lattice M
sage: np.nabla(0).vertices()
```

```
M(-1, 0, 0),
M( 1, 0, 0),
M( 0, 1, 0)
in 3-d lattice M

sage: np.nabla().vertices()
M(-1, 0, 1),
M(-1, 0, -1),
M( 1, 0, -1),
M( 1, 0, -1),
M( 0, 1, 1),
M( 0, 1, -1),
M( 0, 1, -1),
M( 1, -1, 0),
M(-1, -1, 0)
in 3-d lattice M
```

#### nabla\_polar()

Return the polytope  $\nabla^{\circ}$  corresponding to self.

## **OUTPUT**:

• a lattice polytope.

See *nef-partition* class documentation for definitions and notation.

#### **EXAMPLES:**

```
sage: o = lattice_polytope.cross_polytope(3)
sage: np = NefPartition([0, 0, 1, 0, 1, 1], o); np
Nef-partition \{0, 1, 3\} \sqcup \{2, 4, 5\}
sage: np.nabla_polar().vertices()
N(-1, -1, 0),
N(1, -1,
          0),
N(1, 0, 0),
N(-1, 0, 0),
N(0, 1, -1),
N(0, 1, 1),
N(0, 0, 1),
N(0, 0, -1)
in 3-d lattice N
sage: np.nabla_polar() is np.dual().Delta_polar()
True
```

#### nablas()

Return the polytopes  $\nabla_i$  corresponding to self.

## **OUTPUT**:

• a tuple of lattice polytopes.

See *nef-partition* class documentation for definitions and notation.

## **EXAMPLES:**

```
sage: o = lattice_polytope.cross_polytope(3)
sage: np = NefPartition([0, 0, 1, 0, 1, 1], o); np
Nef-partition {0, 1, 3} \( \preceq \) {2, 4, 5}
```

```
sage: np.Delta_polar().vertices()
M(1, 0, 0),
M(0, 1, 0),
M(0, 0, 1),
M(-1, 0, 0),
M(0, -1, 0),
M(0, 0, -1)
in 3-d lattice M
sage: [nabla_i.vertices() for nabla_i in np.nablas()]
[M(-1, 0, 0),
M(1, 0, 0),
M(0, 1, 0)
in 3-d lattice M,
M(0, -1, 0),
M(0, 0, -1),
M(0, 0, 1)
in 3-d lattice M]
```

## nparts()

Return the number of parts in self.

#### **OUTPUT**:

• an integer.

## **EXAMPLES:**

```
sage: o = lattice_polytope.cross_polytope(3)
sage: np = NefPartition([0, 0, 1, 0, 1, 1], o); np
Nef-partition {0, 1, 3} \( \preceq \) {2, 4, 5}
sage: np.nparts()
2
```

## part(i, all\_points=False)

Return the i-th part of self.

## INPUT:

- i an integer
- all\_points (default: False) whether to list all lattice points or just vertices

#### **OUTPUT:**

• a tuple of integers, indices of vertices (or all lattice points) of  $\Delta^{\circ}$  belonging to  $V_i$ .

See *nef-partition* class documentation for definitions and notation.

## **EXAMPLES:**

```
(0, 1, 3)
sage: np.dual().part(0)
(0, 1, 2, 3)
sage: np.dual().part(0, all_points=True)

→ palp
(0, 1, 2, 3, 8)

# optional -
```

#### part\_of(i)

Return the index of the part containing the i-th vertex.

#### INPUT:

• i – an integer.

#### **OUTPUT**:

• an integer j such that the i-th vertex of  $\Delta^{\circ}$  belongs to  $V_i$ .

See *nef-partition* class documentation for definitions and notation.

#### **EXAMPLES:**

```
sage: o = lattice_polytope.cross_polytope(3)
sage: np = NefPartition([0, 0, 1, 0, 1, 1], o); np
Nef-partition {0, 1, 3} \( \preceq \) {2, 4, 5}
sage: np.part_of(3)
0
sage: np.part_of(2)
1
```

#### part\_of\_point(i)

Return the index of the part containing the i-th point.

#### INPUT:

• i - an integer.

#### OUTPUT

• an integer j such that the i-th point of  $\Delta^{\circ}$  belongs to  $\nabla_{i}$ .

**Note:** Since a nef-partition induces a partition on the set of boundary lattice points of  $\Delta^{\circ}$ , the value of j is well-defined for all i but the one that corresponds to the origin, in which case this method will raise a ValueError exception. (The origin always belongs to all  $\nabla_{j}$ .)

See *nef-partition* class documentation for definitions and notation.

## **EXAMPLES:**

202

We consider a relatively complicated reflexive polytope #2252 (easily accessible in Sage as ReflexivePolytope(3, 2252), we create it here explicitly to avoid loading the whole database):

```
sage: p.nvertices()
9
sage: p.npoints() # optional -
    palp
15
```

We see that the polytope has 6 more points in addition to vertices. One of them is the origin:

```
sage: p.origin()  # optional -
    palp
14
sage: np.part_of_point(14)  # optional -
    palp
Traceback (most recent call last):
...
ValueError: the origin belongs to all parts!
```

But the remaining 5 are partitioned by np:

parts(all\_points=False)

Return all parts of self.

## INPUT:

• all\_points – (default: False) whether to list all lattice points or just vertices

## **OUTPUT**:

• a tuple of tuples of integers. The *i*-th tuple contains indices of vertices (or all lattice points) of  $\Delta^{\circ}$  belonging to  $V_i$ 

See *nef-partition* class documentation for definitions and notation.

#### **EXAMPLES:**

```
sage: o = lattice_polytope.cross_polytope(3)
sage: np = NefPartition([0, 0, 1, 0, 1, 1], o); np
Nef-partition {0, 1, 3} □ {2, 4, 5}
sage: np.parts()
((0, 1, 3), (2, 4, 5))
sage: np.parts(all_points=True) # optional -
→ palp
((0, 1, 3), (2, 4, 5))
sage: np.dual().parts()
((0, 1, 2, 3), (4, 5, 6, 7))
```

```
sage: np.dual().parts(all_points=True) # optional - \rightarrow palp ((0, 1, 2, 3, 8), (4, 5, 6, 7, 10))
```

sage.geometry.lattice\_polytope.ReflexivePolytope(dim, n)

Return the n-th 2- or 3-dimensional reflexive polytope.

#### Note:

- 1. Numeration starts with zero:  $0 \le n \le 15$  for dim = 2 and  $0 \le n \le 4318$  for dim = 3.
- 2. During the first call, all reflexive polytopes of requested dimension are loaded and cached for future use, so the first call for 3-dimensional polytopes can take several seconds, but all consecutive calls are fast.
- 3. Equivalent to ReflexivePolytopes(dim)[n] but checks bounds first.

#### **EXAMPLES:**

The 3rd 2-dimensional polytope is "the diamond":

```
sage: ReflexivePolytope(2, 3)
2-d reflexive polytope #3 in 2-d lattice M
sage: lattice_polytope.ReflexivePolytope(2,3).vertices()
M( 1,  0),
M( 0,  1),
M( 0,  -1),
M(-1,  0)
in 2-d lattice M
```

There are 16 reflexive polygons and numeration starts with 0:

```
sage: ReflexivePolytope(2,16)
Traceback (most recent call last):
...
ValueError: there are only 16 reflexive polygons!
```

It is not possible to load a 4-dimensional polytope in this way:

```
sage: ReflexivePolytope(4,16)
Traceback (most recent call last):
...
NotImplementedError: only 2- and 3-dimensional reflexive polytopes are available!
```

```
sage.geometry.lattice_polytope.ReflexivePolytopes(dim)
```

Return the sequence of all 2- or 3-dimensional reflexive polytopes.

**Note:** During the first call the database is loaded and cached for future use, so repetitive calls will return the same object in memory.

Parameters dim (2 or 3) – dimension of required reflexive polytopes

Return type list of lattice polytopes

#### **EXAMPLES:**

There are 16 reflexive polygons:

```
sage: len(ReflexivePolytopes(2))
16
```

It is not possible to load 4-dimensional polytopes in this way:

```
sage: ReflexivePolytopes(4)
Traceback (most recent call last):
...
NotImplementedError: only 2- and 3-dimensional reflexive polytopes are available!
```

## class sage.geometry.lattice\_polytope.SetOfAllLatticePolytopesClass

Bases: sage.structure.parent.Set\_generic

```
sage.geometry.lattice_polytope.all_cached_data(polytopes)
```

Compute all cached data for all given polytopes and their polars.

This functions does it MUCH faster than member functions of LatticePolytope during the first run. So it is recommended to use this functions if you work with big sets of data. None of the polytopes in the given sequence should be constructed as the polar polytope to another one.

INPUT: a sequence of lattice polytopes.

EXAMPLES: This function has no output, it is just a fast way to work with long sequences of polytopes. Of course, you can use short sequences as well:

## sage.geometry.lattice\_polytope.all\_facet\_equations(polytopes)

Compute polar polytopes for all reflexive and equations of facets for all non-reflexive polytopes.

all\_facet\_equations and all\_polars are synonyms.

This functions does it MUCH faster than member functions of LatticePolytope during the first run. So it is recommended to use this functions if you work with big sets of data.

INPUT: a sequence of lattice polytopes.

EXAMPLES: This function has no output, it is just a fast way to work with long sequences of polytopes. Of course, you can use short sequences as well:

# sage.geometry.lattice\_polytope.all\_nef\_partitions(polytopes, keep\_symmetric=False) Compute nef-partitions for all given polytopes.

This functions does it MUCH faster than member functions of LatticePolytope during the first run. So it is recommended to use this functions if you work with big sets of data.

Note: member function is\_reflexive will be called separately for each polytope. It is strictly recommended to call all\_polars on the sequence of polytopes before using this function.

INPUT: a sequence of lattice polytopes.

EXAMPLES: This function has no output, it is just a fast way to work with long sequences of polytopes. Of course, you can use short sequences as well:

You cannot use this function for non-reflexive polytopes:

#### sage.geometry.lattice\_polytope.all\_points(polytopes)

Compute lattice points for all given polytopes.

This functions does it MUCH faster than member functions of LatticePolytope during the first run. So it is recommended to use this functions if you work with big sets of data.

INPUT: a sequence of lattice polytopes.

EXAMPLES: This function has no output, it is just a fast way to work with long sequences of polytopes. Of course, you can use short sequences as well:

```
sage.geometry.lattice_polytope.all_polars(polytopes)
```

Compute polar polytopes for all reflexive and equations of facets for all non-reflexive polytopes.

all\_facet\_equations and all\_polars are synonyms.

This functions does it MUCH faster than member functions of LatticePolytope during the first run. So it is recommended to use this functions if you work with big sets of data.

INPUT: a sequence of lattice polytopes.

EXAMPLES: This function has no output, it is just a fast way to work with long sequences of polytopes. Of course, you can use short sequences as well:

## sage.geometry.lattice\_polytope.convex\_hull(points)

Compute the convex hull of the given points.

Note: points might not span the space. Also, it fails for large numbers of vertices in dimensions 4 or greater

## INPUT:

• points - a list that can be converted into vectors of the same dimension over ZZ.

OUTPUT: list of vertices of the convex hull of the given points (as vectors).

EXAMPLES: Let's compute the convex hull of several points on a line in the plane:

```
sage: lattice_polytope.convex_hull([[1,2],[3,4],[5,6],[7,8]])
[(1, 2), (7, 8)]
```

## sage.geometry.lattice\_polytope.cross\_polytope(dim)

Return a cross-polytope of the given dimension.

#### INPUT:

• dim - an integer.

## **OUTPUT**:

• a lattice polytope.

#### **EXAMPLES:**

```
sage: o = lattice_polytope.cross_polytope(3)
sage: o
3-d reflexive polytope in 3-d lattice M
sage: o.vertices()
M( 1,  0,  0),
M( 0,  1,  0),
M( 0,  0,  1),
M(-1,  0,  0),
M(-1,  0,  0),
```

```
M(0, 0, -1)
in 3-d lattice M
```

sage.geometry.lattice\_polytope.is\_LatticePolytope(x)

Check if x is a lattice polytope.

## INPUT:

• x -anything.

#### **OUTPUT**:

• True if x is a *lattice polytope*, False otherwise.

#### **EXAMPLES:**

## sage.geometry.lattice\_polytope.is\_NefPartition(x)

Check if **x** is a nef-partition.

## INPUT:

• x -anything.

## **OUTPUT**:

• True if x is a *nef-partition* and False otherwise.

# **EXAMPLES:**

## sage.geometry.lattice\_polytope.minkowski\_sum(points1, points2)

Compute the Minkowski sum of two convex polytopes.

**Note:** Polytopes might not be of maximal dimension.

INPUT:

• points1, points2 - lists of objects that can be converted into vectors of the same dimension, treated as vertices of two polytopes.

OUTPUT: list of vertices of the Minkowski sum, given as vectors.

EXAMPLES: Let's compute the Minkowski sum of two line segments:

```
sage: lattice_polytope.minkowski_sum([[1,0],[-1,0]],[[0,1],[0,-1]])
[(1, 1), (1, -1), (-1, 1), (-1, -1)]
```

sage.geometry.lattice\_polytope.positive\_integer\_relations(points)

Return relations between given points.

INPUT:

• points - lattice points given as columns of a matrix

OUTPUT: matrix of relations between given points with non-negative integer coefficients

EXAMPLES: This is a 3-dimensional reflexive polytope:

We can compute linear relations between its points in the following way:

However, the above relations may contain negative and rational numbers. This function transforms them in such a way, that all coefficients are non-negative integers:

sage.geometry.lattice\_polytope.read\_all\_polytopes(file\_name)

Read all polytopes from the given file.

INPUT:

• file\_name – a string with the name of a file with VERTICES of polytopes.

#### **OUTPUT:**

• a sequence of polytopes.

#### **EXAMPLES:**

We use poly.x to compute two polar polytopes and read them:

```
sage: d = lattice_polytope.cross_polytope(2)
sage: o = lattice_polytope.cross_polytope(3)
sage: result_name = lattice_polytope._palp("poly.x -fe", [d, o])
                                                                        # optional -
sage: with open(result_name) as f:
                                                                        # optional -
→ palp
. . . . :
         print(f.read())
4 2 Vertices of P-dual <-> Equations of P
 - 1
   1
     1
  -1 -1
   1 -1
8 3 Vertices of P-dual <-> Equations of P
  -1 -1
   1 -1
           1
  -1
     1
          1
  1
      1
          1
  -1
     -1 -1
  1 -1 -1
 -1
     1 -1
     1 -1
  1
sage: lattice_polytope.read_all_polytopes(result_name)
                                                                        # optional -
→ palp
[2-d reflexive polytope #14 in 2-d lattice M,
3-d reflexive polytope in 3-d lattice M]
sage: os.remove(result name)
                                                                        # optional -
→ palp
```

## sage.geometry.lattice\_polytope.read\_palp\_matrix(data, permutation=False)

Read and return an integer matrix from a string or an opened file.

First input line must start with two integers m and n, the number of rows and columns of the matrix. The rest of the first line is ignored. The next m lines must contain n numbers each.

If m>n, returns the transposed matrix. If the string is empty or EOF is reached, returns the empty matrix, constructed by matrix().

## INPUT:

- data Either a string containing the filename or the file itself containing the output by PALP.
- permutation (default: False) If True, try to retrieve the permutation output by PALP. This parameter makes sense only when PALP computed the normal form of a lattice polytope.

#### **OUTPUT**:

A matrix or a tuple of a matrix and a permutation.

## **EXAMPLES:**

## sage.geometry.lattice\_polytope.set\_palp\_dimension(d)

Set the dimension for PALP calls to d.

## INPUT:

• d - an integer from the list [4,5,6,11] or None.

#### **OUTPUT**:

• none.

PALP has many hard-coded limits, which must be specified before compilation, one of them is dimension. Sage includes several versions with different dimension settings (which may also affect other limits and enable certain features of PALP). You can change the version which will be used by calling this function. Such a change is not done automatically for each polytope based on its dimension, since depending on what you are doing it may be necessary to use dimensions higher than that of the input polytope.

#### **EXAMPLES:**

Let's try to work with a 7-dimensional polytope:

However, we can work with this polytope by changing PALP dimension to 11:

Let's go back to default settings:

```
sage: lattice_polytope.set_palp_dimension(None)
```

sage.geometry.lattice\_polytope.skip\_palp\_matrix(data, n=1) Skip matrix data in a file.

## INPUT:

- data opened file with blocks of matrix data in the following format: A block consisting of m+1 lines has the number m as the first element of its first line.
- n (default: 1) integer, specifies how many blocks should be skipped

If EOF is reached during the process, raises ValueError exception.

EXAMPLES: We create a file with vertices of the square and the cube, but read only the second set:

```
sage: d = lattice_polytope.cross_polytope(2)
sage: o = lattice_polytope.cross_polytope(3)
sage: result_name = lattice_polytope._palp("poly.x -fe", [d, o])
                                                                          # optional -
→ palp
sage: with open(result_name) as f:
                                                                          # optional -
→ palp
          print(f.read())
4 2 Vertices of P-dual <-> Equations of P
 -1
     1
  1
     1
  -1 -1
   1 -1
8 3 Vertices of P-dual <-> Equations of P
 -1 -1
           1
   1 -1
           1
           1
  _ 1
     1
      1
          1
  -1 -1 -1
  1
     -1
         -1
 -1
     1 -1
  1
     1 -1
sage: f = open(result_name)
                                                                          # optional -
→ palp
sage: lattice_polytope.skip_palp_matrix(f)
                                                                          # optional -
→ palp
                                                                          # optional -
sage: lattice_polytope.read_palp_matrix(f)
→ palp
[-1 \quad 1 \quad -1 \quad 1 \quad -1 \quad 1 \quad -1 \quad 1]
[-1 -1 1 1 -1 -1 1 1]
[1 1 1 1 1 -1 -1 -1]
sage: f.close()
                                                                          # optional -
→ palp
sage: os.remove(result_name)
                                                                          # optional -
→ palp
```

sage.geometry.lattice\_polytope.write\_palp\_matrix(m, ofile=None, comment=", format=None)
Write m into ofile in PALP format.

## INPUT:

- m a matrix over integers or a point collection.
- ofile a file opened for writing (default: stdout)
- comment a string (default: empty) see output description
- format a format string used to print matrix entries.

## **OUTPUT**:

- nothing is returned, output written to ofile has the format
  - First line: number\_of\_rows number\_of\_columns comment
  - Next number\_of\_rows lines: rows of the matrix.

### **EXAMPLES:**

```
sage: o = lattice_polytope.cross_polytope(3)
sage: lattice_polytope.write_palp_matrix(o.vertices(), comment="3D Octahedron")
3 6 3D Octahedron
1 0 0 -1 0 0
0 1 0 0 -1 0
0 0 1 0 0 -1
sage: lattice_polytope.write_palp_matrix(o.vertices(), format="%4d")
3 6
1 0 0 -1 0 0
0 1 0 0 -1 0 0
0 1 0 0 -1 0 0
```

# 2.2.2 Lattice Euclidean Group Elements

The classes here are used to return particular isomorphisms of *PPL lattice polytopes*.

class sage.geometry.polyhedron.lattice\_euclidean\_group\_element.LatticeEuclideanGroupElement(A,

```
Bases: sage.structure.sage_object.SageObject
```

An element of the lattice Euclidean group.

Note that this is just intended as a container for results from LatticePolytope\_PPL. There is no group-theoretic functionality to speak of.

```
sage: from sage.geometry.polyhedron.ppl_lattice_polytope import LatticePolytope_PPL,
→ C_Polyhedron
sage: from sage.geometry.polyhedron.lattice_euclidean_group_element import_
→LatticeEuclideanGroupElement
sage: M = LatticeEuclideanGroupElement([[1,2],[2,3],[-1,2]], [1,2,3])
sage: M
The map A*x+b with A=
[12]
[2 3]
Γ-1 27
b =
(1, 2, 3)
sage: M._A
Γ 1 2<sub>1</sub>
Γ 2 31
[-1 2]
sage: M._b
(1, 2, 3)
sage: M(vector([0,0]))
(1, 2, 3)
sage: M(LatticePolytope\_PPL((0,0),(1,0),(0,1)))
A 2-dimensional lattice polytope in ZZ^3 with 3 vertices
sage: _.vertices()
((1, 2, 3), (2, 4, 2), (3, 5, 5))
```

### codomain\_dim()

Return the dimension of the codomain lattice

**EXAMPLES:** 

Note that this is not the same as the rank. In fact, the codomain dimension depends only on the matrix shape, and not on the rank of the linear mapping:

```
sage: zero_map = LatticeEuclideanGroupElement([[0,0],[0,0],[0,0]], [0,0,0])
sage: zero_map.codomain_dim()
3
```

### domain dim()

Return the dimension of the domain lattice

**EXAMPLES:** 

exception sage.geometry.polyhedron.lattice\_euclidean\_group\_element.LatticePolytopeError
Bases: Exception

Base class for errors from lattice polytopes

#### exception

 $sage.geometry.polyhedron.lattice\_euclidean\_group\_element. \textbf{LatticePolytopeNoEmbeddingError}\\ Bases: sage.geometry.polyhedron.lattice\_euclidean\_group\_element.LatticePolytopeError$ 

Raised when no embedding of the desired kind can be found.

exception sage.geometry.polyhedron.lattice\_euclidean\_group\_element.
LatticePolytopesNotIsomorphicError

Bases: sage.geometry.polyhedron.lattice\_euclidean\_group\_element.LatticePolytopeError

Raised when two lattice polytopes are not isomorphic.

# 2.2.3 Access the PALP database(s) of reflexive lattice polytopes

### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.palp_database import PALPreader
sage: for lp in PALPreader(2):
          cone = Cone([(1,r[0],r[1]) \text{ for } r \text{ in } lp.vertices()])
          fan = Fan([cone])
          X = ToricVariety(fan)
          ideal = X.affine_algebraic_patch(cone).defining_ideal()
          print("{} {}".format(lp.n_vertices(), ideal.hilbert_series()))
3(t^2 + 7^*t + 1)/(-t^3 + 3^*t^2 - 3^*t + 1)
3(t^2 + t + 1)/(-t^3 + 3*t^2 - 3*t + 1)
3 (t^2 + 6*t + 1)/(-t^3 + 3*t^2 - 3*t + 1)
3 (t^2 + 2^t + 1)/(-t^3 + 3^t^2 - 3^t + 1)
3(t^2 + 4^*t + 1)/(-t^3 + 3^*t^2 - 3^*t + 1)
4 (t^2 + 5*t + 1)/(-t^3 + 3*t^2 - 3*t + 1)
4 (t^2 + 3*t + 1)/(-t^3 + 3*t^2 - 3*t + 1)
4 (t^2 + 2*t + 1)/(-t^3 + 3*t^2 - 3*t + 1)
4 (t^2 + 6*t + 1)/(-t^3 + 3*t^2 - 3*t + 1)
4 (t^2 + 6*t + 1)/(-t^3 + 3*t^2 - 3*t + 1)
4 (t^2 + 2*t + 1)/(-t^3 + 3*t^2 - 3*t + 1)
4 (t^2 + 4^*t + 1)/(-t^3 + 3^*t^2 - 3^*t + 1)
5 (t^2 + 3*t + 1)/(-t^3 + 3*t^2 - 3*t + 1)
5 (t^2 + 5*t + 1)/(-t^3 + 3*t^2 - 3*t + 1)
5 (t^2 + 4*t + 1)/(-t^3 + 3*t^2 - 3*t + 1)
6 (t^2 + 4^*t + 1)/(-t^3 + 3^*t^2 - 3^*t + 1)
```

```
Bases: sage.structure.sage_object.SageObject
```

Read PALP database of polytopes.

### INPUT:

- dim integer. The dimension of the polyhedra
- data\_basename string or None (default). The directory and database base filename (PALP usually uses 'zzdb') name containing the PALP database to read. Defaults to the built-in database location.
- output string. How to return the reflexive polyhedron data. Allowed values = 'list', 'Polyhedron' (default), 'pointcollection', and 'PPL'. Case is ignored.

### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.palp_database import PALPreader
sage: polygons = PALPreader(2)
sage: [ (p.n_Vrepresentation(), len(p.integral_points())) for p in polygons ]
[(3, 4), (3, 10), (3, 5), (3, 9), (3, 7), (4, 6), (4, 8), (4, 9),
        (4, 5), (4, 5), (4, 9), (4, 7), (5, 8), (5, 6), (5, 7), (6, 7)]

sage: next(iter(PALPreader(2, output='list')))
[[1, 0], [0, 1], [-1, -1]]
```

```
sage: type(_)
<... 'list'>
sage: next(iter(PALPreader(2, output='Polyhedron')))
A 2-dimensional polyhedron in ZZ^2 defined as the convex hull of 3 vertices
sage: type(_)
class 'sage.geometry.polyhedron.parent.Polyhedra_ZZ_ppl_with_category.element_class<
'>
sage: next(iter(PALPreader(2, output='PPL')))
A 2-dimensional lattice polytope in ZZ^2 with 3 vertices
<class 'sage.geometry.polyhedron.ppl_lattice_polygon.LatticePolygon_PPL_class'>
sage: next(iter(PALPreader(2, output='PointCollection')))
[1, 0],
[0, 1],
[-1, -1]
in Ambient free module of rank 2 over the principal ideal domain Integer Ring
sage: type(_)
<class 'sage.geometry.point_collection.PointCollection'>
```

Bases: sage.geometry.polyhedron.palp\_database.PALPreader

Read the PALP database for Hodge numbers of 4d polytopes.

The database is very large and not installed by default. You can install it with the shell command sage -i polytopes\_db\_4d.

### INPUT:

• h11, h21 – Integers. The Hodge numbers of the reflexive polytopes to list.

Any additional keyword arguments are passed to PALPreader.

```
sage: from sage.geometry.polyhedron.palp_database import Reflexive4dHodge
sage: ref = Reflexive4dHodge(1,101)  # optional - polytopes_db_4d
sage: next(iter(ref)).Vrepresentation()  # optional - polytopes_db_4d
(A vertex at (-1, -1, -1, -1), A vertex at (0, 0, 0, 1),
A vertex at (0, 0, 1, 0), A vertex at (0, 1, 0, 0), A vertex at (1, 0, 0, 0))
```

# 2.2.4 Fast Lattice Polygons using PPL

See ppl\_lattice\_polytope for the implementation of arbitrary-dimensional lattice polytopes. This module is about the specialization to 2 dimensions. To be more precise, the <code>LatticePolygon\_PPL\_class</code> is used if the ambient space is of dimension 2 or less. These all allow you to cyclically order (see <code>LatticePolygon\_PPL\_class.ordered\_vertices())</code> the vertices, which is in general not possible in higher dimensions.

### class sage.geometry.polyhedron.ppl\_lattice\_polygon.LatticePolygon\_PPL\_class

```
Bases: sage.geometry.polyhedron.ppl_lattice_polytope.LatticePolytope_PPL_class
```

A lattice polygon

This includes 2-dimensional polytopes as well as degenerate (0 and 1-dimensional) lattice polygons. Any polytope in 2d is a polygon.

### find\_isomorphism(polytope)

Return a lattice isomorphism with polytope.

### INPUT:

• polytope – a polytope, potentially higher-dimensional.

#### **OUTPUT**:

A LatticeEuclideanGroupElement. It is not necessarily invertible if the affine dimension of self or polytope is not two. A LatticePolytopesNotIsomorphicError is raised if no such isomorphism exists.

#### **EXAMPLES:**

The following polygons are isomorphic over Q, but not as lattice polytopes:

```
sage: L1 = LatticePolytope_PPL((1,0),(0,1),(-1,-1))
sage: L2 = LatticePolytope_PPL((0, 0), (0, 1), (1, 0))
sage: L1.find_isomorphism(L2)
Traceback (most recent call last):
...
LatticePolytopesNotIsomorphicError: different number of integral points
sage: L2.find_isomorphism(L1)
Traceback (most recent call last):
...
LatticePolytopesNotIsomorphicError: different number of integral points
```

### is\_isomorphic(polytope)

Test if self and polytope are isomorphic.

### INPUT:

• polytope – a lattice polytope.

**OUTPUT**:

Boolean.

**EXAMPLES:** 

### ordered\_vertices()

Return the vertices of a lattice polygon in cyclic order.

OUTPUT

A tuple of vertices ordered along the perimeter of the polygon. The first point is arbitrary.

**EXAMPLES:** 

### plot()

Plot the lattice polygon.

OUTPUT:

A graphics object.

**EXAMPLES:** 

# sub\_polytopes()

Return a list of all lattice sub-polygons up to isomorphism.

**OUTPUT**:

All non-empty sub-lattice polytopes up to isomorphism. This includes self as improper sub-polytope, but excludes the empty polytope. Isomorphic sub-polytopes that can be embedded in different places are only returned once.

### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.ppl_lattice_polytope import LatticePolytope_
→PPL
sage: P1xP1 = LatticePolytope_PPL((1,0), (0,1), (-1,0), (0,-1))
sage: P1xP1.sub_polytopes()
(A 2-dimensional lattice polytope in ZZ^2 with 4 vertices,
A 2-dimensional lattice polytope in ZZ^2 with 3 vertices,
A 2-dimensional lattice polytope in ZZ^2 with 3 vertices,
A 1-dimensional lattice polytope in ZZ^2 with 2 vertices,
A 1-dimensional lattice polytope in ZZ^2 with 2 vertices,
A 0-dimensional lattice polytope in ZZ^2 with 1 vertex)
```

sage.geometry.polyhedron.ppl\_lattice\_polygon.polar\_P1xP1\_polytope()

The polar of the  $P^1 \times P^1$  polytope

#### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.ppl_lattice_polygon import polar_P1xP1_polytope
sage: polar_P1xP1_polytope()
A 2-dimensional lattice polytope in ZZ^2 with 4 vertices
sage: _.vertices()
((0, 0), (0, 2), (2, 0), (2, 2))
```

sage.geometry.polyhedron.ppl\_lattice\_polygon.polar\_P2\_112\_polytope()

The polar of the  $P^2[1, 1, 2]$  polytope

### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.ppl_lattice_polygon import polar_P2_112_polytope
sage: polar_P2_112_polytope()
A 2-dimensional lattice polytope in ZZ^2 with 3 vertices
sage: _.vertices()
((0, 0), (0, 2), (4, 0))
```

sage.geometry.polyhedron.ppl\_lattice\_polygon.polar\_P2\_polytope()

The polar of the  $P^2$  polytope

### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.ppl_lattice_polygon import polar_P2_polytope
sage: polar_P2_polytope()
A 2-dimensional lattice polytope in ZZ^2 with 3 vertices
sage: _.vertices()
((0, 0), (0, 3), (3, 0))
```

sage.geometry.polyhedron.ppl\_lattice\_polygon.sub\_reflexive\_polygons()

Return all lattice sub-polygons of reflexive polygons.

### **OUTPUT:**

A tuple of all lattice sub-polygons. Each sub-polygon is returned as a pair sub-polygon, containing reflexive polygon.

sage.geometry.polyhedron.ppl\_lattice\_polygon.subpolygons\_of\_polar\_P1xP1()

The lattice sub-polygons of the polar  $P^1 \times P^1$  polytope

**OUTPUT**:

A tuple of lattice polytopes.

**EXAMPLES:** 

sage.geometry.polyhedron.ppl\_lattice\_polygon.subpolygons\_of\_polar\_P2()

The lattice sub-polygons of the polar  $P^2$  polytope

**OUTPUT**:

A tuple of lattice polytopes.

**EXAMPLES:** 

sage.geometry.polyhedron.ppl\_lattice\_polygon.subpolygons\_of\_polar\_P2\_112()

The lattice sub-polygons of the polar  $P^2[1, 1, 2]$  polytope

**OUTPUT**:

A tuple of lattice polytopes.

```
sage: from sage.geometry.polyhedron.ppl_lattice_polygon import subpolygons_of_polar_
    P2_112
sage: len(subpolygons_of_polar_P2_112())
28
```

# 2.2.5 Fast Lattice Polytopes using PPL.

The *LatticePolytope\_PPL()* class is a thin wrapper around PPL polyhedra. Its main purpose is to be fast to construct, at the cost of being much less full-featured than the usual polyhedra. This makes it possible to iterate with it over the list of all 473800776 reflexive polytopes in 4 dimensions.

**Note:** For general lattice polyhedra you should use *Polyhedron()* with base\_ring=ZZ.

The class derives from the PPL ppl.polyhedron.C\_Polyhedron class, so you can work with the underlying generator and constraint objects. However, integral points are generally represented by **Z**-vectors. In the following, we always use *generator* to refer the PPL generator objects and *vertex* (or integral point) for the corresponding **Z**-vector.

#### **EXAMPLES:**

Fibrations of the lattice polytopes are defined as lattice sub-polytopes and give rise to fibrations of toric varieties for suitable fan refinements. We can compute them using fibration\_generator()

```
sage: F = next(P.fibration_generator(2))
sage: F.vertices()
((1, 0, 0, 0), (0, 1, 0, 0), (-3, -2, 0, 0))
```

Finally, we can compute automorphisms and identify fibrations that only differ by a lattice automorphism:

```
sage: square = LatticePolytope_PPL((-1,-1),(-1,1),(1,-1),(1,1))
sage: fibers = [ f.vertices() for f in square.fibration_generator(1) ]; fibers
[((1, 0), (-1, 0)), ((0, 1), (0, -1)), ((-1, -1), (1, 1)), ((-1, 1), (1, -1))]
sage: square.pointsets_mod_automorphism(fibers)
(frozenset({(-1, -1), (1, 1)}), frozenset({(-1, 0), (1, 0)}))
```

### **AUTHORS:**

• Volker Braun: initial version, 2012

 $sage.geometry.polyhedron.ppl\_lattice\_polytope. \textbf{LatticePolytope\_PPL}(*args)\\ Construct a new instance of the PPL-based lattice polytope class.$ 

```
sage: from sage.geometry.polyhedron.ppl_lattice_polytope import LatticePolytope_PPL
sage: LatticePolytope_PPL((0,0),(1,0),(0,1))
A 2-dimensional lattice polytope in ZZ^2 with 3 vertices

sage: from ppl import point, Generator_System, C_Polyhedron, Linear_Expression,
Variable (continues on next page)
```

```
sage: p = point(Linear_Expression([2,3],0)); p
point(2/1, 3/1)
sage: LatticePolytope_PPL(p)
A 0-dimensional lattice polytope in ZZ^2 with 1 vertex

sage: P = C_Polyhedron(Generator_System(p)); P
A 0-dimensional polyhedron in QQ^2 defined as the convex hull of 1 point
sage: LatticePolytope_PPL(P)
A 0-dimensional lattice polytope in ZZ^2 with 1 vertex
```

A TypeError is raised if the arguments do not specify a lattice polytope:

```
sage: from sage.geometry.polyhedron.ppl_lattice_polytope import LatticePolytope_PPL
sage: LatticePolytope_PPL((0,0),(1/2,1))
Traceback (most recent call last):
TypeError: unable to convert rational 1/2 to an integer
sage: from ppl import point, Generator_System, C_Polyhedron, Linear_Expression,
→Variable
sage: p = point(Linear_Expression([2,3],0), 5); p
point(2/5, 3/5)
sage: LatticePolytope_PPL(p)
Traceback (most recent call last):
TypeError: generator is not a lattice polytope generator
sage: P = C_Polyhedron(Generator_System(p)); P
A 0-dimensional polyhedron in QQ^2 defined as the convex hull of 1 point
sage: LatticePolytope_PPL(P)
Traceback (most recent call last):
TypeError: polyhedron has non-integral generators
```

### class sage.geometry.polyhedron.ppl\_lattice\_polytope.LatticePolytope\_PPL\_class

Bases: ppl.polyhedron.C\_Polyhedron

The lattice polytope class.

You should use LatticePolytope\_PPL() to construct instances.

**EXAMPLES:** 

```
sage: from sage.geometry.polyhedron.ppl_lattice_polytope import LatticePolytope_PPL
sage: LatticePolytope_PPL((0,0),(1,0),(0,1))
A 2-dimensional lattice polytope in ZZ^2 with 3 vertices
```

### affine\_lattice\_polytope()

Return the lattice polytope restricted to affine\_space().

OUTPUT

A new, full-dimensional lattice polytope.

```
sage: from sage.geometry.polyhedron.ppl_lattice_polytope import LatticePolytope_
→PPL
sage: poly_4d = LatticePolytope_PPL((-9,-6,0,0),(0,1,0,0),(1,0,0,0)); poly_4d
A 2-dimensional lattice polytope in ZZ^4 with 3 vertices
sage: poly_4d.space_dimension()
4
sage: poly_2d = poly_4d.affine_lattice_polytope(); poly_2d
A 2-dimensional lattice polytope in ZZ^2 with 3 vertices
sage: poly_2d.space_dimension()
2
```

### affine\_space()

Return the affine space spanned by the polytope.

**OUTPUT:** 

The free module  $\mathbb{Z}^n$ , where n is the dimension of the affine space spanned by the points of the polytope.

#### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.ppl_lattice_polytope import LatticePolytope_
_PPL
sage: point = LatticePolytope_PPL((1,2,3))
sage: point.affine_space()
Free module of degree 3 and rank 0 over Integer Ring
Echelon basis matrix:
[]
sage: line = LatticePolytope_PPL((1,1,1), (1,2,3))
sage: line.affine_space()
Free module of degree 3 and rank 1 over Integer Ring
Echelon basis matrix:
[0 1 2]
```

### ambient\_space()

Return the ambient space.

OUTPUT:

The free module  $\mathbb{Z}^d$ , where d is the ambient space dimension.

### **EXAMPLES:**

### base\_projection(fiber)

The projection that maps the sub-polytope fiber to a single point.

OUTPUT

The quotient module of the ambient space modulo the affine\_space() spanned by the fiber.

### base\_projection\_matrix(fiber)

The projection that maps the sub-polytope fiber to a single point.

### **OUTPUT**:

An integer matrix that represents the projection to the base.

#### See also:

The <code>base\_projection()</code> yields equivalent information, and is easier to use. However, just returning the matrix has lower overhead.

#### **EXAMPLES:**

Note that the basis choice in base\_projection() for the quotient is usually different:

```
sage: proj = poly.base_projection(fiber)
sage: proj_matrix = poly.base_projection_matrix(fiber)
sage: [ proj(p) for p in poly.integral_points() ]
[(-1, -1), (0, 0), (0, 0), (0, 0), (0, 0), (0, 0), (0, 0), (0, 0), (0, 1), (1, 0, 0)]
sage: [ proj_matrix*p for p in poly.integral_points() ]
[(-1, -1), (0, 0), (0, 0), (0, 0), (0, 0), (0, 0), (0, 0), (0, 0), (0, 1), (1, 0, 0)]
```

### base\_rays(fiber, points)

Return the primitive lattice vectors that generate the direction given by the base projection of points.

### INPUT:

- fiber a sub-lattice polytope defining the base\_projection().
- points the points to project to the base.

### OUTPUT:

A tuple of primitive **Z**-vectors.

### bounding\_box()

Return the coordinates of a rectangular box containing the non-empty polytope.

### **OUTPUT**:

A pair of tuples (box\_min, box\_max) where box\_min are the coordinates of a point bounding the coordinates of the polytope from below and box\_max bounds the coordinates from above.

### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.ppl_lattice_polytope import LatticePolytope_\rightarrowPPL sage: LatticePolytope_PPL((0,0),(1,0),(0,1)).bounding_box() ((0, 0), (1, 1))
```

### contains(point\_coordinates)

Test whether point is contained in the polytope.

### INPUT:

• point\_coordinates – a list/tuple/iterable of rational numbers. The coordinates of the point.

### **OUTPUT**:

Boolean.

### **EXAMPLES:**

### contains\_origin()

Test whether the polytope contains the origin

**OUTPUT**:

Boolean.

### embed\_in\_reflexive\_polytope(output='hom')

Find an embedding as a sub-polytope of a maximal reflexive polytope.

### INPUT:

• hom – string. One of 'hom' (default), 'polytope', or points. How the embedding is returned. See the output section for details.

### **OUTPUT**:

An embedding into a reflexive polytope. Depending on the output option slightly different data is returned.

- If output='hom', a map from a reflexive polytope onto self is returned.
- If output='polytope', a reflexive polytope that contains self (up to a lattice linear transformation) is returned. That is, the domain of the output='hom' map is returned. If the affine span of self is less or equal 2-dimensional, the output is one of the following three possibilities:

```
polar_P2_polytope(), polar_P1xP1_polytope(), or polar_P2_112_polytope().
```

• If output='points', a dictionary containing the integral points of self as keys and the corresponding integral point of the reflexive polytope as value.

If there is no such embedding, a *LatticePolytopeNoEmbeddingError* is raised. Even if it exists, the ambient reflexive polytope is usually not uniquely determined and a random but fixed choice will be returned.

### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.ppl_lattice_polytope import LatticePolytope_
←PPL
sage: polygon = LatticePolytope_PPL(((0,0,2,1),(0,1,2,0),(2,3,0,0),(2,0,0,3))
sage: polygon.embed_in_reflexive_polytope()
The map A*x+b with A=
[1 1]
[ 0 1]
\lceil -1 -1 \rceil
Γ 1 0T
b =
(-1, 0, 3, 0)
sage: polygon.embed_in_reflexive_polytope('polytope')
A 2-dimensional lattice polytope in ZZ^2 with 3 vertices
sage: polygon.embed_in_reflexive_polytope('points')
\{(0, 0, 2, 1): (1, 0),
 (0, 1, 2, 0): (0, 1),
 (1, 0, 1, 2): (2, 0),
 (1, 1, 1, 1): (1, 1),
 (1, 2, 1, 0): (0, 2),
 (2, 0, 0, 3): (3, 0),
 (2, 1, 0, 2): (2, 1),
 (2, 2, 0, 1): (1, 2),
```

```
(2, 3, 0, 0): (0, 3)}
sage: LatticePolytope_PPL((0,0), (4,0), (0,4)).embed_in_reflexive_polytope()
Traceback (most recent call last):
...
LatticePolytopeNoEmbeddingError: not a sub-polytope of a reflexive polygon
```

### fibration\_generator(dim)

Generate the lattice polytope fibrations.

For the purposes of this function, a lattice polytope fiber is a sub-lattice polytope. Projecting the plane spanned by the subpolytope to a point yields another lattice polytope, the base of the fibration.

### INPUT:

• dim – integer. The dimension of the lattice polytope fiber.

#### **OUTPUT**:

A generator yielding the distinct lattice polytope fibers of given dimension.

#### **EXAMPLES:**

### has\_IP\_property()

Whether the lattice polytope has the IP property.

That is, the polytope is full-dimensional and the origin is a interior point not on the boundary.

### **OUTPUT**:

Boolean.

### **EXAMPLES:**

### integral\_points()

Return the integral points in the polyhedron.

Uses the naive algorithm (iterate over a rectangular bounding box).

### **OUTPUT**:

The list of integral points in the polyhedron. If the polyhedron is not compact, a ValueError is raised.

```
sage: from sage.geometry.polyhedron.ppl_lattice_polytope import LatticePolytope_
→PPL
sage: LatticePolytope_PPL((-1,-1),(1,0),(1,1),(0,1)).integral_points()
((-1, -1), (0, 0), (0, 1), (1, 0), (1, 1))
sage: simplex = LatticePolytope_PPL((1,2,3), (2,3,7), (-2,-3,-11))
sage: simplex.integral_points()
((-2, -3, -11), (0, 0, -2), (1, 2, 3), (2, 3, 7))
```

The polyhedron need not be full-dimensional:

```
sage: simplex = LatticePolytope_PPL((1,2,3,5), (2,3,7,5), (-2,-3,-11,5))
sage: simplex.integral_points()
((-2, -3, -11, 5), (0, 0, -2, 5), (1, 2, 3, 5), (2, 3, 7, 5))

sage: point = LatticePolytope_PPL((2,3,7))
sage: point.integral_points()
((2, 3, 7),)

sage: empty = LatticePolytope_PPL()
sage: empty.integral_points()
()
```

Here is a simplex where the naive algorithm of running over all points in a rectangular bounding box no longer works fast enough:

```
sage: v = [(1,0,7,-1), (-2,-2,4,-3), (-1,-1,-1,4), (2,9,0,-5), (-2,-1,5,1)]
sage: simplex = LatticePolytope_PPL(v); simplex
A 4-dimensional lattice polytope in ZZ^4 with 5 vertices
sage: len(simplex.integral_points())
49
```

Finally, the 3-d reflexive polytope number 4078:

```
sage: v = [(1,0,0), (0,1,0), (0,0,1), (0,0,-1), (0,-2,1),
          (-1,2,-1), (-1,2,-2), (-1,1,-2), (-1,-1,2), (-1,-3,2)
sage: P = LatticePolytope_PPL(*v)
sage: pts1 = P.integral_points()
                                                     # Sage's own code
sage: pts2 = LatticePolytope(v).points()
                                                                    # optional -
→ palp
sage: for p in pts1: p.set_immutable()
sage: set(pts1) == set(pts2)
                                                                    # optional -
→ palp
True
sage: len(Polyhedron(v).integral_points()) # takes about 1 ms
sage: len(LatticePolytope(v).points()) # takes about 13 ms
                                                                  # optional -
→ palp
23
sage: len(LatticePolytope_PPL(*v).integral_points()) # takes about 0.5 ms
23
```

# integral\_points\_not\_interior\_to\_facets()

Return the integral points not interior to facets

#### **OUTPUT**:

A tuple whose entries are the coordinate vectors of integral points not interior to facets (codimension one faces) of the lattice polytope.

### **EXAMPLES:**

### is\_bounded()

Return whether the lattice polytope is compact.

### **OUTPUT**:

Always True, since polytopes are by definition compact.

#### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.ppl_lattice_polytope import LatticePolytope_\rightarrowPPL sage: LatticePolytope_PPL((0,0),(1,0),(0,1)).is_bounded() True
```

### is\_full\_dimensional()

Return whether the lattice polytope is full dimensional.

### **OUTPUT**:

Boolean. Whether the affine\_dimension() equals the ambient space dimension.

#### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.ppl_lattice_polytope import LatticePolytope_
→PPL
sage: p = LatticePolytope_PPL((0,0),(0,1))
sage: p.is_full_dimensional()
False
sage: q = LatticePolytope_PPL((0,0),(0,1),(1,0))
sage: q.is_full_dimensional()
True
```

### is\_simplex()

Return whether the polyhedron is a simplex.

### **OUTPUT**:

Boolean, whether the polyhedron is a simplex (possibly of strictly smaller dimension than the ambient space).

```
sage: from sage.geometry.polyhedron.ppl_lattice_polytope import LatticePolytope_\rightarrowPPL sage: LatticePolytope_PPL((0,0,0), (1,0,0), (0,1,0)).is_simplex() True
```

### lattice\_automorphism\_group(points=None, point\_labels=None)

The integral subgroup of the restricted automorphism group.

#### INPUT:

- points A tuple of coordinate vectors or None (default). If specified, the points must form complete orbits under the lattice automorphism group. If None all vertices are used.
- point\_labels A tuple of labels for the points or None (default). These will be used as labels for the do permutation group. If None the points will be used themselves.

### **OUTPUT**:

The integral subgroup of the restricted automorphism group acting on the given points, or all vertices if not specified.

#### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.ppl_lattice_polytope import LatticePolytope_
←PPL
sage: Z3square = LatticePolytope_PPL((0,0), (1,2), (2,1), (3,3))
sage: Z3square.lattice_automorphism_group()
→# optional - sage.groups # optional - sage.graphs
Permutation Group with generators [(), ((1,2),(2,1)),
((0,0),(3,3)),((0,0),(3,3))((1,2),(2,1))]
sage: G1 = Z3square.lattice_automorphism_group(point_labels=(1,2,3,4)); G1
→# optional - sage.groups # optional - sage.graphs
Permutation Group with generators [(), (2,3), (1,4), (1,4)(2,3)]
sage: G1.cardinality()
→# optional - sage.groups # optional - sage.graphs
sage: G2 = Z3square.restricted_automorphism_group(vertex_labels=(1,2,3,4))
→# optional - sage.groups # optional - sage.graphs
sage: G2 = PermutationGroup([[(2,3)], [(1,2),(3,4)], [(1,4)]])
→# optional - sage.groups # optional - sage.graphs
True
sage: G2.cardinality()
→# optional - sage.groups # optional - sage.graphs
sage: points = Z3square.integral_points(); points
((0, 0), (1, 1), (1, 2), (2, 1), (2, 2), (3, 3))
sage: Z3square.lattice_automorphism_group(points, point_labels=(1,2,3,4,5,6))
→# optional - sage.groups # optional - sage.graphs
Permutation Group with generators [(), (3,4), (1,6)(2,5), (1,6)(2,5)(3,4)]
```

Point labels also work for lattice polytopes that are not full-dimensional, see trac ticket #16669:

### n\_integral\_points()

Return the number of integral points.

**OUTPUT:** 

Integer. The number of integral points contained in the lattice polytope.

**EXAMPLES**:

### n\_vertices()

Return the number of vertices.

**OUTPUT:** 

An integer, the number of vertices.

**EXAMPLES:** 

```
sage: from sage.geometry.polyhedron.ppl_lattice_polytope import LatticePolytope_\rightarrowPPL sage: LatticePolytope_PPL((0,0,0), (1,0,0), (0,1,0)).n_vertices() 3
```

### pointsets\_mod\_automorphism(pointsets)

Return pointsets modulo the automorphisms of self.

INPUT:

• polytopes a tuple/list/iterable of subsets of the integral points of self.

**OUTPUT**:

Representatives of the point sets modulo the lattice\_automorphism\_group() of self.

**EXAMPLES:** 

### restricted\_automorphism\_group(vertex\_labels=None)

Return the restricted automorphism group.

First, let the linear automorphism group be the subgroup of the Euclidean group  $E(d) = GL(d, \mathbf{R}) \ltimes \mathbf{R}^d$  preserving the d-dimensional polyhedron. The Euclidean group acts in the usual way  $\vec{x} \mapsto A\vec{x} + b$  on the ambient space. The restricted automorphism group is the subgroup of the linear automorphism group generated by permutations of vertices. If the polytope is full-dimensional, it is equal to the full (unrestricted) automorphism group.

### INPUT:

• vertex\_labels – a tuple or None (default). The labels of the vertices that will be used in the output permutation group. By default, the vertices are used themselves.

### **OUTPUT**:

A PermutationGroup acting on the vertices (or the vertex\_labels, if specified).

### **REFERENCES:**

[BSS2009]

#### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.ppl_lattice_polytope import LatticePolytope_
 ←PPL
sage: Z3square = LatticePolytope_PPL((\emptyset, \emptyset), (1,2), (2,1), (3,3))
sage: G1234 = Z3square.restricted_automorphism_group(vertex_labels=(1,2,3,4))
                                                          # optional - sage.groups # optional - sage.graphs
sage: G1234 == PermutationGroup([[(2,3)],[(1,2),(3,4)]])
                                                          # optional - sage.groups # optional - sage.graphs
True
sage: G = Z3square.restricted_automorphism_group()
                                                          # optional - sage.groups # optional - sage.graphs
sage: G = PermutationGroup([((1,2),(2,1))],((0,0),(1,2)),((2,1),(3,3))],[((0,0),(1,2)),((2,1),(3,3))],[((0,0),(1,2)),((2,1),(3,3))],[((0,0),(1,2)),((2,1),(3,3))],[((0,0),(1,2)),((2,1),(3,3))],[((0,0),(1,2)),((2,1),(3,3))],[((0,0),(1,2)),((2,1),(3,3))],[((0,0),(1,2)),((2,1),(3,3))],[((0,0),(1,2)),((2,1),(3,3))],[((0,0),(1,2)),((2,1),(3,3))],[((0,0),(1,2)),((2,1),(3,3))],[((0,0),(1,2)),((2,1),(3,3))],[((0,0),(1,2)),((2,1),(3,3))],[((0,0),(1,2)),((2,1),(3,3))],[((0,0),(1,2)),((2,1),(3,3))],[((0,0),(1,2)),((2,1),(3,3))],[((0,0),(1,2)),((2,1),(3,3))],[((0,0),(1,2)),((2,1),(3,3))],[((0,0),(1,2)),((2,1),(3,3))],[((0,0),(1,2)),((2,1),(3,3))],[((0,0),(1,2)),((2,1),(3,3))],[((0,0),(1,2)),((2,1),(3,3))],[((0,0),(1,2)),((2,1),(2,3))],[((0,0),(1,2)),((2,1),(2,3))],[((0,0),(1,2)),((2,1),(2,3))],[((0,0),(1,2)),((2,1),(2,3))],[((0,0),(1,2)),((2,1),(2,3))],[((0,0),(1,2)),((2,1)),((2,1)),((2,1))],[((0,0),(1,2)),((2,1)),((2,1))],[((0,0),(1,2)),((2,1)),((2,1)),((2,1))],[((0,0),(1,2)),((2,1)),((2,1)),((2,1))],[((0,0),(1,2)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1)),((2,1))
 (3,3)
                                                          # optional - sage.groups # optional - sage.graphs
True
sage: set(G.domain()) == set(Z3square.vertices())
 _
                                                          # optional - sage.groups # optional - sage.graphs
True
sage: set(map(tuple,G.orbit(Z3square.vertices()[0]))) == set([(0, 0), (1, 2), ...))
 \rightarrow(3, 3), (2, 1)]) # optional - sage.groups # optional - sage.graphs
True
```

### sub\_polytope\_generator()

Generate the maximal lattice sub-polytopes.

### **OUTPUT**:

A generator yielding the maximal (with respect to inclusion) lattice sub polytopes. That is, each can be gotten as the convex hull of the integral points of self with one vertex removed.

### **EXAMPLES:**

### vertices()

Return the vertices as a tuple of **Z**-vectors.

#### OUTPUT:

A tuple of **Z**-vectors. Each entry is the coordinate vector of an integral points of the lattice polytope.

### **EXAMPLES:**

### vertices\_saturating(constraint)

Return the vertices saturating the constraint

### INPUT:

• constraint – a constraint (inequality or equation) of the polytope.

### **OUTPUT**:

The tuple of vertices saturating the constraint. The vertices are returned as **Z**-vectors, as in *vertices()*.

### **EXAMPLES:**

sage.geometry.polyhedron.ppl\_lattice\_polytope.line(cls, expression)

Generator.line(type cls, expression)

Construct a line.

### INPUT:

• expression – a Linear\_Expression or something convertible to it (Variable or integer).

### **OUTPUT**:

A new Generator representing the line.

Raises a ValueError` if the homogeneous part of ``expression represents the origin of the vector space.

### Examples:

```
>>> from ppl import Generator, Variable
>>> y = Variable(1)
>>> Generator.line(2*y)
line(0, 1)
>>> Generator.line(y)
line(0, 1)
>>> Generator.line(1)
Traceback (most recent call last):
...
ValueError: PPL::line(e):
e == 0, but the origin cannot be a line.
```

sage.geometry.polyhedron.ppl\_lattice\_polytope.point(cls, expression=0, divisor=1)
Generator.point(type cls, expression=0, divisor=1)

Construct a point.

### INPUT:

- expression a Linear\_Expression or something convertible to it (Variable or integer).
- divisor an integer.

### **OUTPUT**:

A new Generator representing the point.

Raises a ValueError` if ``divisor==0.

# Examples:

```
>>> from ppl import Generator, Variable
>>> y = Variable(1)
```

```
>>> Generator.point(2*y+7, 3)
point(0/3, 2/3)
>>> Generator.point(y+7, 3)
point(0/3, 1/3)
>>> Generator.point(7, 3)
point()
>>> Generator.point(0, 0)
Traceback (most recent call last):
...
ValueError: PPL::point(e, d):
d == 0.
```

# 2.3 Combinatorial Polyhedra

# 2.3.1 Combinatorial polyhedron

This module gathers algorithms for polyhedra that only depend on the vertex-facet incidences and that are called combinatorial polyhedron. The main class is *CombinatorialPolyhedron*. Most importantly, this class allows to iterate quickly through the faces (possibly of given dimension) via the *FaceIterator* object. The *CombinatorialPolyhedron* uses this iterator to quickly generate the f-vector, the edges, the ridges and the face lattice.

Terminology used in this module:

- Vrep [vertices, rays, lines] of the polyhedron.
- Hrep inequalities and equations of the polyhedron.
- Facets facets of the polyhedron.
- Vrepresentation represents a face by the list of Vrep it contains.
- Hrepresentation represents a face by a list of Hrep it is contained in.
- bit representation represents incidences as bitset, where each bit represents one incidence. There might be trailing zeros, to fit alignment requirements. In most instances, faces are represented by the bit representation, where each bit corresponds to a Vrep or facet. Thus a bit representation can either be a Vrep or facet representation depending on context.

### **EXAMPLES:**

Construction:

```
sage: P = polytopes.hypercube(4)
sage: C = CombinatorialPolyhedron(P); C
A 4-dimensional combinatorial polyhedron with 8 facets
```

Obtaining edges and ridges:

```
sage: C.edges()[:2]
((A vertex at (1, -1, -1, -1), A vertex at (-1, -1, -1, -1)),
  (A vertex at (-1, -1, -1, 1), A vertex at (-1, -1, -1, -1)))
sage: C.edges(names=False)[:2]
((6, 15), (14, 15))
```

```
sage: C.ridges()[:2]
((An inequality (0, 0, 1, 0) x + 1 >= 0,
    An inequality (0, 1, 0, 0) x + 1 >= 0),
(An inequality (0, 0, 0, 1) x + 1 >= 0,
    An inequality (0, 1, 0, 0) x + 1 >= 0))
sage: C.ridges(names=False)[:2]
((6, 7), (5, 7))
```

Vertex-graph and facet-graph:

Face lattice:

Face iterator:

```
sage: C.face_generator()
Iterator over the proper faces of a 4-dimensional combinatorial polyhedron
sage: C.face_generator(2)
Iterator over the 2-faces of a 4-dimensional combinatorial polyhedron
```

### **AUTHOR:**

• Jonathan Kliem (2019-04)

The class of the Combinatorial Type of a Polyhedron, a Polytope.

INPUT:

- data an instance of
  - Polyhedron\_base
  - or a LatticePolytopeClass
  - or a ConvexRationalPolyhedralCone
  - or an incidence\_matrix as in incidence\_matrix() In this case you should also specify the
     Vrep and facets arguments
  - or list of facets, each facet given as a list of [vertices, rays, lines] if the polyhedron is unbounded, then rays and lines and the extra argument nr\_lines are required if the polyhedron contains no lines, the rays can be thought of as the vertices of the facets deleted from a bounded polyhedron\_base on how to use rays and lines

- or an integer, representing the dimension of a polyhedron equal to its affine hull
- or a tuple consisting of facets and vertices as two *ListOfFaces*.
- Vrep (optional) when data is an incidence matrix, it should be the list of [vertices, rays, lines], if the rows in the incidence\_matrix should correspond to names
- facets (optional) when data is an incidence matrix or a list of facets, it should be a list of facets that would be used instead of indices (of the columns of the incidence matrix).
- unbounded value will be overwritten if data is a polyhedron; if unbounded and data is incidence matrix or a list of facets, need to specify far\_face
- far\_face (semi-optional); if the polyhedron is unbounded this needs to be set to the list of indices of the rays and line unless data is an instance of Polyhedron\_base.

#### **EXAMPLES:**

We illustrate all possible input: a polyhedron:

sage: P = polytopes.cube() sage: CombinatorialPolyhedron(P) A 3-dimensional combinatorial polyhedron with 6 facets

a lattice polytope:

```
sage: points = [(1,0,0), (0,1,0), (0,0,1),
....: (-1,0,0), (0,-1,0), (0,0,-1)]
sage: L = LatticePolytope(points)
sage: CombinatorialPolyhedron(L)
A 3-dimensional combinatorial polyhedron with 8 facets
```

a cone:

```
sage: M = Cone([(1,0), (0,1)])
sage: CombinatorialPolyhedron(M)
A 2-dimensional combinatorial polyhedron with 2 facets
```

an incidence matrix:

```
sage: P = Polyhedron(rays=[[0,1]])
sage: data = P.incidence_matrix()
sage: far_face = [i for i in range(2) if not P.Vrepresentation()[i].is_vertex()]
sage: CombinatorialPolyhedron(data, unbounded=True, far_face=far_face)
A 1-dimensional combinatorial polyhedron with 1 facet
sage: C = CombinatorialPolyhedron(data, Vrep=['myvertex'],
....: facets=['myfacet'], unbounded=True, far_face=far_face)
sage: C.Vrepresentation()
('myvertex',)
sage: C.Hrepresentation()
```

a list of facets:

```
sage: CombinatorialPolyhedron(((1,2,3),(1,2,4),(1,3,4),(2,3,4)))
A 3-dimensional combinatorial polyhedron with 4 facets
sage: facetnames = ['facet0', 'facet1', 'facet2', 'myfacet3']
sage: facetinc = ((1,2,3),(1,2,4),(1,3,4),(2,3,4))
sage: C = CombinatorialPolyhedron(facetinc, facets=facetnames)
```

```
sage: C.Vrepresentation()
(1, 2, 3, 4)
sage: C.Hrepresentation()
('facet0', 'facet1', 'facet2', 'myfacet3')
```

an integer:

```
sage: CombinatorialPolyhedron(-1).f_vector()
(1)
sage: CombinatorialPolyhedron(0).f_vector()
(1, 1)
sage: CombinatorialPolyhedron(5).f_vector()
(1, 0, 0, 0, 0, 0, 1)
```

tuple of ListOfFaces:

Specifying that a polyhedron is unbounded is important. The following with a polyhedron works fine:

```
sage: P = Polyhedron(ieqs=[[1,-1,0],[1,1,0]])
sage: C = CombinatorialPolyhedron(P) # this works fine
sage: C
A 2-dimensional combinatorial polyhedron with 2 facets
```

The following is incorrect, as unbounded is implicitly set to False:

```
sage: data = P.incidence_matrix()
sage: vert = P.Vrepresentation()
sage: C = CombinatorialPolyhedron(data, Vrep=vert)
sage: C
A 2-dimensional combinatorial polyhedron with 2 facets
sage: C.f_vector()
Traceback (most recent call last):
...
ValueError: not all vertices are intersections of facets
sage: C.vertices()
(A line in the direction (0, 1), A vertex at (1, 0), A vertex at (-1, 0))
```

The correct usage is:

```
sage: C
A 2-dimensional combinatorial polyhedron with 2 facets
sage: C.f_vector()
(1, 0, 2, 1)
sage: C.vertices()
()
```

### Hrepresentation()

Return a list of names of facets and possibly some equations.

**EXAMPLES**:

```
sage: P = polytopes.permutahedron(3)
                                                                      # optional -
→ sage.combinat
sage: C = CombinatorialPolyhedron(P)
                                                                      # optional -
→ sage.combinat
sage: C.Hrepresentation()
                                                                      # optional -
→ sage.combinat
(An inequality (1, 1, 0) x - 3 >= 0,
An inequality (-1, -1, 0) x + 5 >= 0,
An inequality (0, 1, 0) \times -1 >= 0,
An inequality (-1, 0, 0) x + 3 >= 0,
An inequality (1, 0, 0) \times -1 >= 0,
An inequality (0, -1, 0) \times + 3 >= 0,
An equation (1, 1, 1) \times -6 == 0
sage: points = [(1,0,0), (0,1,0), (0,0,1),
(-1,0,0), (0,-1,0), (0,0,-1)
sage: L = LatticePolytope(points)
sage: C = CombinatorialPolyhedron(L)
sage: C.Hrepresentation()
(N(1, -1, -1),
N(1, 1, -1),
N(1, 1, 1),
N(1, -1, 1),
N(-1, -1, 1),
N(-1, -1, -1),
N(-1, 1, -1),
N(-1, 1, 1)
sage: M = Cone([(1,0), (0,1)])
sage: CombinatorialPolyhedron(M).Hrepresentation()
(M(0, 1), M(1, 0))
```

# Vrepresentation()

Return a list of names of [vertices, rays, lines].

**EXAMPLES**:

```
(A line in the direction (0, 0, 1),
A ray in the direction (1, 0, 0),
A vertex at (0, 0, 0),
A ray in the direction (0, 1, 0))

sage: points = [(1,0,0), (0,1,0), (0,0,1),
...: (-1,0,0), (0,-1,0), (0,0,-1)]
sage: L = LatticePolytope(points)
sage: C = CombinatorialPolyhedron(L)
sage: C.Vrepresentation()
(M(1, 0, 0), M(0, 1, 0), M(0, 0, 1), M(-1, 0, 0), M(0, -1, 0), M(0, 0, -1))

sage: M = Cone([(1,0), (0,1)])
sage: CombinatorialPolyhedron(M).Vrepresentation()
(N(1, 0), N(0, 1), N(0, 0))
```

### a\_maximal\_chain(Vindex=None, Hindex=None)

Return a maximal chain of the face lattice in increasing order without empty face and whole polyhedron/maximal face.

### INPUT:

- Vindex integer (default: None); prescribe the index of the vertex in the chain
- Hindex integer (default: None); prescribe the index of the facet in the chain

Each face is given as CombinatorialFace.

```
sage: P = polytopes.cross_polytope(4)
sage: C = P.combinatorial_polyhedron()
sage: chain = C.a_maximal_chain(); chain
[A O-dimensional face of a 4-dimensional combinatorial polyhedron,
A 1-dimensional face of a 4-dimensional combinatorial polyhedron,
A 2-dimensional face of a 4-dimensional combinatorial polyhedron,
A 3-dimensional face of a 4-dimensional combinatorial polyhedron]
sage: [face.ambient_V_indices() for face in chain]
[(7,), (6, 7), (5, 6, 7), (4, 5, 6, 7)]
sage: P = polytopes.hypercube(4)
sage: C = P.combinatorial_polyhedron()
sage: chain = C.a_maximal_chain(); chain
[A 0-dimensional face of a 4-dimensional combinatorial polyhedron,
A 1-dimensional face of a 4-dimensional combinatorial polyhedron,
A 2-dimensional face of a 4-dimensional combinatorial polyhedron,
A 3-dimensional face of a 4-dimensional combinatorial polyhedron]
sage: [face.ambient_V_indices() for face in chain]
[(15,), (6, 15), (5, 6, 14, 15), (0, 5, 6, 7, 8, 9, 14, 15)]
sage: P = polytopes.permutahedron(4)
                                                                     # optional -
→ sage.combinat
sage: C = P.combinatorial_polyhedron()
                                                                     # optional -
→ sage.combinat
sage: chain = C.a_maximal_chain(); chain
                                                                     # optional -
                                                                   (continues on next page)
→ sage.combinat
```

```
[A 0-dimensional face of a 3-dimensional combinatorial polyhedron,
A 1-dimensional face of a 3-dimensional combinatorial polyhedron,
A 2-dimensional face of a 3-dimensional combinatorial polyhedron]
sage: [face.ambient_V_indices() for face in chain]
                                                                     # optional -
→ sage.combinat
[(16,), (15, 16), (8, 9, 14, 15, 16, 17)]
sage: P = Polyhedron(rays=[[1,0]], lines=[[0,1]])
sage: C = P.combinatorial_polyhedron()
sage: chain = C.a_maximal_chain()
sage: [face.ambient_V_indices() for face in chain]
[(0, 1)]
sage: P = Polyhedron(rays=[[1,0,0],[0,0,1]], lines=[[0,1,0]])
sage: C = P.combinatorial_polyhedron()
sage: chain = C.a_maximal_chain()
sage: [face.ambient_V_indices() for face in chain]
[(0, 1), (0, 1, 3)]
sage: P = Polyhedron(rays=[[1,0,0]], lines=[[0,1,0],[0,0,1]])
sage: C = P.combinatorial_polyhedron()
sage: chain = C.a_maximal_chain()
sage: [face.ambient_V_indices() for face in chain]
[(0, 1, 2)]
```

Specify an index for the vertex of the chain:

```
sage: P = polytopes.cube()
sage: C = P.combinatorial_polyhedron()
sage: [face.ambient_V_indices() for face in C.a_maximal_chain()]
[(5,), (0, 5), (0, 3, 4, 5)]
sage: [face.ambient_V_indices() for face in C.a_maximal_chain(Vindex=2)]
[(2,), (2, 7), (2, 3, 4, 7)]
```

Specify an index for the facet of the chain:

```
sage: [face.ambient_H_indices() for face in C.a_maximal_chain()]
[(3, 4, 5), (4, 5), (5,)]
sage: [face.ambient_H_indices() for face in C.a_maximal_chain(Hindex=3)]
[(3, 4, 5), (3, 4), (3,)]
sage: [face.ambient_H_indices() for face in C.a_maximal_chain(Hindex=2)]
[(2, 3, 5), (2, 3), (2,)]
```

If the specified vertex is not contained in the specified facet an error is raised:

```
sage: C.a_maximal_chain(Vindex=0, Hindex=3)
Traceback (most recent call last):
...
ValueError: the given Vindex is not compatible with the given Hindex
```

An error is raised, if the specified index does not correspond to a facet:

```
sage: C.a_maximal_chain(Hindex=40)
Traceback (most recent call last):
...
ValueError: the given Hindex does not correspond to a facet
```

An error is raised, if the specified index does not correspond to a vertex:

```
sage: C.a_maximal_chain(Vindex=40)
Traceback (most recent call last):
...
ValueError: the given Vindex does not correspond to a vertex
```

```
sage: P = Polyhedron(rays=[[1,0,0],[0,0,1]], lines=[[0,1,0]])
sage: C = P.combinatorial_polyhedron()
sage: C.a_maximal_chain(Vindex=0)
Traceback (most recent call last):
...
ValueError: the given Vindex does not correspond to a vertex
```

```
sage: P = Polyhedron(rays=[[1,0,0],[0,0,1]])
sage: C = P.combinatorial_polyhedron()
sage: C.a_maximal_chain(Vindex=0)
[A 0-dimensional face of a 2-dimensional combinatorial polyhedron,
A 1-dimensional face of a 2-dimensional combinatorial polyhedron]
sage: C.a_maximal_chain(Vindex=1)
Traceback (most recent call last):
...
ValueError: the given Vindex does not correspond to a vertex
```

### dim()

Return the dimension of the polyhedron.

**EXAMPLES:** 

dim is an alias:

```
sage: CombinatorialPolyhedron(P).dim()
3
```

### dimension()

Return the dimension of the polyhedron.

dim is an alias:

```
sage: CombinatorialPolyhedron(P).dim()
3
```

#### dual()

Return the dual/polar of self.

Only defined for bounded polyhedra.

### See also:

polar().

**EXAMPLES:** 

Polar is an alias to be consistent with *Polyhedron\_base*:

```
sage: C.polar().f_vector()
(1, 6, 12, 8, 1)
```

For unbounded polyhedra, an error is raised:

# edges(names=True, algorithm=None)

Return the edges of the polyhedron, i.e. the rank 1 faces.

INPUT:

• names – boolean (default: True); if False, then the Vrepresentatives in the edges are given by their indices in the Vrepresentation

• algorithm – string (optional); specify whether the face generator starts with facets or vertices: \* 'primal' – start with the facets \* 'dual' – start with the vertices \* None – choose automatically

**Note:** To compute edges and f\_vector, first compute the edges. This might be faster.

#### **EXAMPLES:**

```
sage: P = polytopes.cyclic_polytope(3,5)
sage: C = CombinatorialPolyhedron(P)
sage: C.edges()
((A vertex at (3, 9, 27), A vertex at (4, 16, 64)),
 (A vertex at (2, 4, 8), A vertex at (4, 16, 64)),
 (A vertex at (1, 1, 1), A vertex at (4, 16, 64)),
 (A vertex at (0, 0, 0), A vertex at (4, 16, 64)),
 (A vertex at (2, 4, 8), A vertex at (3, 9, 27)),
 (A vertex at (0, 0, 0), A vertex at (3, 9, 27)),
 (A vertex at (1, 1, 1), A vertex at (2, 4, 8)),
 (A vertex at (0, 0, 0), A vertex at (2, 4, 8)),
(A vertex at (0, 0, 0), A vertex at (1, 1, 1))
sage: C.edges(names=False)
((3, 4), (2, 4), (1, 4), (0, 4), (2, 3), (0, 3), (1, 2), (0, 2), (0, 1))
sage: P = Polyhedron(rays=[[-1,0],[1,0]])
sage: C = CombinatorialPolyhedron(P)
sage: C.edges()
((A line in the direction (1, 0), A vertex at (0, 0)),)
sage: P = Polyhedron(vertices=[[0,0],[1,0]])
sage: C = CombinatorialPolyhedron(P)
sage: C.edges()
((A vertex at (0, 0), A vertex at (1, 0)),)
sage: from itertools import combinations
sage: N = combinations(['a','b','c','d','e'], 4)
sage: C = CombinatorialPolyhedron(N)
sage: C.edges()
(('d', 'e'),
 ('c', 'e'),
 ('b', 'e'),
 ('a', 'e'),
 ('c', 'd'),
 ('b', 'd'),
 ('a', 'd'),
 ('b', 'c'),
 ('a', 'c'),
 ('a', 'b'))
```

**f\_vector**(num\_threads=None, parallelization\_depth=None, algorithm=None)
Compute the **f\_vector** of the polyhedron.

The f\_vector contains the number of faces of dimension k for each k in range(-1, self.dimension() + 1).

### INPUT:

- num\_threads integer (optional); specify the number of threads
- parallelization\_depth integer (optional); specify how deep in the lattice the parallelization is done
- algorithm string (optional); specify whether the face generator starts with facets or vertices:
  - 'primal' start with the facets
  - 'dual' start with the vertices
  - None choose automatically

**Note:** To obtain edges and/or ridges as well, first do so. This might already compute the f\_vector.

### **EXAMPLES:**

# Using two threads:

### face\_by\_face\_lattice\_index(index)

Return the element of CombinatorialPolyhedron.face\_lattice() with corresponding index.

The element will be returned as CombinatorialFace.

```
sage: G.level_sets()[0]
                                                                     # optional -
→ sage.combinat
[A -1-dimensional face of a 3-dimensional combinatorial polyhedron]
sage: G.level_sets()[3]
                                                                     # optional -
→ sage.combinat
[A 2-dimensional face of a 3-dimensional combinatorial polyhedron,
A 2-dimensional face of a 3-dimensional combinatorial polyhedron]
sage: P = Polyhedron(rays=[[0,1], [1,0]])
sage: C = CombinatorialPolyhedron(P)
sage: F = C.face_lattice()
                                                                     # optional -
→ sage.combinat
sage: G = F.relabel(C.face_by_face_lattice_index)
                                                                     # optional -
→ sage.combinat
sage: G._elements
                                                                     # optional -
→ sage.combinat
(A -1-dimensional face of a 2-dimensional combinatorial polyhedron,
 A 0-dimensional face of a 2-dimensional combinatorial polyhedron,
 A 1-dimensional face of a 2-dimensional combinatorial polyhedron,
 A 1-dimensional face of a 2-dimensional combinatorial polyhedron,
 A 2-dimensional face of a 2-dimensional combinatorial polyhedron)
sage: def f(i): return C.face_by_face_lattice_index(i).ambient_V_indices()
sage: G = F.relabel(f)
                                                                     # optional -
→ sage.combinat
sage: G._elements
                                                                     # optional -
→ sage.combinat
((), (0,), (0, 1), (0, 2), (0, 1, 2))
```

### face\_generator(dimension=None, algorithm=None, \*\*kwds)

Iterator over all proper faces of specified dimension.

### INPUT:

- dimension if specified, then iterate over only this dimension
- algorithm string (optional); specify whether the face generator starts with facets or vertices:
  - 'primal' start with the facets
  - 'dual' start with the vertices
  - None choose automatically

### OUTPUT:

• FaceIterator

**Note:** FaceIterator can ignore subfaces or supfaces of the current face.

```
sage: P = polytopes.permutahedron(5)
                                                                     # optional -
→ sage.combinat
sage: C = CombinatorialPolyhedron(P)
                                                                      # optional -
→ sage.combinat
sage: it = C.face_generator(dimension=2)
                                                                      # optional -
→ sage.combinat
sage: face = next(it); face
                                                                     # optional -
→ sage.combinat
A 2-dimensional face of a 4-dimensional combinatorial polyhedron
sage: face.ambient_Vrepresentation()
                                                                      # optional -
→ sage.combinat
(A vertex at (1, 3, 2, 5, 4),
A vertex at (2, 3, 1, 5, 4),
A vertex at (3, 1, 2, 5, 4),
A vertex at (3, 2, 1, 5, 4),
A vertex at (2, 1, 3, 5, 4),
A vertex at (1, 2, 3, 5, 4)
sage: face = next(it); face
                                                                      # optional -
→ sage.combinat
A 2-dimensional face of a 4-dimensional combinatorial polyhedron
sage: face.ambient_Vrepresentation()
                                                                      # optional -
→ sage.combinat
(A vertex at (2, 1, 4, 5, 3),
A vertex at (3, 2, 4, 5, 1),
A vertex at (3, 1, 4, 5, 2),
A vertex at (1, 3, 4, 5, 2),
A vertex at (1, 2, 4, 5, 3),
A vertex at (2, 3, 4, 5, 1))
sage: face.ambient_Hrepresentation()
                                                                      # optional -
→ sage.combinat
(An inequality (0, 0, -1, -1, 0) x + 9 >= 0,
An inequality (0, 0, 0, -1, 0) x + 5 >= 0,
An equation (1, 1, 1, 1, 1) \times -15 == 0
sage: face.ambient_H_indices()
                                                                      # optional -
→ sage.combinat
(25, 29, 30)
                                                                      # optional -
sage: face = next(it); face
→ sage.combinat
A 2-dimensional face of a 4-dimensional combinatorial polyhedron
sage: face.ambient_H_indices()
                                                                     # optional -
→ sage.combinat
(24, 29, 30)
sage: face.ambient_V_indices()
                                                                      # optional -
→ sage.combinat
(32, 89, 90, 94)
sage: C = CombinatorialPolyhedron([[0,1,2],[0,1,3],[0,2,3],[1,2,3]])
sage: it = C.face_generator()
sage: for face in it: face.ambient_Vrepresentation()
(1, 2, 3)
(0, 2, 3)
(0, 1, 3)
(0, 1, 2)
                                                                   (continues on next page)
```

```
(2, 3)
(1, 3)
(1, 2)
(3,)
(2,)
(1,)
(0, 3)
(0, 2)
(0,)
(0, 1)
sage: P = Polyhedron(rays=[[1,0],[0,1]], vertices=[[1,0],[0,1]])
sage: C = CombinatorialPolyhedron(P)
sage: it = C.face_generator(1)
sage: for face in it: face.ambient_Vrepresentation()
(A vertex at (0, 1), A vertex at (1, 0))
(A ray in the direction (1, 0), A vertex at (1, 0))
(A ray in the direction (0, 1), A vertex at (0, 1))
```

#### See also:

FaceIterator, CombinatorialFace.

face\_iter(dimension=None, algorithm=None, \*\*kwds)

Iterator over all proper faces of specified dimension.

### INPUT:

- dimension if specified, then iterate over only this dimension
- algorithm string (optional); specify whether the face generator starts with facets or vertices:
  - 'primal' start with the facets
  - 'dual' start with the vertices
  - None choose automatically

# OUTPUT:

• FaceIterator

**Note:** FaceIterator can ignore subfaces or supfaces of the current face.

```
sage: P = polytopes.permutahedron(5)
                                                                       # optional -
→ sage.combinat
sage: C = CombinatorialPolyhedron(P)
                                                                       # optional -
→ sage.combinat
sage: it = C.face_generator(dimension=2)
                                                                       # optional -
→ sage.combinat
sage: face = next(it); face
                                                                       # optional -
→ sage.combinat
A 2-dimensional face of a 4-dimensional combinatorial polyhedron
sage: face.ambient_Vrepresentation()
                                                                       # optional -

→ sage.combinat

                                                                    (continues on next page)
```

```
(A \text{ vertex at } (1, 3, 2, 5, 4),
A vertex at (2, 3, 1, 5, 4),
A vertex at (3, 1, 2, 5, 4),
A vertex at (3, 2, 1, 5, 4),
A vertex at (2, 1, 3, 5, 4),
A vertex at (1, 2, 3, 5, 4)
sage: face = next(it); face
                                                                      # optional -
→ sage.combinat
A 2-dimensional face of a 4-dimensional combinatorial polyhedron
sage: face.ambient_Vrepresentation()
                                                                      # optional -
→ sage.combinat
(A vertex at (2, 1, 4, 5, 3),
A vertex at (3, 2, 4, 5, 1),
A vertex at (3, 1, 4, 5, 2),
A vertex at (1, 3, 4, 5, 2),
A vertex at (1, 2, 4, 5, 3),
A vertex at (2, 3, 4, 5, 1)
sage: face.ambient_Hrepresentation()
                                                                      # optional -
→ sage.combinat
(An inequality (0, 0, -1, -1, 0) x + 9 >= 0,
An inequality (0, 0, 0, -1, 0) \times + 5 >= 0,
An equation (1, 1, 1, 1, 1) \times -15 == 0)
sage: face.ambient_H_indices()
                                                                      # optional -
→ sage.combinat
(25, 29, 30)
sage: face = next(it); face
                                                                      # optional -
→ sage.combinat
A 2-dimensional face of a 4-dimensional combinatorial polyhedron
sage: face.ambient_H_indices()
                                                                      # optional -
→ sage.combinat
(24, 29, 30)
sage: face.ambient_V_indices()
                                                                      # optional -
→ sage.combinat
(32, 89, 90, 94)
sage: C = CombinatorialPolyhedron([[0,1,2],[0,1,3],[0,2,3],[1,2,3]])
sage: it = C.face_generator()
sage: for face in it: face.ambient_Vrepresentation()
(1, 2, 3)
(0, 2, 3)
(0, 1, 3)
(0, 1, 2)
(2, 3)
(1, 3)
(1, 2)
(3,)
(2,)
(1,)
(0, 3)
(0, 2)
(0,)
(0, 1)
```

```
sage: P = Polyhedron(rays=[[1,0],[0,1]], vertices=[[1,0],[0,1]])
sage: C = CombinatorialPolyhedron(P)
sage: it = C.face_generator(1)
sage: for face in it: face.ambient_Vrepresentation()
(A vertex at (0, 1), A vertex at (1, 0))
(A ray in the direction (1, 0), A vertex at (1, 0))
(A ray in the direction (0, 1), A vertex at (0, 1))
```

#### See also:

FaceIterator, CombinatorialFace.

### face\_lattice()

Generate the face-lattice.

#### OUTPUT:

• FiniteLatticePoset

**Note:** Use *CombinatorialPolyhedron.face\_by\_face\_lattice\_index()* to get the face for each index.

**Warning:** The labeling of the face lattice might depend on architecture and implementation. Relabeling the face lattice with *CombinatorialPolyhedron.face\_by\_face\_lattice\_index()* or the properties obtained from this face will be platform independent.

### **EXAMPLES:**

```
sage: P = Polyhedron(rays=[[1,0],[0,1]])
sage: C = CombinatorialPolyhedron(P)
sage: C.face_lattice()
Finite lattice containing 5 elements
sage: P = Polyhedron(rays=[[1,0,0], [-1,0,0], [0,-1,0], [0,1,0]])
sage: C = CombinatorialPolyhedron(P)
sage: P1 = Polyhedron(rays=[[1,0], [-1,0]])
sage: C1 = CombinatorialPolyhedron(P1)
sage: C.face_lattice().is_isomorphic(C1.face_lattice())
True
sage: P = polytopes.permutahedron(5)
                                                                     # optional -
→ sage.combinat
sage: C = CombinatorialPolyhedron(P)
                                                                     # optional -
→ sage.combinat
sage: C.face_lattice()
                                                                     # optional -
→ sage.combinat
Finite lattice containing 542 elements
```

### facet\_adjacency\_matrix(algorithm=None)

Return the binary matrix of facet adjacencies.

INPUT:

• algorithm — string (optional); specify whether the face generator starts with facets or vertices: \* 'primal' — start with the facets \* 'dual' — start with the vertices \* None — choose automatically

#### See also:

vertex\_adjacency\_matrix().

### **EXAMPLES**:

```
sage: P = polytopes.cube()
sage: C = P.combinatorial_polyhedron()
sage: C.facet_adjacency_matrix()
[0 1 1 0 1 1]
[1 0 1 1 1 0]
[1 1 0 1 0 1]
[0 1 1 0 1 0 1]
[1 1 0 1 0 1]
[1 1 0 1 0 1]
```

# facet\_graph(names=True, algorithm=None)

Return the facet graph.

The facet graph of a polyhedron consists of ridges as edges and facets as vertices.

#### INPUT:

- algorithm string (optional); specify whether the face generator starts with facets or vertices:
  - 'primal' start with the facets
  - 'dual' start with the vertices
  - None choose automatically

If names is False, the vertices of the graph will be the indices of the facets in the Hrepresentation.

### **EXAMPLES**:

```
sage: P = polytopes.cyclic_polytope(4,6)
sage: C = CombinatorialPolyhedron(P)
sage: C.facet_graph()
Graph on 9 vertices
```

# facets(names=True)

Return the facets as lists of [vertices, rays, lines].

If names is False, then the Vrepresentatives in the facets are given by their indices in the Vrepresentation.

The facets are the maximal nontrivial faces.

### **EXAMPLES:**

```
sage: P = polytopes.cube()
sage: C = CombinatorialPolyhedron(P)
sage: C.facets()
((A vertex at (1, -1, -1),
    A vertex at (1, 1, -1),
    A vertex at (1, 1, 1),
    A vertex at (1, -1, 1)),
    (A vertex at (1, 1, -1),
    A vertex at (1, 1, -1),
    (A vertex at (1, 1, -1),
    (A vertex at (1, 1, 1),
```

```
A vertex at (-1, 1, -1),
 A vertex at (-1, 1, 1),
 (A vertex at (1, 1, 1),
 A vertex at (1, -1, 1),
 A vertex at (-1, -1, 1),
 A vertex at (-1, 1, 1),
 (A vertex at (-1, -1, 1),
 A vertex at (-1, -1, -1),
 A vertex at (-1, 1, -1),
 A vertex at (-1, 1, 1),
 (A vertex at (1, -1, -1),
 A vertex at (1, 1, -1),
 A vertex at (-1, -1, -1),
 A vertex at (-1, 1, -1),
 (A vertex at (1, -1, -1),
 A vertex at (1, -1, 1),
 A vertex at (-1, -1, 1),
 A vertex at (-1, -1, -1))
sage: C.facets(names=False)
((0, 1, 2, 3),
(1, 2, 6, 7),
 (2, 3, 4, 7),
 (4, 5, 6, 7),
 (0, 1, 5, 6),
 (0, 3, 4, 5))
```

The empty face is trivial and hence the 0-dimensional polyhedron does not have facets:

```
sage: C = CombinatorialPolyhedron(0)
sage: C.facets()
()
```

### flag\_f\_vector(\*args)

Return the flag f-vector.

For each  $-1 < i_0 < \cdots < i_n < d$  the flag f-vector counts the number of flags  $F_0 \subset \cdots \subset F_n$  with  $F_j$  of dimension  $i_j$  for each  $0 \le j \le n$ , where d is the dimension of the polyhedron.

### INPUT:

• args – integers (optional); specify an entry of the flag-f-vector; must be an increasing sequence of integers

### **OUTPUT**:

- · a dictionary, if no arguments were given
- an Integer, if arguments were given

# **EXAMPLES:**

Obtain the entire flag-f-vector:

```
\{(-1,): 1,
 (0,): 16,
 (0, 1): 64,
 (0, 1, 2): 192,
 (0, 1, 2, 3): 384,
 (0, 1, 3): 192,
 (0, 2): 96,
 (0, 2, 3): 192,
 (0, 3): 64,
 (1,): 32,
 (1, 2): 96,
 (1, 2, 3): 192,
 (1, 3): 96,
 (2,): 24,
 (2, 3): 48,
 (3,):8,
 (4,): 1
```

Specify an entry:

```
sage: C.flag_f_vector(0,3)  # optional -
sage.combinat
64
sage: C.flag_f_vector(2)  # optional -
sage.combinat
24
```

Leading -1 and trailing entry of dimension are allowed:

```
sage: C.flag_f_vector(-1,0,3)  # optional -
    sage.combinat
64
sage: C.flag_f_vector(-1,0,3,4)  # optional -
    sage.combinat
64
```

One can get the number of trivial faces:

Polyhedra with lines, have 0 entries accordingly:

If the arguments are not stricly increasing or out of range, a key error is raised:

### graph(names=True, algorithm=None)

Return a graph in which the vertices correspond to vertices of the polyhedron, and edges to bounded rank 1 faces.

### INPUT:

- names boolean (default: True); if False, then the nodes of the graph are labeld by the indices of the Vrepresentation
- algorithm string (optional); specify whether the face generator starts with facets or vertices: \* 'primal' start with the facets \* 'dual' start with the vertices \* None choose automatically

### **EXAMPLES:**

```
sage: P = polytopes.cyclic_polytope(3,5)
sage: C = CombinatorialPolyhedron(P)
sage: C.vertex_graph()
Graph on 5 vertices
sage: G = C.vertex_graph()
sage: sorted(G.degree())
[3, 3, 4, 4, 4]

sage: P = Polyhedron(rays=[[1]])
sage: C = CombinatorialPolyhedron(P)
sage: C.graph()
Graph on 1 vertex
```

### hasse\_diagram()

Return the Hasse diagram of self.

This is the Hasse diagram of the poset of the faces of self: A directed graph consisting of a vertex for each face and an edge for each minimal inclusion of faces.

**Note:** The vertices of the Hasse diagram are given by indices. Use *CombinatorialPolyhedron*.  $face\_by\_face\_lattice\_index()$  to relabel.

**Warning:** The indices of the Hasse diagram might depend on architecture and implementation. Relabeling the face lattice with *CombinatorialPolyhedron.face\_by\_face\_lattice\_index()* or the properties obtained from this face will be platform independent

#### **EXAMPLES:**

```
sage: P = polytopes.regular_polygon(4).pyramid()
                                                                            #. .
→optional - sage.rings.number_field
sage: C = CombinatorialPolyhedron(P)
                                                                            #.
→optional - sage.rings.number_field
                                                  # optional - sage.graphs
sage: D = C.hasse_diagram(); D
→optional - sage.rings.number_field
Digraph on 20 vertices
sage: D.average_degree()
                                                  # optional - sage.graphs #_
→optional - sage.rings.number_field
21/5
sage: D.relabel(C.face_by_face_lattice_index)
                                                  # optional - sage.graphs #_
→optional - sage.rings.number_field
sage: dim_0_vert = D.vertices(sort=True)[1:6]; dim_0_vert # optional - sage.
→graphs # optional - sage.rings.number_field
[A 0-dimensional face of a 3-dimensional combinatorial polyhedron,
A 0-dimensional face of a 3-dimensional combinatorial polyhedron,
A 0-dimensional face of a 3-dimensional combinatorial polyhedron,
A 0-dimensional face of a 3-dimensional combinatorial polyhedron.
A 0-dimensional face of a 3-dimensional combinatorial polyhedron]
sage: sorted(D.out_degree(vertices=dim_0_vert)) # optional - sage.graphs #_
→optional - sage.rings.number_field
[3, 3, 3, 3, 4]
```

### incidence\_matrix()

Return the incidence matrix.

**Note:** The columns correspond to inequalities/equations in the order *Hrepresentation()*, the rows correspond to vertices/rays/lines in the order *Vrepresentation()*.

#### See also:

incidence\_matrix().

**EXAMPLES**:

```
sage: P = polytopes.cube()
sage: C = P.combinatorial_polyhedron()
sage: C.incidence_matrix()
[1 0 0 0 1 1]
[1 1 0 0 0 1 0]
[1 1 1 0 0 0]
[1 0 1 0 0 1]
[0 0 1 1 0 1]
[0 0 0 1 1 1 0]
[0 1 0 1 1 0]
```

In this case the incidence matrix is only computed once:

```
sage: P.incidence_matrix() is C.incidence_matrix()
True
sage: C.incidence_matrix.clear_cache()
sage: C.incidence_matrix() is P.incidence_matrix()
```

```
False
sage: C.incidence_matrix() == P.incidence_matrix()
True
```

The incidence matrix is consistent with incidence\_matrix():

```
sage: P = Polyhedron([[0,0]])
sage: P.incidence_matrix()
[1 1]
sage: C = P.combinatorial_polyhedron()
sage: C.incidence_matrix.clear_cache()
sage: P.combinatorial_polyhedron().incidence_matrix()
[1 1]
```

### is\_bipyramid(certificate=False)

Test whether the polytope is a bipyramid over some other polytope.

### INPUT:

• certificate – boolean (default: False); specifies whether to return a vertex of the polytope which is the apex of a pyramid, if found

### INPUT:

• certificate – boolean (default: False); specifies whether to return two vertices of the polytope which are the apices of a bipyramid, if found

## **OUTPUT**:

If certificate is True, returns a tuple containing:

- 1. Boolean.
- 2. None or a tuple containing:
  - a. The first apex.
  - b. The second apex.

If certificate is False returns a boolean.

# **EXAMPLES:**

```
sage: C = polytopes.hypercube(4).combinatorial_polyhedron()
sage: C.is_bipyramid()
False
sage: C.is_bipyramid(certificate=True)
(False, None)
```

```
sage: C = polytopes.cross_polytope(4).combinatorial_polyhedron()
sage: C.is_bipyramid()
True
sage: C.is_bipyramid(certificate=True)
(True, [A vertex at (1, 0, 0, 0), A vertex at (-1, 0, 0, 0)])
```

For unbounded polyhedra, an error is raised:

### ALGORITHM:

Assume all faces of a polyhedron to be given as lists of vertices.

A polytope is a bipyramid with apexes v, w if and only if for each proper face  $v \in F$  there exists a face G with  $G \setminus \{w\} = F \setminus \{v\}$  and vice versa (for each proper face  $w \in F$  there exists ...).

To check this property it suffices to check for all facets of the polyhedron.

#### is\_compact()

Return whether the polyhedron is compact

#### **EXAMPLES:**

```
sage: C = CombinatorialPolyhedron([[0,1], [0,2]], far_face=[1,2],
unbounded=True)
sage: C.is_compact()
False
sage: C = CombinatorialPolyhedron([[0,1], [0,2], [1,2]])
sage: C.is_compact()
True
sage: P = polytopes.simplex()
sage: P.combinatorial_polyhedron().is_compact()
True
sage: P = Polyhedron(rays=P.vertices())
sage: P.combinatorial_polyhedron().is_compact()
False
```

# is\_lawrence\_polytope()

Return True if self is a Lawrence polytope.

A polytope is called a Lawrence polytope if it has a centrally symmetric (normalized) Gale diagram.

Equivalently, there exists a partition  $P_1, \dots, P_k$  of the vertices V such that each part  $P_i$  has size 2 or 1 and for each part there exists a facet with vertices exactly  $V \setminus P_i$ .

### **EXAMPLES:**

```
sage: C = polytopes.simplex(5).combinatorial_polyhedron()
sage: C.is_lawrence_polytope()
True
```

```
sage: P = polytopes.hypercube(4).lawrence_polytope()
sage: C = P.combinatorial_polyhedron()
sage: C.is_lawrence_polytope()
True
sage: P = polytopes.hypercube(4)
sage: C = P.combinatorial_polyhedron()
sage: C.is_lawrence_polytope()
False
```

For unbounded polyhedra, an error is raised:

```
sage: C = CombinatorialPolyhedron([[0,1], [0,2]], far_face=[1,2],
unbounded=True)
sage: C.is_lawrence_polytope()
Traceback (most recent call last):
...
NotImplementedError: this function is implemented for polytopes only
```

### **AUTHORS:**

- · Laith Rastanawi
- · Jonathan Kliem

#### REFERENCES:

For more information, see [BaSt1990].

### is\_neighborly(k=None)

Return whether the polyhedron is neighborly.

If the input k is provided, then return whether the polyhedron is k-neighborly.

A polyhedron is neighborly if every set of n vertices forms a face for n up to floor of half the dimension of the polyhedron. It is k-neighborly if this is true for n up to k.

# INPUT:

• k – the dimension up to which to check if every set of k vertices forms a face. If no k is provided, check up to floor of half the dimension of the polyhedron.

#### **OUTPUT**:

- True if the every set of up to k vertices forms a face,
- · False otherwise

### See also:

neighborliness()

### **EXAMPLES:**

```
sage: P = polytopes.cyclic_polytope(8,12)
sage: C = P.combinatorial_polyhedron()
sage: C.is_neighborly()
True
sage: P = polytopes.simplex(6)
sage: C = P.combinatorial_polyhedron()
sage: C.is_neighborly()
```

```
True
sage: P = polytopes.cyclic_polytope(4,10)
sage: P = P.join(P)
sage: C = P.combinatorial_polyhedron()
sage: C.is_neighborly()
False
sage: C.is_neighborly(k=2)
True
```

# is\_prism(certificate=False)

Test whether the polytope is a prism of some polytope.

### INPUT:

• certificate – boolean (default: False); specifies whether to return two facets of the polytope which are the bases of a prism, if found

#### **OUTPUT:**

If certificate is True, returns a tuple containing:

- 1. Boolean.
- 2. None or a tuple containing:
  - a. List of the vertices of the first base facet.
  - b. List of the vertices of the second base facet.

If certificate is False returns a boolean.

# is\_pyramid(certificate=False)

Test whether the polytope is a pyramid over one of its facets.

### INPUT:

• certificate – boolean (default: False); specifies whether to return a vertex of the polytope which is the apex of a pyramid, if found

# OUTPUT:

If certificate is True, returns a tuple containing:

- 1. Boolean.
- 2. The apex of the pyramid or None.

If certificate is False returns a boolean.

# **AUTHORS:**

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### **EXAMPLES:**

```
sage: C = polytopes.cross_polytope(4).combinatorial_polyhedron()
sage: C.is_pyramid()
False
sage: C.is_pyramid(certificate=True)
(False, None)
sage: C = polytopes.cross_polytope(4).pyramid().combinatorial_polyhedron()
```

```
sage: C.is_pyramid()
True
sage: C.is_pyramid(certificate=True)
(True, A vertex at (1, 0, 0, 0, 0))
sage: C = polytopes.simplex(5).combinatorial_polyhedron()
sage: C.is_pyramid(certificate=True)
(True, A vertex at (1, 0, 0, 0, 0, 0))
```

For unbounded polyhedra, an error is raised:

#### is\_simple()

Test whether the polytope is simple.

If the polyhedron is unbounded, return False.

A polytope is simple, if each vertex is contained in exactly d facets, where d is the dimension of the polytope.

### **EXAMPLES:**

```
sage: P = polytopes.cyclic_polytope(4,10)
sage: C = P.combinatorial_polyhedron()
sage: C.is_simple()
False
sage: P = polytopes.hypercube(4)
sage: C = P.combinatorial_polyhedron()
sage: C.is_simple()
True
```

Return False for unbounded polyhedra:

# is\_simplex()

Return whether the polyhedron is a simplex.

A simplex is a bounded polyhedron with d+1 vertices, where d is the dimension.

### **EXAMPLES:**

```
sage: CombinatorialPolyhedron(2).is_simplex()
False
sage: CombinatorialPolyhedron([[0,1],[0,2],[1,2]]).is_simplex()
True
```

# is\_simplicial()

Test whether the polytope is simplicial.

This method is not implemented for unbounded polyhedra.

A polytope is simplicial, if each facet contains exactly d vertices, where d is the dimension of the polytope.

### **EXAMPLES:**

```
sage: P = polytopes.cyclic_polytope(4,10)
sage: C = P.combinatorial_polyhedron()
sage: C.is_simplicial()
True
sage: P = polytopes.hypercube(4)
sage: C = P.combinatorial_polyhedron()
sage: C.is_simplicial()
False
```

For unbounded polyhedra, an error is raised:

### join\_of\_Vrep(\*indices)

Return the smallest face containing all Vrepresentatives indicated by the indices.

### See also:

join\_of\_Vrep().

**EXAMPLES:** 

```
sage: P = polytopes.permutahedron(4)
                                                                     # optional -
→ sage.combinat
sage: C = CombinatorialPolyhedron(P)
                                                                     # optional -
→ sage.combinat
sage: C.join_of_Vrep(0,1)
                                                                     # optional -
→ sage.combinat
A 1-dimensional face of a 3-dimensional combinatorial polyhedron
sage: C.join_of_Vrep(0,11).ambient_V_indices()
                                                                     # optional -
→ sage.combinat
(0, 1, 10, 11, 12, 13)
sage: C.join_of_Vrep(8).ambient_V_indices()
                                                                     # optional -
→ sage.combinat
(8,)
sage: C.join_of_Vrep().ambient_V_indices()
                                                                     # optional -
→ sage.combinat
()
```

# meet\_of\_Hrep(\*indices)

Return the largest face contained in all facets indicated by the indices.

# See also:

```
meet_of_Hrep().
```

**EXAMPLES:** 

```
sage: P = polytopes.dodecahedron()
                                                                     # optional -
→ sage.rings.number_field
sage: C = CombinatorialPolyhedron(P)
                                                                     # optional -
→ sage.rings.number_field
sage: C.meet_of_Hrep(0)
                                                                     # optional -
→ sage.rings.number_field
A 2-dimensional face of a 3-dimensional combinatorial polyhedron
sage: C.meet_of_Hrep(0).ambient_H_indices()
                                                                     # optional -
→ sage.rings.number_field
(0,)
                                                                     # optional -
sage: C.meet_of_Hrep(0,1).ambient_H_indices()
→ sage.rings.number_field
(0, 1)
sage: C.meet_of_Hrep(0,2).ambient_H_indices()
                                                                     # optional -
→ sage.rings.number_field
(0, 2)
sage: C.meet_of_Hrep(0,2,3).ambient_H_indices()
                                                                     # optional -
→ sage.rings.number_field
(0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11)
sage: C.meet_of_Hrep().ambient_H_indices()
                                                                     # optional -
→ sage.rings.number_field
()
```

# n\_facets()

Return the number of facets.

Is equivalent to len(self.facets()).

# **EXAMPLES:**

```
sage: P = polytopes.cube()
sage: C = CombinatorialPolyhedron(P)
sage: C.n_facets()
sage: P = polytopes.cyclic_polytope(4,20)
sage: C = CombinatorialPolyhedron(P)
sage: C.n_facets()
170
sage: P = Polyhedron(lines=[[0,1]], vertices=[[1,0], [-1,0]])
sage: C = CombinatorialPolyhedron(P)
sage: C.n_facets()
sage: P = Polyhedron(rays=[[1,0], [-1,0], [0,1]])
sage: C = CombinatorialPolyhedron(P)
sage: C.n_facets()
sage: C = CombinatorialPolyhedron(-1)
sage: C.f_vector()
(1)
sage: C.n_facets()
```

```
0
```

Facets are defined to be the maximal nontrivial faces. The 0-dimensional polyhedron does not have non-trivial faces:

```
sage: C = CombinatorialPolyhedron(0)
sage: C.f_vector()
(1, 1)
sage: C.n_facets()
0
```

### n\_vertices()

Return the number of vertices.

Is equivalent to len(self.vertices()).

### **EXAMPLES:**

```
sage: P = polytopes.cube()
sage: C = CombinatorialPolyhedron(P)
sage: C.n_vertices()
sage: P = polytopes.cyclic_polytope(4,20)
sage: C = CombinatorialPolyhedron(P)
sage: C.n_vertices()
20
sage: P = Polyhedron(lines=[[0,1]], vertices=[[1,0], [-1,0]])
sage: C = CombinatorialPolyhedron(P)
sage: C.n_vertices()
sage: P = Polyhedron(rays=[[1,0,0], [0,1,0]], lines=[[0,0,1]])
sage: C = CombinatorialPolyhedron(P)
sage: C.n_vertices()
sage: C = CombinatorialPolyhedron(4)
sage: C.f_vector()
(1, 0, 0, 0, 0, 1)
sage: C.n_vertices()
sage: C = CombinatorialPolyhedron(0)
sage: C.f_vector()
(1, 1)
sage: C.n_vertices()
1
```

### neighborliness()

Return the largest k, such that the polyhedron is k-neighborly.

A polyhedron is k-neighborly if every set of n vertices forms a face for n up to k.

In case of the d-dimensional simplex, it returns d + 1.

### See also:

```
is_neighborly()
```

### **EXAMPLES:**

```
sage: P = polytopes.cyclic_polytope(8,12)
sage: C = P.combinatorial_polyhedron()
sage: C.neighborliness()
4
sage: P = polytopes.simplex(6)
sage: C = P.combinatorial_polyhedron()
sage: C.neighborliness()
7
sage: P = polytopes.cyclic_polytope(4,10)
sage: P = P.join(P)
sage: C = P.combinatorial_polyhedron()
sage: C.neighborliness()
2
```

#### polar()

Return the dual/polar of self.

Only defined for bounded polyhedra.

### See also:

polar().

**EXAMPLES:** 

Polar is an alias to be consistent with *Polyhedron\_base*:

```
sage: C.polar().f_vector()
(1, 6, 12, 8, 1)
```

For unbounded polyhedra, an error is raised:

```
sage: C = CombinatorialPolyhedron([[0,1], [0,2]], far_face=[1,2],
unbounded=True)
sage: C.dual()
Traceback (most recent call last):
...
ValueError: self must be bounded
```

pyramid(new\_vertex=None, new\_facet=None)

Return the pyramid of self.

#### INPUT:

- new\_vertex (optional); specify a new vertex name to set up the pyramid with vertex names
- new\_facet (optional); specify a new facet name to set up the pyramid with facet names

#### **EXAMPLES:**

```
sage: C = CombinatorialPolyhedron(((1,2,3),(1,2,4),(1,3,4),(2,3,4)))
sage: C1 = C.pyramid()
sage: C1.facets()
((0, 1, 2, 4), (0, 1, 3, 4), (0, 2, 3, 4), (1, 2, 3, 4), (0, 1, 2, 3))
```

One can specify a name for the new vertex:

```
sage: P = polytopes.cyclic_polytope(4,10)
sage: C = P.combinatorial_polyhedron()
sage: C1 = C.pyramid(new_vertex='apex')
sage: C1.is_pyramid(certificate=True)
(True, 'apex')
sage: C1.facets()[0]
(A vertex at (0, 0, 0, 0),
A vertex at (1, 1, 1, 1),
A vertex at (2, 4, 8, 16),
A vertex at (3, 9, 27, 81),
'apex')
```

One can specify a name for the new facets:

```
sage: P = polytopes.regular_polygon(4)
                                                                     # optional -
→ sage.rings.number_field
sage: C = P.combinatorial_polyhedron()
                                                                      # optional -
→ sage.rings.number_field
                                                                     # optional -
sage: C1 = C.pyramid(new_facet='base')
→ sage.rings.number_field
                                                                      # optional -
sage: C1.Hrepresentation()
→ sage.rings.number_field
(An inequality (-1/2, 1/2) x + 1/2 >= 0,
An inequality (-1/2, -1/2) x + 1/2 >= 0,
An inequality (1/2, 0.50000000000000000) x + 1/2 >= 0,
An inequality (1/2, -1/2) \times + 1/2 >= 0,
 'base')
```

For unbounded polyhedra, an error is raised:

```
sage: C = CombinatorialPolyhedron([[0,1], [0,2]], far_face=[1,2],
    unbounded=True)
sage: C.pyramid()
Traceback (most recent call last):
...
ValueError: self must be bounded
```

**ridges**(add\_equations=False, names=True, add\_equalities=False, algorithm=None)
Return the ridges.

The ridges of a polyhedron are the faces contained in exactly two facets.

To obtain all faces of codimension 1 use CombinatorialPolyhedron.face\_generator() instead.

The ridges will be given by the facets, they are contained in.

### INPUT:

- add\_equations if True, then equations of the polyhedron will be added (only applicable when names is True)
- names boolean (default: True); if False, then the facets are given by their indices
- algorithm string (optional); specify whether the face generator starts with facets or vertices: \* 'primal' start with the facets \* 'dual' start with the vertices \* None choose automatically

**Note:** To compute ridges and f\_vector, compute the ridges first. This might be faster.

### **EXAMPLES:**

```
sage: P = polytopes.permutahedron(2)
                                                                      # optional -
→ sage.combinat
sage: C = CombinatorialPolyhedron(P)
                                                                      # optional -
→ sage.combinat
sage: C.ridges()
                                                                      # optional -
→ sage.combinat
((An inequality (1, 0) \times -1 >= 0, An inequality (-1, 0) \times +2 >= 0),)
sage: C.ridges(add_equations=True)
                                                                      # optional -
→ sage.combinat
(((An inequality (1, 0) x - 1 >= 0, An equation (1, 1) x - 3 == 0),
  (An inequality (-1, 0) x + 2 >= 0, An equation (1, 1) x - 3 == 0)),)
sage: P = polytopes.cyclic_polytope(4,5)
sage: C = CombinatorialPolyhedron(P)
sage: C.ridges()
((An inequality (24, -26, 9, -1) x + 0 >= 0,
 An inequality (-50, 35, -10, 1) x + 24 >= 0),
 (An inequality (-12, 19, -8, 1) x + 0 >= 0,
 An inequality (-50, 35, -10, 1) x + 24 >= 0),
 (An inequality (8, -14, 7, -1) x + 0 >= 0,
 An inequality (-50, 35, -10, 1) x + 24 >= 0),
 (An inequality (-6, 11, -6, 1) \times + 0 >= 0,
 An inequality (-50, 35, -10, 1) x + 24 >= 0),
 (An inequality (-12, 19, -8, 1) x + 0 >= 0,
 An inequality (24, -26, 9, -1) x + 0 >= 0),
```

```
(An inequality (8, -14, 7, -1) \times + 0 >= 0,
 An inequality (24, -26, 9, -1) x + 0 >= 0),
 (An inequality (-6, 11, -6, 1) x + 0 >= 0,
 An inequality (24, -26, 9, -1) \times + 0 >= 0),
 (An inequality (8, -14, 7, -1) \times + 0 >= 0,
 An inequality (-12, 19, -8, 1) x + 0 >= 0),
 (An inequality (-6, 11, -6, 1) x + 0 >= 0,
 An inequality (-12, 19, -8, 1) \times + 0 >= 0,
 (An inequality (-6, 11, -6, 1) x + 0 >= 0,
 An inequality (8, -14, 7, -1) \times + 0 >= 0)
sage: C.ridges(names=False)
((3, 4),
(2, 4),
 (1, 4),
 (0, 4),
 (2, 3),
 (1, 3),
 (0, 3),
 (1, 2),
 (0, 2),
(0, 1))
sage: P = Polyhedron(rays=[[1,0]])
sage: C = CombinatorialPolyhedron(P)
sage: C
A 1-dimensional combinatorial polyhedron with 1 facet
sage: C.ridges()
()
sage: it = C.face_generator(0)
sage: for face in it: face.ambient_Hrepresentation()
(An inequality (1, 0) x + 0 \ge 0, An equation (0, 1) x + 0 = 0)
```

### simpliciality()

Return the largest k such that the polytope is k-simplicial.

Return the dimension in case of a simplex.

A polytope is k-simplicial, if every k-face is a simplex.

#### **EXAMPLES:**

```
sage: cyclic = polytopes.cyclic_polytope(10,4)
sage: CombinatorialPolyhedron(cyclic).simpliciality()

sage: hypersimplex = polytopes.hypersimplex(5,2)
sage: CombinatorialPolyhedron(hypersimplex).simpliciality()

sage: cross = polytopes.cross_polytope(4)
sage: P = cross.join(cross)
sage: CombinatorialPolyhedron(P).simpliciality()
```

```
sage: P = polytopes.simplex(3)
sage: CombinatorialPolyhedron(P).simpliciality()
3
sage: P = polytopes.simplex(1)
sage: CombinatorialPolyhedron(P).simpliciality()
1
```

### simplicity()

Return the largest k such that the polytope is k-simple.

Return the dimension in case of a simplex.

A polytope P is k-simple, if every (d-1-k)-face is contained in exactly k+1 facets of P for  $1 \le k \le d-1$ .

Equivalently it is k-simple if the polar/dual polytope is k-simplicial.

#### **EXAMPLES:**

```
sage: hyper4 = polytopes.hypersimplex(4,2)
sage: CombinatorialPolyhedron(hyper4).simplicity()
1

sage: hyper5 = polytopes.hypersimplex(5,2)
sage: CombinatorialPolyhedron(hyper5).simplicity()
2

sage: hyper6 = polytopes.hypersimplex(6,2)
sage: CombinatorialPolyhedron(hyper6).simplicity()
3

sage: P = polytopes.simplex(3)
sage: CombinatorialPolyhedron(P).simplicity()
3

sage: P = polytopes.simplex(1)
sage: CombinatorialPolyhedron(P).simplicity()
```

## vertex\_adjacency\_matrix(algorithm=None)

Return the binary matrix of vertex adjacencies.

### INPUT:

• algorithm — string (optional); specify whether the face generator starts with facets or vertices: \* 'primal' — start with the facets \* 'dual' — start with the vertices \* None — choose automatically

### See also:

vertex\_adjacency\_matrix().

#### **EXAMPLES:**

```
sage: P = polytopes.cube()
sage: C = P.combinatorial_polyhedron()
sage: C.vertex_adjacency_matrix()
[0 1 0 1 0 1 0 0]
```

```
      [1 0 1 0 0 0 1 0]

      [0 1 0 1 0 0 0 1]

      [1 0 1 0 1 0 0 0]

      [0 0 0 1 0 1 0 1]

      [1 0 0 0 1 0 1 0]

      [0 1 0 0 0 1 0 1]

      [0 0 1 0 1 0 1 0]
```

# vertex\_facet\_graph(names=True)

Return the vertex-facet graph.

This method constructs a directed bipartite graph. The nodes of the graph correspond to elements of the Vrepresentation and facets. There is a directed edge from Vrepresentation to facets for each incidence.

If names is set to False, then the vertices (of the graph) are given by integers.

#### INPUT:

• names – boolean (default: True); if True label the vertices of the graph by the corresponding names of the Vrepresentation resp. Hrepresentation; if False label the vertices of the graph by integers

### **EXAMPLES:**

```
sage: P = polytopes.hypercube(2).pyramid()
sage: C = CombinatorialPolyhedron(P)
sage: G = C.vertex_facet_graph(); G
Digraph on 10 vertices
sage: C.Vrepresentation()
(A vertex at (0, -1, -1),
   A vertex at (0, -1, 1),
   A vertex at (0, 1, -1),
   A vertex at (0, 1, 1),
   A vertex at (1, 0, 0))
sage: sorted(G.neighbors_out(C.Vrepresentation()[4]))
[An inequality (-1, -1, 0) x + 1 >= 0,
   An inequality (-1, 0, -1) x + 1 >= 0,
   An inequality (-1, 0, 1) x + 1 >= 0,
   An inequality (-1, 1, 0) x + 1 >= 0]
```

If names is True (the default) but the combinatorial polyhedron has been initialized without specifying names to Vrepresentation and Hrepresentation, then indices of the Vrepresentation and the facets will be used along with a string 'H' or 'V':

If names is False then the vertices of the graph are given by integers:

```
sage: C.vertex_facet_graph(names=False).vertices(sort=True)
[0, 1, 2, 3, 4, 5, 6, 7, 8, 9]
```

### vertex\_graph(names=True, algorithm=None)

Return a graph in which the vertices correspond to vertices of the polyhedron, and edges to bounded rank 1 faces.

### INPUT:

- names boolean (default: True); if False, then the nodes of the graph are labeld by the indices of the Vrepresentation
- algorithm string (optional); specify whether the face generator starts with facets or vertices: \* 'primal' start with the facets \* 'dual' start with the vertices \* None choose automatically

### **EXAMPLES:**

```
sage: P = polytopes.cyclic_polytope(3,5)
sage: C = CombinatorialPolyhedron(P)
sage: C.vertex_graph()
Graph on 5 vertices
sage: G = C.vertex_graph()
sage: sorted(G.degree())
[3, 3, 4, 4, 4]

sage: P = Polyhedron(rays=[[1]])
sage: C = CombinatorialPolyhedron(P)
sage: C.graph()
Graph on 1 vertex
```

### vertices(names=True)

Return the elements in the Vrepresentation that are vertices.

In case of an unbounded polyhedron, there might be lines and rays in the Vrepresentation.

If names is set to False, then the vertices are given by their indices in the Vrepresentation.

#### **EXAMPLES:**

```
sage: P = Polyhedron(rays=[[1,0,0],[0,1,0],[0,0,1]])
sage: C = CombinatorialPolyhedron(P)
sage: C.vertices()
(A vertex at (0, 0, 0),)
sage: C.Vrepresentation()
(A vertex at (0, 0, 0),
A ray in the direction (0, 0, 1),
A ray in the direction (0, 1, 0),
A ray in the direction (1, 0, 0)
sage: P = polytopes.cross_polytope(3)
sage: C = CombinatorialPolyhedron(P)
sage: C.vertices()
(A vertex at (-1, 0, 0),
A vertex at (0, -1, 0),
A vertex at (0, 0, -1),
A vertex at (0, 0, 1),
```

```
A vertex at (0, 1, 0),
A vertex at (1, 0, 0))
sage: C.vertices(names=False)
(0, 1, 2, 3, 4, 5)
sage: points = [(1,0,0), (0,1,0), (0,0,1),
                (-1,0,0), (0,-1,0), (0,0,-1)]
sage: L = LatticePolytope(points)
sage: C = CombinatorialPolyhedron(L)
sage: C.vertices()
(M(1, 0, 0), M(0, 1, 0), M(0, 0, 1), M(-1, 0, 0), M(0, -1, 0), M(0, 0, -1))
sage: C.vertices(names=False)
(0, 1, 2, 3, 4, 5)
sage: P = Polyhedron(vertices=[[0,0]])
sage: C = CombinatorialPolyhedron(P)
sage: C.vertices()
(A vertex at (0, 0),)
```

# 2.3.2 Combinatorial face of a polyhedron

This module provides the combinatorial type of a polyhedral face.

### See also:

```
sage.geometry.polyhedron.combinatorial_polyhedron.base,
combinatorial_polyhedron.face_iterator.
sage.geometry.polyhedron.
```

### **EXAMPLES**:

Obtain a face from a face iterator:

```
sage: P = polytopes.cube()
sage: C = CombinatorialPolyhedron(P)
sage: it = C.face_generator()
sage: face = next(it); face
A 2-dimensional face of a 3-dimensional combinatorial polyhedron
```

Obtain a face from a face lattice index:

Obtain further information regarding a face:

```
sage: P = polytopes.octahedron()
sage: C = CombinatorialPolyhedron(P)
```

```
sage: it = C.face_generator(2)
sage: face = next(it); face
A 2-dimensional face of a 3-dimensional combinatorial polyhedron
sage: face.ambient_Vrepresentation()
(A vertex at (0, 0, 1), A vertex at (0, 1, 0), A vertex at (1, 0, 0))
sage: face.n_ambient_Vrepresentation()
3
sage: face.ambient_H_indices()
(5,)
sage: face.dimension()
2
sage: face.ambient_dimension()
3
```

#### See also:

sage.geometry.polyhedron.combinatorial\_polyhedron.base.CombinatorialPolyhedron.

### AUTHOR:

• Jonathan Kliem (2019-05)

#### class

sage.geometry.polyhedron.combinatorial\_polyhedron.combinatorial\_face.CombinatorialFace
Bases: sage.structure.sage\_object.SageObject

A class of the combinatorial type of a polyhedral face.

### **EXAMPLES:**

Obtain a combinatorial face from a face iterator:

```
sage: P = polytopes.cyclic_polytope(5,8)
sage: C = CombinatorialPolyhedron(P)
sage: it = C.face_generator()
sage: next(it)
A 0-dimensional face of a 5-dimensional combinatorial polyhedron
```

Obtain a combinatorial face from an index of the face lattice:

Obtain the dimension of a combinatorial face:

```
sage: face = next(it)
sage: face.dimension()
0
```

The dimension of the polyhedron:

```
sage: face.ambient_dimension()
5
```

The Vrepresentation:

```
sage: face.ambient_Vrepresentation()
(A vertex at (6, 36, 216, 1296, 7776),)
sage: face.ambient_V_indices()
(6,)
sage: face.n_ambient_Vrepresentation()
1
```

The Hrepresentation:

```
sage: face.ambient_Hrepresentation()
(An inequality (60, -112, 65, -14, 1) x + 0 >= 0,
An inequality (180, -216, 91, -16, 1) x + 0 >= 0,
An inequality (360, -342, 119, -18, 1) x + 0 >= 0,
An inequality (840, -638, 179, -22, 1) x + 0 >= 0,
An inequality (-2754, 1175, -245, 25, -1) x + 2520 >= 0,
An inequality (504, -450, 145, -20, 1) x + 0 >= 0,
An inequality (-1692, 853, -203, 23, -1) \times + 1260 >= 0,
An inequality (252, -288, 113, -18, 1) x + 0 >= 0,
An inequality (-844, 567, -163, 21, -1) x + 420 >= 0,
An inequality (84, -152, 83, -16, 1) x + 0 >= 0,
An inequality (-210, 317, -125, 19, -1) x + 0 >= 0)
sage: face.ambient_H_indices()
(3, 4, 5, 6, 7, 8, 9, 10, 11, 18, 19)
sage: face.n_ambient_Hrepresentation()
11
```

### ambient\_H\_indices(add\_equations=True)

Return the indices of the Hrepresentation objects of the ambient polyhedron defining the face.

### INPUT:

• add\_equations – boolean (default: True); whether or not to include the equations

### **EXAMPLES:**

```
# optional - sage.combinat
sage: P = polytopes.permutahedron(5)
sage: C = CombinatorialPolyhedron(P)
                                                     # optional - sage.combinat
sage: it = C.face_generator(2)
                                                     # optional - sage.combinat
sage: face = next(it)
                                                     # optional - sage.combinat
sage: face.ambient_H_indices(add_equations=False)
                                                     # optional - sage.combinat
(28, 29)
sage: face2 = next(it)
                                                     # optional - sage.combinat
sage: face2.ambient_H_indices(add_equations=False)
                                                     # optional - sage.combinat
(25, 29)
```

Add the indices of the equation:

```
sage: face.ambient_H_indices(add_equations=True) # optional - sage.combinat
(28, 29, 30)
```

```
sage: face2.ambient_H_indices(add_equations=True) # optional - sage.combinat
(25, 29, 30)
```

### Another example:

```
sage: P = polytopes.cyclic_polytope(4,6)
sage: C = CombinatorialPolyhedron(P)
sage: it = C.face_generator()
sage: _ = next(it); _ = next(it)
sage: next(it).ambient_H_indices()
(0, 1, 2, 4, 5, 7)
sage: next(it).ambient_H_indices()
(0, 1, 5, 6, 7, 8)
sage: next(it).ambient_H_indices()
(0, 1, 2, 3, 6, 8)
sage: [next(it).dimension() for _ in range(2)]
[0, 1]
sage: face = next(it)
sage: face.ambient_H_indices()
(4, 5, 7)
```

#### See also:

ambient\_Hrepresentation().

### ambient\_Hrepresentation()

Return the Hrepresentation objects of the ambient polyhedron defining the face.

It consists of the facets/inequalities that contain the face and the equations defining the ambient polyhedron.

# **EXAMPLES:**

```
sage: P = polytopes.permutahedron(5)
                                              # optional - sage.combinat
                                              # optional - sage.combinat
sage: C = CombinatorialPolyhedron(P)
sage: it = C.face_generator(2)
                                              # optional - sage.combinat
sage: next(it).ambient_Hrepresentation()
                                              # optional - sage.combinat
(An inequality (1, 1, 1, 0, 0) x - 6 >= 0,
An inequality (0, 0, 0, -1, 0) x + 5 >= 0,
An equation (1, 1, 1, 1, 1) \times -15 == 0
sage: next(it).ambient_Hrepresentation()
                                              # optional - sage.combinat
(An inequality (0, 0, -1, -1, 0) x + 9 >= 0,
An inequality (0, 0, 0, -1, 0) x + 5 >= 0,
An equation (1, 1, 1, 1, 1) \times -15 == 0)
sage: P = polytopes.cyclic_polytope(4,6)
sage: C = CombinatorialPolyhedron(P)
sage: it = C.face_generator()
sage: next(it).ambient_Hrepresentation()
(An inequality (-20, 29, -10, 1) x + 0 >= 0,
An inequality (60, -47, 12, -1) x + 0 >= 0,
An inequality (30, -31, 10, -1) \times + 0 >= 0,
An inequality (10, -17, 8, -1) x + 0 >= 0,
An inequality (-154, 71, -14, 1) x + 120 >= 0,
An inequality (-78, 49, -12, 1) x + 40 >= 0)
```

```
sage: next(it).ambient_Hrepresentation()
(An inequality (-50, 35, -10, 1) x + 24 >= 0,
An inequality (-12, 19, -8, 1) x + 0 >= 0,
An inequality (-20, 29, -10, 1) x + 0 >= 0,
An inequality (60, -47, 12, -1) x + 0 >= 0,
An inequality (-154, 71, -14, 1) x + 120 >= 0,
An inequality (-78, 49, -12, 1) x + 40 >= 0)
```

#### See also:

ambient\_H\_indices().

# ambient\_V\_indices()

Return the indices of the Vrepresentation objects of the ambient polyhedron defining the face.

### **EXAMPLES:**

```
sage: P = polytopes.permutahedron(5)
                                             # optional - sage.combinat
sage: C = CombinatorialPolyhedron(P)
                                             # optional - sage.combinat
sage: it = C.face_generator(dimension=2)
                                           # optional - sage.combinat
sage: face = next(it)
                                             # optional - sage.combinat
sage: next(it).ambient_V_indices()
                                             # optional - sage.combinat
(32, 91, 92, 93, 94, 95)
sage: next(it).ambient_V_indices()
                                             # optional - sage.combinat
(32, 89, 90, 94)
sage: C = CombinatorialPolyhedron([[0,1,2],[0,1,3],[0,2,3],[1,2,3]])
sage: it = C.face_generator()
sage: for face in it: (face.dimension(), face.ambient_V_indices())
(2, (1, 2, 3))
(2, (0, 2, 3))
(2, (0, 1, 3))
(2, (0, 1, 2))
(1, (2, 3))
(1, (1, 3))
(1, (1, 2))
(0, (3,))
(0, (2,))
(0, (1,))
(1, (0, 3))
(1, (0, 2))
(0, (0,))
(1, (0, 1))
```

# See also:

ambient\_Vrepresentation().

### ambient\_Vrepresentation()

Return the Vrepresentation objects of the ambient polyhedron defining the face.

It consists of the vertices/rays/lines that face contains.

**EXAMPLES:** 

```
sage: P = polytopes.permutahedron(5)
                                             # optional - sage.combinat
sage: C = CombinatorialPolyhedron(P)
                                             # optional - sage.combinat
sage: it = C.face_generator(dimension=2)
                                            # optional - sage.combinat
                                              # optional - sage.combinat
sage: face = next(it)
sage: face.ambient_Vrepresentation()
                                             # optional - sage.combinat
(A vertex at (1, 3, 2, 5, 4),
A vertex at (2, 3, 1, 5, 4),
A vertex at (3, 1, 2, 5, 4),
A vertex at (3, 2, 1, 5, 4),
A vertex at (2, 1, 3, 5, 4),
A vertex at (1, 2, 3, 5, 4)
sage: face = next(it)
                                              # optional - sage.combinat
sage: face.ambient_Vrepresentation()
                                             # optional - sage.combinat
(A \text{ vertex at } (2, 1, 4, 5, 3),
A vertex at (3, 2, 4, 5, 1),
A vertex at (3, 1, 4, 5, 2),
A vertex at (1, 3, 4, 5, 2),
A vertex at (1, 2, 4, 5, 3),
A vertex at (2, 3, 4, 5, 1)
sage: C = CombinatorialPolyhedron([[0,1,2],[0,1,3],[0,2,3],[1,2,3]])
sage: it = C.face_generator()
sage: for face in it: (face.dimension(), face.ambient_Vrepresentation())
(2, (1, 2, 3))
(2, (0, 2, 3))
(2, (0, 1, 3))
(2, (0, 1, 2))
(1, (2, 3))
(1, (1, 3))
(1, (1, 2))
(0, (3,))
(0, (2,))
(0, (1,))
(1, (0, 3))
(1, (0, 2))
(0, (0,))
(1, (0, 1))
```

### See also:

```
ambient_V_indices().
```

### ambient\_dimension()

Return the dimension of the polyhedron.

# **EXAMPLES:**

```
sage: P = polytopes.cube()
sage: C = CombinatorialPolyhedron(P)
sage: it = C.face_generator()
sage: face = next(it)
sage: face.ambient_dimension()
3
```

### as\_combinatorial\_polyhedron(quotient=False)

Return self as combinatorial polyhedron.

If quotient is True, return the quotient of the polyhedron by self. Let G be the face corresponding to self in the dual/polar polytope. The quotient is the dual/polar of G.

Let  $[\hat{0}, \hat{1}]$  be the face lattice of the ambient polyhedron and F be self as element of the face lattice. The face lattice of self as polyhedron corresponds to  $[\hat{0}, F]$  and the face lattice of the quotient by self corresponds to  $[F, \hat{1}]$ .

### **EXAMPLES:**

### Obtaining the quotient:

```
sage: Q = f.as_combinatorial_polyhedron(quotient=True); Q
A 2-dimensional combinatorial polyhedron with 6 facets
sage: Q
A 2-dimensional combinatorial polyhedron with 6 facets
sage: Q.f_vector()
(1, 6, 6, 1)
```

The Vrepresentation of the face as polyhedron is given by the ambient Vrepresentation of the face in that order:

```
sage: P = polytopes.cube()
sage: C = CombinatorialPolyhedron(P)
sage: it = C.face_generator(2)
sage: f = next(it)
sage: F = f.as_combinatorial_polyhedron()
sage: C.Vrepresentation()
(A vertex at (1, -1, -1),
A vertex at (1, 1, -1),
A vertex at (1, 1, 1),
A vertex at (1, -1, 1),
A vertex at (-1, -1, 1),
A vertex at (-1, -1, -1),
A vertex at (-1, 1, -1),
A vertex at (-1, 1, 1)
sage: f.ambient_Vrepresentation()
(A vertex at (1, -1, -1),
A vertex at (1, -1, 1),
```

```
A vertex at (-1, -1, 1),
A vertex at (-1, -1, -1))

sage: F.Vrepresentation()
(0, 1, 2, 3)
```

To obtain the facets of the face as polyhedron, we compute the meet of each facet with the face. The first representative of each element strictly contained in the face is kept:

```
sage: C.facets(names=False)
((0, 1, 2, 3),
  (1, 2, 6, 7),
  (2, 3, 4, 7),
  (4, 5, 6, 7),
  (0, 1, 5, 6),
  (0, 3, 4, 5))
sage: F.facets(names=False)
((0, 1), (1, 2), (2, 3), (0, 3))
```

The Hrepresentation of the quotient by the face is given by the ambient Hrepresentation of the face in that order:

```
sage: it = C.face_generator(1)
sage: f = next(it)
sage: Q = f.as_combinatorial_polyhedron(quotient=True)
sage: C.Hrepresentation()
(An inequality (-1, 0, 0) x + 1 >= 0,
An inequality (0, -1, 0) x + 1 >= 0,
An inequality (0, 0, -1) x + 1 >= 0,
An inequality (1, 0, 0) x + 1 >= 0,
An inequality (0, 0, 1) x + 1 >= 0,
An inequality (0, 1, 0) x + 1 >= 0)
sage: f.ambient_Hrepresentation()
(An inequality (0, 0, 1) x + 1 >= 0, An inequality (0, 1, 0) x + 1 >= 0)
sage: Q.Hrepresentation()
(0, 1)
```

To obtain the vertices of the face as polyhedron, we compute the join of each vertex with the face. The first representative of each element strictly containing the face is kept:

```
sage: [g.ambient_H_indices() for g in C.face_generator(0)]
[(3, 4, 5),
(0, 4, 5),
(2, 3, 5),
(0, 2, 5),
(1, 3, 4),
(0, 1, 4),
(1, 2, 3),
(0, 1, 2)]
sage: [g.ambient_H_indices() for g in Q.face_generator(0)]
[(1,), (0,)]
```

The method is not implemented for unbounded polyhedra:

```
sage: P = Polyhedron(rays=[[0,1]])*polytopes.cube()
sage: C = CombinatorialPolyhedron(P)
sage: it = C.face_generator(2)
sage: f = next(it)
sage: f.as_combinatorial_polyhedron()
Traceback (most recent call last):
...
NotImplementedError: only implemented for bounded polyhedra
```

### REFERENCES:

For more information, see Exercise 2.9 of [Zie2007].

**Note:** This method is tested in \_test\_combinatorial\_face\_as\_combinatorial\_polyhedron().

### dim()

Return the dimension of the face.

#### **EXAMPLES:**

```
sage: P = polytopes.associahedron(['A', 3]) # optional - sage.combinat
sage: C = CombinatorialPolyhedron(P) # optional - sage.combinat
sage: it = C.face_generator() # optional - sage.combinat
sage: face = next(it) # optional - sage.combinat
sage: face.dimension() # optional - sage.combinat
```

dim is an alias:

```
sage: face.dim() # optional - sage.combinat
2
```

# dimension()

Return the dimension of the face.

### **EXAMPLES:**

```
sage: P = polytopes.associahedron(['A', 3]) # optional - sage.combinat
sage: C = CombinatorialPolyhedron(P) # optional - sage.combinat
sage: it = C.face_generator() # optional - sage.combinat
sage: face = next(it) # optional - sage.combinat
sage: face.dimension() # optional - sage.combinat
2
```

dim is an alias:

```
sage: face.dim() # optional - sage.combinat
2
```

### is\_subface(other)

Return whether self is contained in other.

**EXAMPLES:** 

```
sage: P = polytopes.cube()
sage: C = P.combinatorial_polyhedron()
sage: it = C.face_generator()
sage: face = next(it)
sage: face.ambient_V_indices()
(0, 3, 4, 5)
sage: face2 = next(it)
sage: face2.ambient_V_indices()
(0, 1, 5, 6)
sage: face.is_subface(face2)
False
sage: face2.is_subface(face)
False
sage: it.only_subfaces()
sage: face3 = next(it)
sage: face3.ambient_V_indices()
(0, 5)
sage: face3.is_subface(face2)
True
sage: face3.is_subface(face)
True
```

Works for faces of the same combinatorial polyhedron; also from different iterators:

```
sage: it = C.face_generator(algorithm='dual')
sage: v7 = next(it); v7.ambient_V_indices()
(7,)
sage: v6 = next(it); v6.ambient_V_indices()
(6,)
sage: v5 = next(it); v5.ambient_V_indices()
(5,)
sage: face.ambient_V_indices()
(0, 3, 4, 5)
sage: face.is_subface(v7)
False
sage: v7.is_subface(face)
False
sage: v6.is_subface(face)
False
sage: v5.is_subface(face)
True
sage: face2.ambient_V_indices()
(0, 1, 5, 6)
sage: face2.is_subface(v7)
False
sage: v7.is_subface(face2)
False
sage: v6.is_subface(face2)
sage: v5.is_subface(face2)
True
```

Only implemented for faces of the same combinatorial polyhedron:

### n\_ambient\_Hrepresentation(add\_equations=True)

Return the length of the CombinatorialFace.ambient\_H\_indices().

Might be faster than then using len.

### INPUT:

• add\_equations – boolean (default: True); whether or not to count the equations

#### **EXAMPLES:**

Specifying whether to count the equations or not:

```
sage: P = polytopes.permutahedron(5)
                                                   # optional - sage.
sage: C = CombinatorialPolyhedron(P)
                                                   # optional - sage.
sage: it = C.face_generator(2)
                                                   # optional - sage.
→combinat
sage: f = next(it)
                                                   # optional - sage.
sage: f.n_ambient_Hrepresentation(add_equations=True)
                                                   # optional - sage.
→ combinat
sage: f.n_ambient_Hrepresentation(add_equations=False) # optional - sage.
```

# n\_ambient\_Vrepresentation()

Return the length of the  $CombinatorialFace.ambient\_V\_indices()$ .

Might be faster than using len.

**EXAMPLES**:

# 2.3.3 PolyhedronFaceLattice

This module provides a class that stores and sorts all faces of the polyhedron.

CombinatorialPolyhedron implicitly uses this class to generate the face lattice of a polyhedron.

Terminology in this module:

- Vrep [vertices, rays, lines] of the polyhedron.
- Hrep inequalities and equations of the polyhedron.
- Facets facets of the polyhedron.
- Coatoms the faces from which all others are constructed in the face iterator. This will be facets or Vrep. In non-dual mode, faces are constructed as intersections of the facets. In dual mode, the are constructed theoretically as joins of vertices. The coatoms are repsented as incidences with the atoms they contain.
- Atoms facets or Vrep depending on application of algorithm. Atoms are repsented as incidences of coatoms they are contained in.
- Vrepresentation represents a face by a list of Vrep it contains.
- Hrepresentation represents a face by a list of Hrep it is contained in.
- bit representation represents incidences as uint64\_t-array, where each bit represents one incidence. There might be trailing zeros, to fit alignment requirements. In most instances, faces are represented by the bit representation, where each bit corresponds to an atom.

# **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.combinatorial_polyhedron.polyhedron_face_lattice \
....: import PolyhedronFaceLattice
sage: P = polytopes.octahedron()
sage: C = CombinatorialPolyhedron(P)
sage: all_faces = PolyhedronFaceLattice(C)
```

# See also:

base, PolyhedronFaceLattice.

# AUTHOR:

• Jonathan Kliem (2019-04)

 ${\bf class} \ \, {\bf sage.geometry.polyhedron.combinatorial\_polyhedron.polyhedron\_face\_lattice.} \\ {\bf PolyhedronFaceLattice}$ 

Bases: object

A class to generate incidences of CombinatorialPolyhedron.

On initialization all faces of the given *CombinatorialPolyhedron* are added and sorted (except coatoms). The incidences can be used to generate the face\_lattice.

Might generate the faces of the dual polyhedron for speed.

### INPUT:

• baseCombinatorialPolyhedron

### See also:

### **EXAMPLES:**

```
sage: P = polytopes.Birkhoff_polytope(3)
sage: C = CombinatorialPolyhedron(P)
sage: C.face_lattice() # indirect doctests
Finite lattice containing 50 elements
```

#### ALGORITHM:

The faces are recorded with *FaceIterator* in Bit-representation. Once created, all level-sets but the coatoms are sorted with merge sort. Non-trivial incidences of elements whose rank differs by 1 are determined by intersecting with all coatoms. Then each intersection is looked up in the sorted level sets.

#### dual

# get\_face(dimension, index)

Return the face of dimension dimension and index index.

### INPUT:

- dimension dimension of the face
- index index of the face
- names if True returns the names of the [vertices, rays, lines] as given on initialization of CombinatorialPolyhedron

### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.combinatorial_polyhedron.polyhedron_face_
→lattice \
              import PolyhedronFaceLattice
. . . . . .
sage: P = polytopes.permutahedron(4)
sage: C = CombinatorialPolyhedron(P)
sage: F = PolyhedronFaceLattice(C)
sage: it = C.face_generator(dimension=1)
sage: face = next(it)
sage: index = F._find_face_from_combinatorial_face(face)
sage: F.get_face(face.dimension(), index).ambient_Vrepresentation()
(A vertex at (2, 1, 4, 3), A vertex at (1, 2, 4, 3))
sage: face.ambient_Vrepresentation()
(A vertex at (2, 1, 4, 3), A vertex at (1, 2, 4, 3))
sage: all(F.get_face(face.dimension(),
. . . . :
                     F._find_face_from_combinatorial_face(face)).ambient_
→Vrepresentation() ==
          face.ambient_Vrepresentation() for face in it)
. . . . .
True
sage: P = polytopes.twenty_four_cell()
```

```
sage: C = CombinatorialPolyhedron(P)
sage: F = PolyhedronFaceLattice(C)
sage: it = C.face_generator()
sage: face = next(it)
sage: while (face.dimension() == 3): face = next(it)
sage: index = F._find_face_from_combinatorial_face(face)
sage: F.get_face(face.dimension(), index).ambient_Vrepresentation()
(A vertex at (-1/2, 1/2, -1/2, -1/2),
A vertex at (-1/2, 1/2, 1/2, -1/2),
A vertex at (0, 0, 0, -1)
sage: all(F.get_face(face.dimension(),
                     F._find_face_from_combinatorial_face(face)).ambient_V_
→indices() ==
          face.ambient_V_indices() for face in it)
. . . . . .
True
```

# 2.3.4 Face iterator for polyhedra

This iterator in principle works on every graded lattice, where every interval of length two has exactly 4 elements (diamond property).

It also works on unbounded polyhedra, as those satisfy the diamond property, except for intervals including the empty face. A (slightly generalized) description of the algorithm can be found in [KS2019].

Terminology in this module:

- Coatoms the faces from which all others are constructed in the face iterator. This will be facets or Vrep. In non-dual mode, faces are constructed as intersections of the facets. In dual mode, they are constructed theoretically as joins of vertices. The coatoms are repsented as incidences with the atoms they contain.
- Atoms facets or Vrep depending on application of algorithm. Atoms are represented as incidences of coatoms they are contained in.

### See also:

sage.geometry.polyhedron.combinatorial\_polyhedron.base.

# **EXAMPLES:**

Construct a face iterator:

```
sage: from sage.geometry.polyhedron.combinatorial_polyhedron.face_iterator \
    import FaceIterator
sage: P = polytopes.octahedron()
sage: C = CombinatorialPolyhedron(P)

sage: FaceIterator(C, False)
Iterator over the proper faces of a 3-dimensional combinatorial polyhedron
sage: FaceIterator(C, False, output_dimension=2)
Iterator over the 2-faces of a 3-dimensional combinatorial polyhedron
```

Iterator in the non-dual mode starts with facets:

```
sage: it = FaceIterator(C, False)
sage: [next(it) for _ in range(9)]
```

```
[A 2-dimensional face of a 3-dimensional combinatorial polyhedron,
A 1-dimensional face of a 3-dimensional combinatorial polyhedron]
```

Iterator in the dual-mode starts with vertices:

```
sage: it = FaceIterator(C, True)
sage: [next(it) for _ in range(7)]
[A 0-dimensional face of a 3-dimensional combinatorial polyhedron,
   A 1-dimensional face of a 3-dimensional combinatorial polyhedron]
```

Obtain the Vrepresentation:

```
sage: it = FaceIterator(C, False)
sage: face = next(it)
sage: face.ambient_Vrepresentation()
(A vertex at (0, -1, 0), A vertex at (0, 0, -1), A vertex at (1, 0, 0))
sage: face.n_ambient_Vrepresentation()
3
```

Obtain the facet-representation:

```
sage: it = FaceIterator(C, True)
sage: face = next(it)
sage: face.ambient_Hrepresentation()
(An inequality (-1, -1, 1) x + 1 >= 0,
    An inequality (-1, -1, -1) x + 1 >= 0,
    An inequality (-1, 1, -1) x + 1 >= 0,
    An inequality (-1, 1, 1) x + 1 >= 0)
sage: face.ambient_H_indices()
(4, 5, 6, 7)
sage: face.n_ambient_Hrepresentation()
4
```

In non-dual mode one can ignore all faces contained in the current face:

```
sage: it = FaceIterator(C, False)
sage: face = next(it)
sage: face.ambient_H_indices()
(7,)
sage: it.ignore_subfaces()
sage: [face.ambient_H_indices() for face in it]
```

```
[(6,),
(5,),
(4,),
(3,),
(2,),
(1,),
(0,),
(5, 6),
(1, 6),
(0, 1, 5, 6),
(4, 5),
(0, 5),
(0, 3, 4, 5),
(3, 4),
(2, 3),
(0, 3),
(0, 1, 2, 3),
(1, 2),
(0, 1)
```

In dual mode one can ignore all faces that contain the current face:

```
sage: it = FaceIterator(C, True)
sage: face = next(it)
sage: face.ambient_V_indices()
(5,)
sage: it.ignore_supfaces()
sage: [face.ambient_V_indices() for face in it]
[(4,),
(3,),
(2,),
(1,),
(0,),
(3, 4),
(2, 4),
(0, 4),
(0, 3, 4),
(0, 2, 4),
(1, 3),
(0, 3),
(0, 1, 3),
(1, 2),
(0, 2),
(0, 1, 2),
(0, 1)
```

There is a special face iterator class for geometric polyhedra. It yields (geometric) polyhedral faces and it also yields trivial faces. Otherwise, it works exactly the same:

```
sage: it = FaceIterator_geom(P)
sage: [next(it) for _ in range(5)]
[A 3-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 8 vertices,
    A -1-dimensional face of a Polyhedron in ZZ^3,
    A 2-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 4 vertices,
    A 2-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 4 vertices,
    A 2-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 4 vertices]
sage: it
Iterator over the faces of a 3-dimensional polyhedron in ZZ^3
```

### **AUTHOR:**

• Jonathan Kliem (2019-04)

A class to iterate over all combinatorial faces of a polyhedron.

Construct all proper faces from the facets. In dual mode, construct all proper faces from the vertices. Dual will be faster for less vertices than facets.

### INPUT:

- C a CombinatorialPolyhedron
- dual if True, then dual polyhedron is used for iteration (only possible for bounded Polyhedra)
- output\_dimension if not None, then the face iterator will only yield faces of this dimension

# See also:

 $Face Iterator, Face Iterator\_geom, Combinatorial Polyhedron.$ 

### **EXAMPLES:**

Construct a face iterator:

```
sage: P = polytopes.cuboctahedron()
sage: C = CombinatorialPolyhedron(P)
sage: it = C.face_generator()
sage: next(it)
A 0-dimensional face of a 3-dimensional combinatorial polyhedron
```

Construct faces by the dual or not:

```
sage: it = C.face_generator(algorithm='primal')
sage: next(it).dimension()
2
sage: it = C.face_generator(algorithm='dual')
sage: next(it).dimension()
0
```

For unbounded polyhedra only non-dual iteration is possible:

```
sage: P = Polyhedron(rays=[[0,0,1], [0,1,0], [1,0,0]])
sage: C = CombinatorialPolyhedron(P)
sage: it = C.face_generator()
sage: [face.ambient_Vrepresentation() for face in it]
[(A vertex at (0, 0, 0),
 A ray in the direction (0, 1, 0),
 A ray in the direction (1, 0, 0),
 (A vertex at (0, 0, 0),
 A ray in the direction (0, 0, 1),
 A ray in the direction (1, 0, 0),
 (A vertex at (0, 0, 0),
 A ray in the direction (0, 0, 1),
 A ray in the direction (0, 1, 0),
 (A vertex at (0, 0, 0), A ray in the direction (1, 0, 0)),
 (A vertex at (0, 0, 0), A ray in the direction (0, 1, 0)),
 (A vertex at (0, 0, 0),),
 (A vertex at (0, 0, 0), A ray in the direction (0, 0, 1))
sage: it = C.face_generator(algorithm='dual')
Traceback (most recent call last):
ValueError: dual algorithm only available for bounded polyhedra
```

Construct a face iterator only yielding dimension 2 faces:

```
sage: P = polytopes.permutahedron(5)
sage: C = CombinatorialPolyhedron(P)
sage: it = C.face_generator(dimension=2)
sage: counter = 0
sage: for _ in it: counter += 1
sage: print ('permutahedron(5) has', counter,
...: 'faces of dimension 2')
permutahedron(5) has 150 faces of dimension 2
sage: C.f_vector()
(1, 120, 240, 150, 30, 1)
```

In non-dual mode one can ignore all faces contained in the current face:

```
sage: P = polytopes.cube()
sage: C = CombinatorialPolyhedron(P)
sage: it = C.face_generator(algorithm='primal')
sage: face = next(it)
sage: face.ambient_H_indices()
(5,)
sage: it.ignore_subfaces()
sage: [face.ambient_H_indices() for face in it]
\lceil (4,), \rceil
(3,),
 (2,),
 (1,),
 (0,),
 (3, 4),
 (1, 4),
 (0, 4),
```

```
(1, 3, 4),
(0, 1, 4),
(2, 3),
(1, 3),
(1, 2, 3),
(1, 2),
(0, 2),
(0, 1, 2),
(0, 1)]

sage: it = C.face_generator(algorithm='dual')
sage: next(it)
A 0-dimensional face of a 3-dimensional combinatorial polyhedron
sage: it.ignore_subfaces()
Traceback (most recent call last):
...
ValueError: only possible when not in dual mode
```

In dual mode one can ignore all faces that contain the current face:

```
sage: it = C.face_generator(algorithm='dual')
sage: next(it)
A 0-dimensional face of a 3-dimensional combinatorial polyhedron
sage: face = next(it)
sage: face.ambient_V_indices()
(6,)
sage: [face.ambient_V_indices() for face in it]
[(5,),
(4,),
 (3,),
 (2,),
 (1,),
 (0,),
 (6, 7),
 (4, 7),
 (2, 7),
 (4, 5, 6, 7),
 (1, 2, 6, 7),
 (2, 3, 4, 7),
 (5, 6),
 (1, 6),
 (0, 1, 5, 6),
 (4, 5),
 (0, 5),
 (0, 3, 4, 5),
 (3, 4),
 (2, 3),
 (0, 3),
 (0, 1, 2, 3),
 (1, 2),
 (0, 1)
```

```
sage: it = C.face_generator(algorithm='primal')
sage: next(it)
A 2-dimensional face of a 3-dimensional combinatorial polyhedron
sage: it.ignore_supfaces()
Traceback (most recent call last):
...
ValueError: only possible when in dual mode
```

### ALGORITHM:

The algorithm to visit all proper faces exactly once is roughly equivalent to the following. A (slightly generalized) description of the algorithm can be found in [KS2019].

Initialization:

```
faces = [set(facet) for facet in P.facets()]
face_iterator(faces, [])
```

The function face\_iterator is defined recursively. It visits all faces of the polyhedron P, except those contained in any of visited\_all. It assumes faces to be exactly those facets of P that are not contained in any of the visited\_all. It assumes visited\_all to be some list of faces of a polyhedron  $P_2$ , which contains P as one of its faces:

```
def face_iterator(faces, visited_all):
    while facets:
        one_face = faces.pop()
        maybe_new_faces = [one_face.intersection(face) for face in faces]
...
```

At this point we claim that maybe\_new\_faces contains all facets of one\_face, which we have not visited before.

Proof: Let F be a facet of one\_face. We have a chain:  $P \supset \text{one}_{\text{face}} \supset F$ . By the diamond property, there exists a second\_face with  $P \supset \text{second}_{\text{face}} \supset F$ .

Now either  $second\_face$  is not an element of faces: Hence  $second\_face$  is contained in one of  $visited\_all$ . In particular, F is contained in  $visited\_all$ .

Or second\_face is an element of faces: Then, intersecting one\_face with second\_face gives F.

This concludes the proof.

Moreover, if an element in maybe\_new\_faces is inclusion-maximal and not contained in any of the visited\_all, it is a facet of one\_face. Any facet in maybe\_new\_faces of one\_face is inclusion-maximal.

Hence, in the following loop, an element face1 in maybe\_new\_faces is a facet of one\_face if and only if it is not contained in another facet:

```
maybe_new_faces2 = []
for i, face1 in enumerate(maybe_new_faces):
    if (all(not face1 < face2 for face2 in maybe_new_faces[:i])
        and all(not face1 <= face2 for face2 in maybe_new_faces[i+1:])):
        maybe_new_faces2.append(face1)
...</pre>
```

Now maybe\_new\_faces2 contains only facets of one\_face and some faces contained in any of visited\_all. It also contains all the facets not contained in any of visited\_all.

We construct new\_faces as the list of all facets of one\_face not contained in any of visited\_all:

```
new_faces = []
for face1 in maybe_new_faces2:
    if all(not face1 < face2 for face2 in visited_all):
        new_faces.append(face1)
...</pre>
```

By induction we can apply the algorithm, to visit all faces of one\_face not contained in visited\_all:

```
face_iterator(new_faces, visited_all)
...
```

Finally we visit one\_face and add it to visited\_all:

```
visit(one_face)
visited_all.append(one_face)
```

Note: At this point, we have visited exactly those faces, contained in any of the visited\_all. The function ends here.

ALGORITHM for the special case that all intervals of the lattice not containing zero are boolean (e.g. when the polyhedron is simple):

We do not assume any other properties of our lattice in this case. Note that intervals of length 2 not containing zero, have exactly 2 elements now. But the atom-representation of faces might not be unique.

We do the following modifications:

- To check whether an intersection of faces is zero, we check whether the atom-representation is zero. Although not unique, it works to distinct from zero.
- The intersection of two (relative) facets has always codimension 1 unless empty.
- To intersect we now additionally unite the coatom representation. This gives the correct representation of the new face unless the intersection is zero.
- To mark a face as visited, we save its coatom representation.
- To check whether we have seen a face already, we check containment of the coatom representation.

A base class to iterate over all faces of a polyhedron.

Construct all proper faces from the facets. In dual mode, construct all proper faces from the vertices. Dual will be faster for less vertices than facets.

See FaceIterator.

## current()

Retrieve the last value of *next(*).

**EXAMPLES:** 

```
sage: P = polytopes.octahedron()
sage: it = P.combinatorial_polyhedron().face_generator()
sage: next(it)
A 0-dimensional face of a 3-dimensional combinatorial polyhedron
sage: it.current()
A 0-dimensional face of a 3-dimensional combinatorial polyhedron
sage: next(it).ambient_V_indices() == it.current().ambient_V_indices()
True
```

### dual

# ignore\_subfaces()

The iterator will not visit any faces of the current face.

Only possible when not in dual mode.

**EXAMPLES:** 

```
sage: P = polytopes.Gosset_3_21()
sage: C = CombinatorialPolyhedron(P)
sage: it = C.face_generator(algorithm='primal')
sage: n_non_simplex_faces = 1
sage: for face in it:
...:     if face.n_ambient_Vrepresentation() > face.dimension() + 1:
...:         n_non_simplex_faces += 1
...:     else:
...:     it.ignore_subfaces()
...:
sage: n_non_simplex_faces
127
```

Face iterator must not be in dual mode:

```
sage: it = C.face_generator(algorithm='dual')
sage: _ = next(it)
sage: it.ignore_subfaces()
Traceback (most recent call last):
...
ValueError: only possible when not in dual mode
```

Ignoring the same face as was requested to visit only consumes the iterator:

```
sage: it = C.face_generator(algorithm='primal')
sage: _ = next(it)
sage: it.only_subfaces()
sage: it.ignore_subfaces()
sage: list(it)
[]
```

Face iterator must be set to a face first:

```
sage: it = C.face_generator(algorithm='primal')
sage: it.ignore_subfaces()
Traceback (most recent call last):
```

```
...
ValueError: iterator not set to a face yet
```

### ignore\_supfaces()

The iterator will not visit any faces containing the current face.

Only possible when in dual mode.

### **EXAMPLES:**

```
sage: P = polytopes.Gosset_3_21()
sage: C = CombinatorialPolyhedron(P)
sage: it = C.face_generator(algorithm='dual')
sage: n_faces_with_non_simplex_quotient = 1
sage: for face in it:
          n_facets = face.n_ambient_Hrepresentation(add_equations=False)
          if n_facets > C.dimension() - face.dimension() + 1:
....:
              n_faces_with_non_simplex_quotient += 1
. . . . .
          else:
. . . . . .
. . . . :
              it.ignore_supfaces()
sage: n_faces_with_non_simplex_quotient
4845
```

Face iterator must be in dual mode:

```
sage: it = C.face_generator(algorithm='primal')
sage: _ = next(it)
sage: it.ignore_supfaces()
Traceback (most recent call last):
...
ValueError: only possible when in dual mode
```

# join\_of\_Vrep(\*indices)

Construct the join of the Vrepresentatives indicated by the indices.

This is the smallest face containing all Vrepresentatives with the given indices.

The iterator must be reset if not newly initialized.

**Note:** In the case of unbounded polyhedra, the smallest face containing given Vrepresentatives may not be well defined.

### **EXAMPLES:**

```
(0, 1, 2, 3)
sage: it.join_of_Vrep(1,5).ambient_V_indices()
(0, 1, 5, 6)

sage: P = polytopes.cross_polytope(4)
sage: it = P.face_generator()
sage: it.join_of_Vrep().ambient_V_indices()
()
sage: it.join_of_Vrep(1,3).ambient_V_indices()
(1, 3)
sage: it.join_of_Vrep(1,2).ambient_V_indices()
(1, 2)
sage: it.join_of_Vrep(1,6).ambient_V_indices()
(0, 1, 2, 3, 4, 5, 6, 7)
sage: it.join_of_Vrep(8)
Traceback (most recent call last):
...
IndexError: coatoms out of range
```

If the iterator has already been used, it must be reset before:

```
sage: P = polytopes.dodecahedron()
                                                          # optional - sage.
→rings.number_field
sage: it = P.face_generator()
                                                          # optional - sage.
⇔rings.number_field
sage: _ = next(it), next(it)
                                                          # optional - sage.
⇔rings.number_field
sage: next(it).ambient_V_indices()
                                                          # optional - sage.
→rings.number_field
(15, 16, 17, 18, 19)
sage: it.join_of_Vrep(1,10)
                                                          # optional - sage.
→rings.number_field
Traceback (most recent call last):
ValueError: please reset the face iterator
sage: it.reset()
                                                          # optional - sage.
⇔rings.number_field
sage: it.join_of_Vrep(1,10).ambient_V_indices()
                                                          # optional - sage.
⇔rings.number_field
(1, 10)
```

In the case of an unbounded polyhedron, we try to make sense of the input:

```
Traceback (most recent call last):
ValueError: the join is not well-defined
sage: P = Polyhedron(vertices=[[1,0], [0,1]], rays=[[1,1]])
sage: it = P.face_generator()
sage: it.join_of_Vrep(0)
A 0-dimensional face of a Polyhedron in QQ^2 defined as the convex hull of 1.
→vertex
sage: it.join_of_Vrep(1)
A 0-dimensional face of a Polyhedron in QQ^2 defined as the convex hull of 1.
sage: it.join_of_Vrep(2)
Traceback (most recent call last):
ValueError: the join is not well-defined
sage: it.join_of_Vrep(0,2)
A 1-dimensional face of a Polyhedron in QQ^2 defined as the convex hull of 1.
→vertex and 1 ray
sage: P = Polyhedron(rays=[[1,0], [0,1]])
sage: it = P.face_generator()
sage: it.join_of_Vrep(0)
A 0-dimensional face of a Polyhedron in ZZ^2 defined as the convex hull of 1.
⊶vertex
sage: it.join_of_Vrep(1,2)
A 2-dimensional face of a Polyhedron in ZZ^2 defined as the convex hull of 1.
→vertex and 2 rays
```

# meet\_of\_Hrep(\*indices)

Construct the meet of the facets indicated by the indices.

This is the largest face contained in all facets with the given indices.

The iterator must be reset if not newly initialized.

# **EXAMPLES:**

```
sage: it.meet_of_Hrep(1,3).ambient_H_indices()
(1, 2, 3, 4)
sage: it.meet_of_Hrep(1,2).ambient_H_indices()
sage: it.meet_of_Hrep(1,6).ambient_H_indices()
(1, 6)
sage: it.meet_of_Hrep(1,2,6).ambient_H_indices()
(1, 2, 6, 7)
sage: it.meet_of_Hrep(1,2,5,6).ambient_H_indices()
(0, 1, 2, 3, 4, 5, 6, 7)
sage: s = cones.schur(4)
sage: C = CombinatorialPolyhedron(s)
sage: it = C.face_generator()
sage: it.meet_of_Hrep(1,2).ambient_H_indices()
sage: it.meet_of_Hrep(1,2,3).ambient_H_indices()
Traceback (most recent call last):
IndexError: coatoms out of range
```

If the iterator has already been used, it must be reset before:

```
sage: P = polytopes.dodecahedron()
                                                          # optional - sage.
⇔rings.number_field
sage: it = P.face_generator()
                                                          # optional - sage.
⇔rings.number_field
sage: _ = next(it), next(it)
                                                          # optional - sage.
→rings.number_field
sage: next(it).ambient_V_indices()
                                                          # optional - sage.
→rings.number_field
(15, 16, 17, 18, 19)
sage: it.meet_of_Hrep(9,11)
                                                          # optional - sage.
→rings.number_field
Traceback (most recent call last):
ValueError: please reset the face iterator
sage: it.reset()
                                                          # optional - sage.
→rings.number_field
sage: it.meet_of_Hrep(9,11).ambient_H_indices()
                                                          # optional - sage.
⇔rings.number_field
(9, 11)
```

# next()

Must be implemented by a derived class.

# only\_subfaces()

The iterator will visit all (remaining) subfaces of the current face and then terminate.

**EXAMPLES:** 

```
sage: P = polytopes.cube()
sage: it = P.face_generator()
```

```
sage: next(it).ambient_H_indices()
()
sage: next(it).ambient_H_indices()
(0, 1, 2, 3, 4, 5)
sage: next(it).ambient_H_indices()
(5,)
sage: next(it).ambient_H_indices()
(4,)
sage: it.only_subfaces()
sage: list(f.ambient_H_indices() for f in it)
[(4, 5), (3, 4), (1, 4), (0, 4), (3, 4, 5), (0, 4, 5), (1, 3, 4), (0, 1, 4)]
```

```
sage: P = polytopes.Birkhoff_polytope(4)
sage: C = P.combinatorial_polyhedron()
sage: it = C.face_generator()
sage: next(it).ambient_H_indices(add_equations=False)
(15,)
sage: next(it).ambient_H_indices(add_equations=False)
(14,)
sage: it.only_subfaces()
sage: all(14 in f.ambient_H_indices() for f in it)
True
```

Face iterator needs to be set to a face first:

```
sage: it = C.face_generator()
sage: it.only_subfaces()
Traceback (most recent call last):
...
ValueError: iterator not set to a face yet
```

Face iterator must not be in dual mode:

```
sage: it = C.face_generator(algorithm='dual')
sage: _ = next(it)
sage: it.only_subfaces()
Traceback (most recent call last):
...
ValueError: only possible when not in dual mode
```

Cannot run only\_subfaces after ignore\_subfaces:

```
sage: it = C.face_generator()
sage: _ = next(it)
sage: it.ignore_subfaces()
sage: it.only_subfaces()
Traceback (most recent call last):
...
ValueError: cannot only visit subsets after ignoring a face
```

# only\_supfaces()

The iterator will visit all (remaining) faces containing the current face and then terminate.

**EXAMPLES:** 

```
sage: P = polytopes.cross_polytope(3)
sage: it = P.face_generator()
sage: next(it).ambient_V_indices()
(0, 1, 2, 3, 4, 5)
sage: next(it).ambient_V_indices()
()
sage: next(it).ambient_V_indices()
(5,)
sage: next(it).ambient_V_indices()
(4,)
sage: it.only_supfaces()
sage: list(f.ambient_V_indices() for f in it)
[(4, 5), (3, 4), (2, 4), (0, 4), (3, 4, 5), (2, 4, 5), (0, 3, 4), (0, 2, 4)]
```

```
sage: P = polytopes.Birkhoff_polytope(4)
sage: C = P.combinatorial_polyhedron()
sage: it = C.face_generator(algorithm='dual')
sage: next(it).ambient_V_indices()
(23,)
sage: next(it).ambient_V_indices()
(22,)
sage: it.only_supfaces()
sage: all(22 in f.ambient_V_indices() for f in it)
True
```

### reset()

Reset the iterator.

The iterator will start with the first face again.

# **EXAMPLES:**

```
sage: P = polytopes.cube()
sage: C = P.combinatorial_polyhedron()
sage: it = C.face_generator()
sage: next(it).ambient_V_indices()
(0, 3, 4, 5)
sage: it.reset()
sage: next(it).ambient_V_indices()
(0, 3, 4, 5)
```

 $\begin{tabular}{ll} {\bf class} & {\bf sage.geometry.polyhedron.combinatorial\_polyhedron.face\_iterator. {\bf FaceIterator\_geom} \\ {\bf Bases:} & {\bf sage.geometry.polyhedron.combinatorial\_polyhedron.face\_iterator.} \end{tabular}$ 

FaceIterator\_base

A class to iterate over all geometric faces of a polyhedron.

Construct all faces from the facets. In dual mode, construct all faces from the vertices. Dual will be faster for less vertices than facets.

# INPUT:

- P an instance of *Polyhedron\_base*
- dual if True, then dual polyhedron is used for iteration (only possible for bounded Polyhedra)
- output\_dimension if not None, then the FaceIterator will only yield faces of this dimension

### **EXAMPLES:**

Construct a geometric face iterator:

Construct faces by the dual or not:

```
sage: it = P.face_generator(algorithm='primal')
sage: _ = next(it), next(it)
sage: next(it).dim()
2

sage: it = P.face_generator(algorithm='dual')
sage: _ = next(it), next(it)
sage: next(it).dim()
0
```

For unbounded polyhedra only non-dual iteration is possible:

```
sage: P = Polyhedron(rays=[[0,0,1], [0,1,0], [1,0,0]])
sage: it = P.face_generator()
sage: [face.ambient_Vrepresentation() for face in it]
[(A vertex at (0, 0, 0),
 A ray in the direction (0, 0, 1),
 A ray in the direction (0, 1, 0),
 A ray in the direction (1, 0, 0),
 (),
 (A vertex at (0, 0, 0),
 A ray in the direction (0, 1, 0),
 A ray in the direction (1, 0, 0),
 (A vertex at (0, 0, 0),
 A ray in the direction (0, 0, 1),
 A ray in the direction (1, 0, 0),
 (A vertex at (0, 0, 0),
 A ray in the direction (0, 0, 1),
 A ray in the direction (0, 1, 0),
 (A vertex at (0, 0, 0), A ray in the direction (1, 0, 0)),
 (A vertex at (0, 0, 0), A ray in the direction (0, 1, 0)),
 (A vertex at (0, 0, 0),),
 (A vertex at (0, 0, 0), A ray in the direction (0, 0, 1))
sage: it = P.face_generator(algorithm='dual')
Traceback (most recent call last):
ValueError: cannot iterate over dual of unbounded Polyedron
```

Construct a FaceIterator only yielding dimension 2 faces:

```
sage: P = polytopes.permutahedron(5)
sage: it = P.face_generator(face_dimension=2)
sage: counter = 0
```

In non-dual mode one can ignore all faces contained in the current face:

```
sage: P = polytopes.cube()
sage: it = P.face_generator(algorithm='primal')
sage: _ = next(it), next(it)
sage: face = next(it)
sage: face.ambient_H_indices()
(5,)
sage: it.ignore_subfaces()
sage: [face.ambient_H_indices() for face in it]
[(4,),
 (3,),
 (2,),
 (1,),
 (0,),
 (3, 4),
 (1, 4),
 (0, 4),
 (1, 3, 4),
 (0, 1, 4),
 (2, 3),
 (1, 3),
 (1, 2, 3),
 (1, 2),
 (0, 2),
 (0, 1, 2),
 (0, 1)
sage: it = P.face_generator(algorithm='dual')
sage: _ = next(it), next(it)
sage: next(it)
A 0-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 1 vertex
sage: it.ignore_subfaces()
Traceback (most recent call last):
ValueError: only possible when not in dual mode
```

In dual mode one can ignore all faces that contain the current face:

```
sage: P = polytopes.cube()
sage: it = P.face_generator(algorithm='dual')
sage: _ = next(it), next(it)
sage: next(it)
A 0-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 1 vertex
sage: face = next(it)
```

```
sage: face.ambient_V_indices()
sage: [face.ambient_V_indices() for face in it]
[(5,),
 (4,),
 (3,),
 (2,),
 (1,),
 (0,),
 (6, 7),
 (4, 7),
 (2, 7),
 (4, 5, 6, 7),
 (1, 2, 6, 7),
 (2, 3, 4, 7),
 (5, 6),
 (1, 6),
 (0, 1, 5, 6),
 (4, 5),
 (0, 5),
 (0, 3, 4, 5),
 (3, 4),
 (2, 3),
 (0, 3),
 (0, 1, 2, 3),
 (1, 2),
 (0, 1)
sage: it = P.face_generator(algorithm='primal')
sage: _ = next(it), next(it)
sage: next(it)
A 2-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 4.
→vertices
sage: it.ignore_supfaces()
Traceback (most recent call last):
ValueError: only possible when in dual mode
```

### See also:

```
FaceIterator_base.
```

P

# current()

Retrieve the last value of \_\_next\_\_().

**EXAMPLES:** 

### reset()

Reset the iterator.

The iterator will start with the first face again.

**EXAMPLES:** 

```
sage: P = polytopes.cube()
sage: it = P.face_generator()
sage: next(it).ambient_V_indices()
(0, 1, 2, 3, 4, 5, 6, 7)
sage: next(it).ambient_V_indices()
()
sage: next(it).ambient_V_indices()
(0, 3, 4, 5)
sage: it.reset()
sage: next(it).ambient_V_indices()
(0, 1, 2, 3, 4, 5, 6, 7)
sage: next(it).ambient_V_indices()
()
sage: next(it).ambient_V_indices()
()
sage: next(it).ambient_V_indices()
()
```

# 2.3.5 List of faces

This module provides a class to store faces of a polyhedron in Bit-representation.

This class allocates memory to store the faces in. A face will be stored as vertex-incidences, where each Bit represents an incidence. In *conversions* there a methods to actually convert facets of a polyhedron to bit-representations of vertices stored in *ListOfFaces*.

Moreover, *ListOfFaces* calculates the dimension of a polyhedron, assuming the faces are the facets of this polyhedron.

Each face is stored over-aligned according to the chunktype.

### See also

sage.geometry.polyhedron.combinatorial\_polyhedron.base.

### **EXAMPLES:**

Provide enough space to store 20 faces as incidences to 60 vertices:

```
sage: from sage.geometry.polyhedron.combinatorial_polyhedron.list_of_faces \
....: import ListOfFaces
sage: face_list = ListOfFaces(20, 60, 20)
sage: face_list.matrix().is_zero()
True
```

Obtain the facets of a polyhedron:

Obtain the Vrepresentation of a polyhedron as facet-incidences:

Obtain the facets of a polyhedron as *ListOfFaces* from a facet list:

Likewise for the Vrepresentatives as facet-incidences:

Obtain the matrix of a list of faces:

```
sage: face_list.matrix()
[1 1 1 0]
[1 1 0 1]
[1 0 1 1]
[0 1 1 1]
```

### See also:

base, face\_iterator, conversions, polyhedron\_faces\_lattice.

# AUTHOR:

• Jonathan Kliem (2019-04)

 ${\bf class} \ \, {\bf sage.geometry.polyhedron.combinatorial\_polyhedron.list\_of\_faces.ListOfFaces} \\ \ \, {\bf Bases:\ object}$ 

A class to store the Bit-representation of faces in.

This class will allocate the memory for the faces.

INPUT:

- n\_faces the number of faces to be stored
- n\_atoms the total number of atoms the faces contain
- n\_coatoms the total number of coatoms of the polyhedron

### See also:

### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.combinatorial_polyhedron.list_of_faces \
....: import ListOfFaces
sage: facets = ListOfFaces(5, 13, 5)
sage: facets.matrix().dimensions()
(5, 13)
```

# compute\_dimension()

Compute the dimension of a polyhedron by its facets.

This assumes that self is the list of facets of a polyhedron.

# **EXAMPLES:**

### ALGORITHM:

This is done by iteration:

Computes the facets of one of the facets (i.e. the ridges contained in one of the facets). Then computes the dimension of the facet, by considering its facets.

Repeats until a face has only one facet. Usually this is a vertex.

However, in the unbounded case, this might be different. The face with only one facet might be a ray or a line. So the correct dimension of a polyhedron with one facet is the number of [lines, rays, vertices] that the facet contains.

Hence, we know the dimension of a face, which has only one facet and iteratively we know the dimension of entire polyhedron we started from.

### matrix()

Obtain the matrix of self.

Each row represents a face and each column an atom.

**EXAMPLES:** 

```
sage: from sage.geometry.polyhedron.combinatorial_polyhedron.conversions \
          import facets_tuple_to_bit_rep_of_facets, \
. . . . :
          facets_tuple_to_bit_rep_of_Vrep
sage: bi_pyr = ((0,1,4), (1,2,4), (2,3,4), (3,0,4), (0,1,5), (1,2,5), (2,3,5), ...
\hookrightarrow (3,0,5))
sage: facets = facets_tuple_to_bit_rep_of_facets(bi_pyr, 6)
sage: Vrep = facets_tuple_to_bit_rep_of_Vrep(bi_pyr, 6)
sage: facets.matrix()
[1 1 0 0 1 0]
[0 1 1 0 1 0]
[0 0 1 1 1 0]
[1 0 0 1 1 0]
[1 1 0 0 0 1]
[0 \ 1 \ 1 \ 0 \ 0 \ 1]
[0 0 1 1 0 1]
[1 0 0 1 0 1]
sage: facets.matrix().transpose() == Vrep.matrix()
```

# pyramid()

Return the list of faces of the pyramid.

### **EXAMPLES:**

Incorrect facets that illustrate how this method works:

```
sage: facets = ((0,1,2,3), (0,1,2,3), (0,1,2,3), (0,1,2,3))
sage: face_list = facets_tuple_to_bit_rep_of_facets(facets, 4)
sage: face_list.matrix()
[1 1 1 1]
[1 1 1 1]
[1 1 1 1]
sage: face_list.pyramid().matrix()
[1 1 1 1 1]
[1 1 1 1]
```

```
[1 1 1 1 1]
[1 1 1 1 0]
```

```
sage: facets = ((), (), (), ())
sage: face_list = facets_tuple_to_bit_rep_of_facets(facets, 4)
sage: face_list.matrix()
[0 0 0 0]
[0 0 0 0]
[0 0 0 0]
[0 0 0 0]
sage: face_list.pyramid().matrix()
[0 0 0 0 1]
[0 0 0 0 1]
[0 0 0 0 1]
[1 1 1 0]
```

# 2.3.6 Conversions

This module provides conversions to *ListOfFaces* from - an incidence matrix of a polyhedron or - a tuple of facets (as tuple of vertices each).

Also this module provides a conversion from the data of *ListOfFaces*, which is a Bit-vector representing incidences of a face, to a list of entries which are incident.

### See also:

list\_of\_faces, face\_iterator, base.

# EXAMPLES:

Obtain the facets of a polyhedron as *ListOfFaces*:

Obtain the Vrepresentation of a polyhedron as facet-incidences stored in *ListOfFaces*:

```
sage: from sage.geometry.polyhedron.combinatorial_polyhedron.conversions \
    import incidence_matrix_to_bit_rep_of_Vrep
sage: P = polytopes.associahedron(['A',4])  # optional -
    sage.combinat
sage: face_list = incidence_matrix_to_bit_rep_of_Vrep(P.incidence_matrix())  # optional -
    sage.combinat
sage: face_list.compute_dimension()  # optional -
    sage.combinat
```

Obtain the facets of a polyhedron as *ListOfFaces* from a facet list:

Likewise for the Vrep as facet-incidences:

### AUTHOR:

• Jonathan Kliem (2019-04)

Initialize Vrepresentatives in Bit-representation as ListOfFaces.

Each Vrepresentative is represented as the facets it is contained in. Those are the facets of the polar polyhedron, if it exists.

### INPUT:

- facets\_input tuple of facets, each facet a tuple of Vrep, Vrep must be exactly range(n\_Vrep)
- n\_Vrep

# **OUTPUT**:

• ListOfFaces

# **EXAMPLES:**

sage.geometry.polyhedron.combinatorial\_polyhedron.conversions.facets\_tuple\_to\_bit\_rep\_of\_facets(facets\_inp\_n\_Vrep)

Initializes facets in Bit-representation as ListOfFaces.

# INPUT:

- facets\_input tuple of facets, each facet a tuple of Vrep, Vrep must be exactly range(n\_Vrep)
- n\_Vrep

### **OUTPUT**:

ListOfFaces

# **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.combinatorial_polyhedron.conversions \
. . . . :
          import facets_tuple_to_bit_rep_of_facets, \
                 _bit_rep_to_Vrep_list_wrapper
. . . . :
sage: bi_pyr = ((0,1,4), (1,2,4), (2,3,4), (3,0,4),
                (0,1,5), (1,2,5), (2,3,5), (3,0,5))
sage: facets = facets_tuple_to_bit_rep_of_facets(bi_pyr, 6)
sage: for i in range(8):
          print(_bit_rep_to_Vrep_list_wrapper(facets, i))
(0, 1, 4)
(1, 2, 4)
(2, 3, 4)
(0, 3, 4)
(0, 1, 5)
(1, 2, 5)
(2, 3, 5)
(0, 3, 5)
```

sage.geometry.polyhedron.combinatorial\_polyhedron.conversions.incidence\_matrix\_to\_bit\_rep\_of\_Vrep(matrix Initialize Vrepresentatives in Bit-representation as ListOfFaces.

Each Vrepresentative is represented as the facets it is contained in. Those are the facets of the polar polyhedron, if it exists.

# INPUT:

• matrix — an incidence matrix as in sage.geometry.polyhedron.base.Polyhedron\_base.incidence\_matrix() with columns corresponding to equations deleted of type sage.matrix.matrix\_dense.Matrix\_dense

# **OUTPUT**:

• ListOfFaces

# **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.combinatorial_polyhedron.conversions \
. . . . :
          import incidence_matrix_to_bit_rep_of_Vrep, \
                 _bit_rep_to_Vrep_list_wrapper
sage: P = polytopes.permutahedron(4)
sage: inc = P.incidence_matrix()
sage: mod_inc = inc.delete_columns([i for i,V in enumerate(P.Hrepresentation()) if_
→V.is_equation()])
sage: vertices = incidence_matrix_to_bit_rep_of_Vrep(mod_inc)
sage: vertices.matrix().dimensions()
(24, 14)
sage: for row in vertices.matrix():
          row.nonzero_positions()
. . . . . .
[8, 9, 11]
[8, 10, 11]
[2, 3, 7]
[1, 5, 7]
[4, 5, 7]
```

```
[1, 3, 7]
[4, 6, 7]
[2, 6, 7]
[1, 5, 13]
[8, 9, 13]
[1, 9, 11]
[2, 10, 11]
[1, 3, 11]
[2, 3, 11]
[4, 5, 13]
[4, 12, 13]
[8, 12, 13]
[1, 9, 13]
[0, 8, 12]
[0, 4, 12]
[0, 2, 10]
[0, 2, 6]
[0, 8, 10]
[0, 4, 6]
```

sage.geometry.polyhedron.combinatorial\_polyhedron.conversions.incidence\_matrix\_to\_bit\_rep\_of\_facets(matrix\_to\_bit\_

### INPUT:

• matrix — an incidence matrix as in sage.geometry.polyhedron.base.Polyhedron\_base.incidence\_matrix() with columns corresponding to equations deleted of type sage.matrix.matrix\_dense.Matrix\_dense

# **OUTPUT**:

• ListOfFaces

### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.combinatorial_polyhedron.conversions \
. . . . :
          import incidence_matrix_to_bit_rep_of_facets, \
                 _bit_rep_to_Vrep_list_wrapper
sage: P = polytopes.permutahedron(4)
sage: inc = P.incidence_matrix()
sage: mod_inc = inc.delete_columns([i for i,V in enumerate(P.Hrepresentation()) if_
→V.is_equation()])
sage: facets = incidence_matrix_to_bit_rep_of_facets(mod_inc)
sage: facets.matrix().dimensions()
(14, 24)
sage: for row in facets.matrix():
         row.nonzero_positions()
[18, 19, 20, 21, 22, 23]
[3, 5, 8, 10, 12, 17]
[2, 7, 11, 13, 20, 21]
[2, 5, 12, 13]
[4, 6, 14, 15, 19, 23]
[3, 4, 8, 14]
[6, 7, 21, 23]
[2, 3, 4, 5, 6, 7]
```

```
[0, 1, 9, 16, 18, 22]

[0, 9, 10, 17]

[1, 11, 20, 22]

[0, 1, 10, 11, 12, 13]

[15, 16, 18, 19]

[8, 9, 14, 15, 16, 17]
```

# 2.4 Polyhedral complexes

# 2.4.1 Finite polyhedral complexes

This module implements the basic structure of finite polyhedral complexes. For more information, see *PolyhedralComplex*.

# **AUTHORS:**

• Yuan Zhou (2021-05): initial implementation

# **List of PolyhedralComplex methods**

# Maximal cells and cells

<pre>maximal_cells()</pre>	Return the dictionary of the maximal cells in this polyhedral complex.
<pre>maximal_cell_iterator()</pre>	Return an iterator over maximal cells in this polyhedral complex.
<pre>maximal_cells_sorted()</pre>	Return the sorted list of all maximal cells in this polyhedral complex.
n_maximal_cells()	List the maximal cells of dimension $n$ in this polyhedral complex.
_n_maximal_cells_sorted()	Return the sorted list of maximal cells of dim $n$ in this complex.
is_maximal_cell()	Return True if the given cell is a maximal cell in this complex.
cells()	Return the dictionary of the cells in this polyhedral complex.
cell_iterator()	Return an iterator over cells in this polyhedral complex.
cells_sorted()	Return the sorted list of all cells in this polyhedral complex.
n_cells()	List the cells of dimension $n$ in this polyhedral complex.
_n_cells_sorted()	Return the sorted list of $n$ -cells in this polyhedral complex.
is_cell()	Return True if the given cell is in this polyhedral complex.
face_poset()	Return the poset of nonempty cells in the polyhedral complex.
relative_boundary_cells()	List the maximal cells on the boundary of the polyhedral complex.

# Properties of the polyhedral complex

dimension()	Return the dimension of the polyhedral complex.
ambient_dimension()	Return the ambient dimension of the polyhedral complex.
is_pure()	Return True if the polyhedral complex is pure.
is_full_dimensional()	Return True if the polyhedral complex is full dimensional.
is_compact()	Return True if the polyhedral complex is bounded.
is_connected()	Return True if the polyhedral complex is connected.
is_subcomplex()	Return True if this complex is a subcomplex of the other.
is_convex()	Return True if the polyhedral complex is convex.
is_mutable()	Return True if the polyhedral complex is mutable.
is_immutable()	Return True if the polyhedral complex is not mutable.
<pre>is_simplicial_complex()</pre>	Return True if the polyhedral complex is a simplicial complex.
is_polyhedral_fan()	Return True if the polyhedral complex is a fan.
is_simplicial_fan()	Return True if the polyhedral complex is a simplicial fan.

# New polyhedral complexes from old ones

<pre>connected_component()</pre>	Return the connected component containing a cell as a subcomplex.
<pre>connected_components()</pre>	Return the connected components of this polyhedral complex.
n_skeleton()	Return the <i>n</i> -skeleton of this polyhedral complex.
stratify()	Return the (pure) subcomplex formed by the maximal cells of dim $n$ in this
	complex.
<pre>boundary_subcomplex()</pre>	Return the boundary subcomplex of this polyhedral complex.
<pre>product()</pre>	Return the (Cartesian) product of this polyhedral complex with another one.
disjoint_union()	Return the disjoint union of this polyhedral complex with another one.
union()	Return the union of this polyhedral complex with another one.
join()	Return the join of this polyhedral complex with another one.
subdivide()	Return a new polyhedral complex (with option make_simplicial) subdividing
	this one.

# **Update polyhedral complex**

set_immutable()	Make this polyhedral complex immutable.
add_cell()	Add a cell to this polyhedral complex.
remove_cell()	Remove a cell from this polyhedral complex.

# Miscellaneous

plot()	Return a Graphic object showing the plot of polyhedral complex.
graph()	Return a directed graph corresponding to the 1-skeleton of this polyhedral com-
	plex, given that it is bounded.
union_as_polyhedron()	Return a Polyhedron which is the union of cells in this polyhedral complex,
	given that it is convex.

### **Classes and functions**

Bases: sage.topology.cell\_complex.GenericCellComplex

A polyhedral complex.

A **polyhedral complex** PC is a collection of polyhedra in a certain ambient space  $\mathbb{R}^n$  such that the following hold.

- If a polyhedron P is in PC, then all the faces of P are in PC.
- If polyhedra P and Q are in PC, then  $P \cap Q$  is either empty or a face of both P and Q.

In this context, a "polyhedron" means the geometric realization of a polyhedron. This is in contrast to simplicial complex, whose cells are abstract simplices. The concept of a polyhedral complex generalizes that of a **geometric** simplicial complex.

**Note:** This class derives from GenericCellComplex, and so inherits its methods. Some of those methods are not listed here; see the Generic Cell Complex page instead.

### INPUT:

- maximal\_cells a list, a tuple, or a dictionary (indexed by dimension) of cells of the Complex. Each cell is of class *Polyhedron* of the same ambient dimension. To set up a :class:PolyhedralComplex, it is sufficient to provide the maximal faces. Use keyword argument partial=True to set up a partial polyhedral complex, which is a subset of the faces (viewed as relatively open) of a polyhedral complex that is not necessarily closed under taking intersection.
- maximality\_check boolean (default: True); if True, then the constructor checks that each given maximal cell is indeed maximal, and ignores those that are not
- face\_to\_face\_check boolean (default: False); if True, then the constructor checks whether the cells are face-to-face, and it raises a ValueError if they are not
- is\_mutable and is\_immutable boolean (default: True and False respectively); set is\_mutable=False or is\_immutable=True to make this polyhedral complex immutable
- backend string (optional); the name of the backend used for computations on Sage polyhedra; if it is not given, then each cell has its own backend; otherwise it must be one of the following:
  - 'ppl' the Parma Polyhedra Library
  - 'cdd' CDD
  - 'normaliz' normaliz
  - 'polymake' polymake
  - 'field' a generic Sage implementation
- ambient\_dim integer (optional); used to set up an empty complex in the intended ambient space

# **EXAMPLES:**

```
sage: pc = PolyhedralComplex([
              Polyhedron(vertices=[(1/3, 1/3), (0, 0), (1/7, 2/7)]),
              Polyhedron(vertices=[(1/7, 2/7), (0, 0), (0, 1/4)])])
. . . . :
sage: [p.Vrepresentation() for p in pc.cells_sorted()]
[(A vertex at (0, 0), A vertex at (0, 1/4), A vertex at (1/7, 2/7)),
(A vertex at (0, 0), A vertex at (1/3, 1/3), A vertex at (1/7, 2/7)),
 (A vertex at (0, 0), A vertex at (0, 1/4)),
 (A vertex at (0, 0), A vertex at (1/7, 2/7)),
 (A vertex at (0, 0), A vertex at (1/3, 1/3)),
 (A vertex at (0, 1/4), A vertex at (1/7, 2/7)),
 (A vertex at (1/3, 1/3), A vertex at (1/7, 2/7)),
 (A vertex at (0, 0),),
 (A vertex at (0, 1/4),),
 (A vertex at (1/7, 2/7),),
 (A vertex at (1/3, 1/3),)]
sage: pc.plot() # optional - sage.plot
Graphics object consisting of 10 graphics primitives
sage: pc.is_pure()
True
sage: pc.is_full_dimensional()
sage: pc.is_compact()
True
sage: pc.boundary_subcomplex()
Polyhedral complex with 4 maximal cells
sage: pc.is_convex()
sage: pc.union_as_polyhedron().Hrepresentation()
(An inequality (1, -4) \times + 1 \ge 0,
An inequality (-1, 1) x + 0 >= 0,
An inequality (1, 0) x + 0 >= 0
sage: pc.face_poset()
Finite poset containing 11 elements
sage: pc.is_connected()
True
sage: pc.connected_component() == pc
```

# add\_cell(cell)

Add a cell to this polyhedral complex.

### INPUT:

• cell – a polyhedron

This **changes** the polyhedral complex, by adding a new cell and all of its subfaces.

## **EXAMPLES:**

Set up an empty complex in the intended ambient space, then add a cell:

```
sage: pc = PolyhedralComplex(ambient_dim=2)
sage: pc.add_cell(Polyhedron(vertices=[(1, 2), (0, 2)]))
sage: pc
Polyhedral complex with 1 maximal cell
```

If you add a cell which is already present, there is no effect:

```
sage: pc.add_cell(Polyhedron(vertices=[(1, 2)]))
sage: pc
Polyhedral complex with 1 maximal cell
sage: pc.dimension()
1
```

Add a cell and check that dimension is correctly updated:

Add another cell and check that the properties are correctly updated:

```
sage: pc.add_cell(Polyhedron(vertices=[(1, 1), (0, 0), (1, 2)]))
sage: pc
Polyhedral complex with 2 maximal cells
sage: len(pc._cells[1])
5
sage: pc._face_poset
Finite poset containing 11 elements
sage: pc._is_convex
True
sage: pc._polyhedron.vertices_list()
[[0, 0], [0, 2], [1, 1], [1, 2]]
```

Add a ray which makes the complex non convex:

```
sage: pc.add_cell(Polyhedron(rays=[(1, 0)]))
sage: pc
Polyhedral complex with 3 maximal cells
sage: len(pc._cells[1])
6
sage: (pc._is_convex is False) and (pc._polyhedron is None)
True
```

# alexander\_whitney(cell, dim\_left)

The decomposition of cell in this complex into left and right factors, suitable for computing cup products.

**Todo:** Implement *alexander\_whitney()* of a polyhedral complex.

# **EXAMPLES:**

```
sage: pc = PolyhedralComplex([Polyhedron(vertices=[[0], [1]])])
sage: pc.alexander_whitney(None, 1)
Traceback (most recent call last):
```

```
...
NotImplementedError: alexander_whitney is not implemented for polyhedral complex
```

### ambient\_dimension()

The ambient dimension of this cell complex: the ambient dimension of each of its cells.

### **EXAMPLES:**

```
sage: pc = PolyhedralComplex([Polyhedron(vertices=[(1, 2, 3)])])
sage: pc.ambient_dimension()
sage: empty_pc = PolyhedralComplex([])
sage: empty_pc.ambient_dimension()
-1
sage: pc0 = PolyhedralComplex(ambient_dim=2)
sage: pc0.ambient_dimension()
2
```

### boundary\_subcomplex()

Return the sub-polyhedral complex that is the boundary of self.

A point P is on the boundary of a set S if P is in the closure of S but not in the interior of S.

### **EXAMPLES:**

```
sage: p1 = Polyhedron(vertices=[(1, 1), (0, 0), (1, 2)])
sage: p2 = Polyhedron(vertices=[(1, 2), (0, 0), (0, 2)])
sage: p3 = Polyhedron(vertices=[(1, 2), (0, 2)])
sage: bd = PolyhedralComplex([p1, p2]).boundary_subcomplex()
sage: len(bd.n_maximal_cells(2))
0
sage: len(bd.n_maximal_cells(1))
4
sage: pt = PolyhedralComplex([p3])
sage: pt.boundary_subcomplex() == pt
True
```

Test on polyhedral complex which is not pure:

```
sage: pc_non_pure = PolyhedralComplex([p1, p3])
sage: pc_non_pure.boundary_subcomplex() == pc_non_pure.n_skeleton(1)
True
```

Test with maximality\_check == False:

Test unbounded cases:

```
sage: pc1.boundary_subcomplex() == pc1.n_skeleton(1)
True
sage: pc1b = PolyhedralComplex([Polyhedron(
              vertices=[[1,0,0], [0,1,0]], rays=[[1,0,0],[0,1,0]])
sage: pc1b.boundary_subcomplex() == pc1b
True
sage: pc2 = PolyhedralComplex([
              Polyhedron(vertices=[[-1,0], [1,0]], lines=[[0,1]])])
sage: pc2.boundary_subcomplex() == pc2.n_skeleton(1)
True
sage: pc3 = PolyhedralComplex([
. . . . . .
              Polyhedron(vertices=[[1,0], [0,1]], rays=[[1,0], [0,1]]),
              Polyhedron(vertices=[[1,0], [0,-1]], rays=[[1,0], [0,-1]])])
sage: pc3.boundary_subcomplex() == pc3.n_skeleton(1)
False
```

# cell\_iterator(increasing=True)

An iterator for the cells in this polyhedral complex.

### INPUT:

• increasing – (default True) if True, return cells in increasing order of dimension, thus starting with the zero-dimensional cells; otherwise it returns cells in decreasing order of dimension

**Note:** Among the cells of a fixed dimension, there is no sorting.

# **EXAMPLES:**

### **cells**(*subcomplex=None*)

The cells of this polyhedral complex, in the form of a dictionary: the keys are integers, representing dimension, and the value associated to an integer d is the set of d-cells.

### INPUT:

• subcomplex – (optional) if a subcomplex is given then return the cells which are **not** in this subcomplex

# **EXAMPLES:**

# cells\_sorted(subcomplex=None)

The sorted list of the cells of this polyhedral complex in non-increasing dimensions.

INPUT:

• subcomplex – (optional) if a subcomplex is given then return the cells which are **not** in this subcomplex

### **EXAMPLES:**

```
sage: pc = PolyhedralComplex([
....: Polyhedron(vertices=[(1, 1), (0, 0), (1, 2)]),
....: Polyhedron(vertices=[(1, 2), (0, 0), (0, 2)])])
sage: len(pc.cells_sorted())
11
sage: pc.cells_sorted()[0].Vrepresentation()
(A vertex at (0, 0), A vertex at (0, 2), A vertex at (1, 2))
```

**chain\_complex**(subcomplex=None, augmented=False, verbose=False, check=True, dimensions=None, base\_ring=Integer Ring, cochain=False)

The chain complex associated to this polyhedral complex.

Todo: Implement chain complexes of a polyhedral complex.

### **EXAMPLES:**

```
sage: pc = PolyhedralComplex([Polyhedron(vertices=[[0], [1]])])
sage: pc.chain_complex()
Traceback (most recent call last):
...
NotImplementedError: chain_complex is not implemented for polyhedral complex
```

# connected\_component(cell=None)

Return the connected component of this polyhedral complex containing a given cell.

### INPUT:

• cell - (default: self.an\_element()) a cell of self

## **OUTPUT**:

The connected component containing cell. If the polyhedral complex is empty or if it does not contain the given cell, raise an error.

# EXAMPLES:

```
sage: t1 = Polyhedron(vertices=[(1, 1), (0, 0), (1, 2)])
sage: t2 = Polyhedron(vertices=[(1, 2), (0, 0), (0, 2)])
sage: v1 = Polyhedron(vertices=[(1, 1)])
sage: v2 = Polyhedron(vertices=[(0, 2)])
sage: v3 = Polyhedron(vertices=[(-1, 0)])
sage: o = Polyhedron(vertices=[(0, 0)])
sage: r = Polyhedron(rays=[(1, 0)])
sage: l = Polyhedron(vertices=[(-1, 0)], lines=[(1, -1)])
sage: pc1 = PolyhedralComplex([t1, t2])
sage: pc1.connected_component() == pc1
True
sage: pc1.connected_component(v1) == pc1
True
sage: pc2 = PolyhedralComplex([t1, v2])
sage: pc2.connected_component(t1) == PolyhedralComplex([t1])
```

```
True
sage: pc2.connected_component(o) == PolyhedralComplex([t1])
sage: pc2.connected_component(v3)
Traceback (most recent call last):
. . .
ValueError: the polyhedral complex does not contain the given cell
sage: pc2.connected_component(r)
Traceback (most recent call last):
ValueError: the polyhedral complex does not contain the given cell
sage: pc3 = PolyhedralComplex([t1, t2, r])
sage: pc3.connected_component(v2) == pc3
sage: pc4 = PolyhedralComplex([t1, t2, r, l])
sage: pc4.connected_component(o) == pc3
True
sage: pc4.connected_component(v3)
Traceback (most recent call last):
ValueError: the polyhedral complex does not contain the given cell
sage: pc5 = PolyhedralComplex([t1, t2, r, 1, v3])
sage: pc5.connected_component(v3) == PolyhedralComplex([v3])
True
sage: PolyhedralComplex([]).connected_component()
Traceback (most recent call last):
ValueError: the empty polyhedral complex has no connected components
```

# connected\_components()

Return the connected components of this polyhedral complex, as list of (sub-)PolyhedralComplexes.

# **EXAMPLES:**

```
sage: t1 = Polyhedron(vertices=[(1, 1), (0, 0), (1, 2)])
sage: t2 = Polyhedron(vertices=[(1, 2), (0, 0), (0, 2)])
sage: v1 = Polyhedron(vertices=[(1, 1)])
sage: v2 = Polyhedron(vertices=[(0, 2)])
sage: v3 = Polyhedron(vertices=[(-1, 0)])
sage: o = Polyhedron(vertices=[(0, 0)])
sage: r = Polyhedron(rays=[(1, 0)])
sage: l = Polyhedron(vertices=[(-1, 0)], lines=[(1, -1)])
sage: pc1 = PolyhedralComplex([t1, t2])
sage: len(pc1.connected_components())
sage: pc2 = PolyhedralComplex([t1, v2])
sage: len(pc2.connected_components())
sage: pc3 = PolyhedralComplex([t1, t2, r])
sage: len(pc3.connected_components())
1
sage: pc4 = PolyhedralComplex([t1, t2, r, 1])
sage: len(pc4.connected_components())
```

```
sage: pc5 = PolyhedralComplex([t1, t2, r, 1, v3])
sage: len(pc5.connected_components())
sage: PolyhedralComplex([]).connected_components()
Traceback (most recent call last):
...
ValueError: the empty polyhedral complex has no connected components
```

# dimension()

The dimension of this cell complex: the maximum dimension of its cells.

### **EXAMPLES:**

# disjoint\_union(right)

The disjoint union of this polyhedral complex with another one.

# INPUT:

• right – the other polyhedral complex (the right-hand factor)

## **EXAMPLES:**

```
sage: p1 = Polyhedron(vertices=[(-1, 0), (0, 0), (0, 1)])
sage: p2 = Polyhedron(vertices=[(0, -1), (0, 0), (1, 0)])
sage: p3 = Polyhedron(vertices=[(0, -1), (1, -1), (1, 0)])
sage: pc = PolyhedralComplex([p1]).disjoint_union(PolyhedralComplex([p3]))
sage: set(pc.maximal_cell_iterator()) == set([p1, p3])
True
sage: pc.disjoint_union(PolyhedralComplex([p2]))
Traceback (most recent call last):
...
ValueError: the two complexes are not disjoint
```

### face\_poset()

The face poset of this polyhedral complex, the poset of nonempty cells, ordered by inclusion.

# **EXAMPLES:**

```
sage: poset.plot(element_labels=d) # optional - sage.plot
Graphics object consisting of 28 graphics primitives
```

For a nonbounded polyhedral complex:

```
sage: pc = PolyhedralComplex([
              Polyhedron(vertices=[(1/3, 1/3), (0, 0), (1, 2)]),
. . . . .
              Polyhedron(vertices=[(1, 2), (0, 0), (0, 1/2)]),
. . . . :
              Polyhedron(vertices=[(-1/2, -1/2)], lines=[(1, -1)]),
              Polyhedron(rays=[(1, 0)])])
. . . . :
sage: poset = pc.face_poset()
sage: poset
Finite poset containing 13 elements
sage: d = \{i:''.join([str(v)+'\n']
           for v in i.Vrepresentation()]) for i in poset}
sage: poset.show(element_labels=d, figsize=15)
                                                  # not tested
sage: pc = PolyhedralComplex([
....: Polyhedron(rays=[(1,0),(0,1)]),
....: Polyhedron(rays=[(-1,0),(0,1)]),
...: Polyhedron(rays=[(-1,0),(0,-1)]),
....: Polyhedron(rays=[(1,0),(0,-1)])
sage: pc.face_poset()
Finite poset containing 9 elements
```

### graph()

The 1-skeleton of this polyhedral complex, as a graph.

The vertices of the graph are of type vector. Raises a NotImplementedError if the polyhedral complex is unbounded.

**Warning:** This may give the wrong answer if the polyhedral complex was constructed with maximality\_check set to False.

# **EXAMPLES:**

Wrong answer due to maximality\_check=False:

```
sage: p1 = Polyhedron(vertices=[(1, 1), (0, 0), (1, 2)])
sage: p2 = Polyhedron(vertices=[(1, 2), (0, 0), (0, 2)])
sage: p3 = Polyhedron(vertices=[(1, 2), (0, 2)])
sage: PolyhedralComplex([p1, p2]).is_pure()
True
sage: PolyhedralComplex([p2, p3], maximality_check=True).is_pure()
True
sage: PolyhedralComplex([p2, p3], maximality_check=False).is_pure()
False
```

# is\_cell(c)

Return whether the given cell c is a cell of self.

#### **EXAMPLES:**

```
sage: p1 = Polyhedron(vertices=[(1, 1), (0, 0), (1, 2)])
sage: p2 = Polyhedron(vertices=[(1, 2), (0, 0), (0, 2)])
sage: p3 = Polyhedron(vertices=[(1, 2), (0, 2)])
sage: pc = PolyhedralComplex([p1, p2])
sage: pc.is_cell(p3)
True
sage: pc.is_cell(Polyhedron(vertices=[(0, 0)]))
True
```

### is\_compact()

Test for boundedness of the polyhedral complex

#### **EXAMPLES:**

```
sage: p1 = Polyhedron(vertices=[(1, 2), (0, 0), (0, 1/2)])
sage: p2 = Polyhedron(rays=[(1, 0)])
sage: PolyhedralComplex([p1]).is_compact()
True
sage: PolyhedralComplex([p1, p2]).is_compact()
False
```

#### is\_connected()

Return whether self is connected.

# EXAMPLES:

```
sage: pc1 = PolyhedralComplex([
              Polyhedron(vertices=[(1, 1), (0, 0), (1, 2)]),
. . . . . .
              Polyhedron(vertices=[(1, 2), (0, 0), (0, 2)])]
. . . . :
sage: pc1.is_connected()
True
sage: pc2 = PolyhedralComplex([
              Polyhedron(vertices=[(1, 1), (0, 0), (1, 2)]),
              Polyhedron(vertices=[(0, 2)])])
sage: pc2.is_connected()
False
sage: pc3 = PolyhedralComplex([
              Polyhedron(vertices=[(1/3, 1/3), (0, 0), (1, 2)]),
. . . . . .
              Polyhedron(vertices=[(1, 2), (0, 0), (0, 1/2)]),
. . . . .
              Polyhedron(vertices=[(-1/2, -1/2)], lines=[(1, -1)]),
```

### is\_convex()

Return whether the set of points in self is a convex set.

When self is convex, the union of its cells is a Polyhedron.

#### See also:

```
union_as_polyhedron()
```

#### **EXAMPLES:**

```
sage: p1 = Polyhedron(vertices=[(1, 1), (0, 0), (1, 2)])
sage: p2 = Polyhedron(vertices=[(1, 2), (0, 0), (0, 2)])
sage: p3 = Polyhedron(vertices=[(0, 0), (1, 1), (2, 0)])
sage: p4 = Polyhedron(vertices=[(2, 2)])
sage: PolyhedralComplex([p1, p2]).is_convex()
True
sage: PolyhedralComplex([p1, p3]).is_convex()
False
sage: PolyhedralComplex([p1, p4]).is_convex()
```

Test unbounded cases:

```
sage: pc1 = PolyhedralComplex([
              Polyhedron(vertices=[[1,0], [0,1]], rays=[[1,0], [0,1]])])
sage: pc1.is_convex()
sage: pc2 = PolyhedralComplex([
              Polyhedron(vertices=[[-1,0], [1,0]], lines=[[0,1]])])
sage: pc2.is_convex()
sage: pc3 = PolyhedralComplex([
. . . . . .
              Polyhedron(vertices=[[1,0], [0,1]], rays=[[1,0], [0,1]]),
              Polyhedron(vertices=[[1,0], [0,-1]], rays=[[1,0], [0,-1]])
sage: pc3.is_convex()
False
sage: pc4 = PolyhedralComplex([Polyhedron(rays=[[1,0], [-1,1]]),
                               Polyhedron(rays=[[1,0], [-1,-1]])])
sage: pc4.is_convex()
False
```

The whole 3d space minus the first orthant is not convex:

```
sage: pc5 = PolyhedralComplex([
....: Polyhedron(rays=[[1,0,0], [0,1,0], [0,0,-1]]),
```

```
Polyhedron(rays=[[1,0,0], [0,-1,0], [0,0,-1]]),
Polyhedron(rays=[[1,0,0], [0,-1,0], [0,0,1]]),
Polyhedron(rays=[[-1,0,0], [0,-1,0], [0,0,-1]]),
Polyhedron(rays=[[-1,0,0], [0,-1,0], [0,0,1]]),
Polyhedron(rays=[[-1,0,0], [0,1,0], [0,0,-1]]),
Polyhedron(rays=[[-1,0,0], [0,1,0], [0,0,1]])])

sage: pc5.is_convex()
False
```

Test some non-full-dimensional examples:

# is\_full\_dimensional()

Return whether this polyhedral complex is full-dimensional: its dimension is equal to its ambient dimension.

# EXAMPLES:

```
sage: p1 = Polyhedron(vertices=[(1, 1), (0, 0), (1, 2)])
sage: p2 = Polyhedron(vertices=[(1, 2), (0, 0), (0, 2)])
sage: p3 = Polyhedron(vertices=[(1, 2), (0, 2)])
sage: pc = PolyhedralComplex([p1, p2, p3])
sage: pc.is_full_dimensional()
True
sage: PolyhedralComplex([p3]).is_full_dimensional()
False
```

## is immutable()

Return whether self is immutable.

#### **EXAMPLES:**

```
sage: pc3.is_immutable()
True
```

### is\_maximal\_cell(c)

Return whether the given cell c is a maximal cell of self.

**Warning:** This may give the wrong answer if the polyhedral complex was constructed with maximality\_check set to False.

#### **EXAMPLES:**

```
sage: p1 = Polyhedron(vertices=[(1, 1), (0, 0), (1, 2)])
sage: p2 = Polyhedron(vertices=[(1, 2), (0, 0), (0, 2)])
sage: p3 = Polyhedron(vertices=[(1, 2), (0, 2)])
sage: pc = PolyhedralComplex([p1, p2, p3])
sage: pc.is_maximal_cell(p1)
True
sage: pc.is_maximal_cell(p3)
False
```

Wrong answer due to maximality\_check=False:

#### is\_mutable()

Return whether self is mutable.

### **EXAMPLES:**

# is\_polyhedral\_fan()

Test if this polyhedral complex is a polyhedral fan.

A polyhedral complex is a **fan** if all of its (maximal) cells are cones.

```
sage: p1 = Polyhedron(vertices=[(0, 0), (1, 1), (1, 2)])
sage: p2 = Polyhedron(rays=[(1, 0)])
sage: PolyhedralComplex([p1]).is_polyhedral_fan()
False
sage: PolyhedralComplex([p2]).is_polyhedral_fan()
True
sage: halfplane = Polyhedron(rays=[(1, 0), (-1, 0), (0, 1)])
sage: PolyhedralComplex([halfplane]).is_polyhedral_fan()
True
```

### is\_pure()

Test if this polyhedral complex is pure.

A polyhedral complex is pure if and only if all of its maximal cells have the same dimension.

**Warning:** This may give the wrong answer if the polyhedral complex was constructed with maximality\_check set to False.

#### **EXAMPLES:**

```
sage: p1 = Polyhedron(vertices=[(1, 1), (0, 0), (1, 2)])
sage: p2 = Polyhedron(vertices=[(1, 2), (0, 0), (0, 2)])
sage: p3 = Polyhedron(vertices=[(1, 2), (0, 2)])
sage: pc = PolyhedralComplex([p1, p2, p3])
sage: pc.is_pure()
True
```

Wrong answer due to maximality\_check=False:

# is\_simplicial\_complex()

Test if this polyhedral complex is a simplicial complex.

A polyhedral complex is **simplicial** if all of its (maximal) cells are simplices, i.e., every cell is a bounded polytope with d+1 vertices, where d is the dimension of the polytope.

# **EXAMPLES:**

```
sage: p1 = Polyhedron(vertices=[(0, 0), (1, 1), (1, 2)])
sage: p2 = Polyhedron(rays=[(1, 0)])
sage: PolyhedralComplex([p1]).is_simplicial_complex()
True
sage: PolyhedralComplex([p2]).is_simplicial_complex()
False
```

#### is\_simplicial\_fan()

Test if this polyhedral complex is a simplicial fan.

A polyhedral complex is a **simplicial fan** if all of its (maximal) cells are simplical cones, i.e., every cell is a pointed cone (with vertex being the origin) generated by d linearly independent rays, where d is the dimension of the cone.

#### **EXAMPLES:**

```
sage: p1 = Polyhedron(vertices=[(0, 0), (1, 1), (1, 2)])
sage: p2 = Polyhedron(rays=[(1, 0)])
sage: PolyhedralComplex([p1]).is_simplicial_fan()
False
sage: PolyhedralComplex([p2]).is_simplicial_fan()
True
sage: halfplane = Polyhedron(rays=[(1, 0), (-1, 0), (0, 1)])
sage: PolyhedralComplex([halfplane]).is_simplicial_fan()
False
```

# is\_subcomplex(other)

Return whether self is a subcomplex of other.

## INPUT:

• other – a polyhedral complex

Each maximal cell of self must be a cell of other for this to be True.

### **EXAMPLES:**

```
sage: p1 = Polyhedron(vertices=[(1/3, 1/3), (0, 0), (1, 2)])
sage: p2 = Polyhedron(vertices=[(1, 2), (0, 0), (0, 1/2)])
sage: p3 = Polyhedron(vertices=[(0, 0), (1, 0)])
sage: pc = PolyhedralComplex([p1, Polyhedron(vertices=[(1, 0)])])
sage: pc.is_subcomplex(PolyhedralComplex([p1, p2, p3]))
True
sage: pc.is_subcomplex(PolyhedralComplex([p1, p2]))
False
```

#### join(right)

The join of this polyhedral complex with another one.

# INPUT:

• right – the other polyhedral complex (the right-hand factor)

#### **EXAMPLES:**

```
sage: pc = PolyhedralComplex([Polyhedron(vertices=[[0], [1]])])
sage: pc_join = pc.join(pc)
sage: pc_join
Polyhedral complex with 1 maximal cell
sage: next(pc_join.maximal_cell_iterator()).vertices()
(A vertex at (0, 0, 0),
   A vertex at (0, 0, 1),
   A vertex at (0, 1, 1),
   A vertex at (1, 0, 0))
```

# maximal\_cell\_iterator(increasing=False)

An iterator for the maximal cells in this polyhedral complex.

## INPUT:

• increasing – (optional, default False) if True, return maximal cells in increasing order of dimension. Otherwise it returns cells in decreasing order of dimension.

**Note:** Among the cells of a fixed dimension, there is no sorting.

**Warning:** This may give the wrong answer if the polyhedral complex was constructed with maximality\_check set to False.

#### **EXAMPLES:**

```
sage: p1 = Polyhedron(vertices=[(1, 1), (0, 0), (1, 2)])
sage: p2 = Polyhedron(vertices=[(1, 2), (0, 0), (0, 2)])
sage: p3 = Polyhedron(vertices=[(1, 2), (0, 2)])
sage: pc = PolyhedralComplex([p1, p2, p3])
sage: len(list(pc.maximal_cell_iterator()))
2
```

Wrong answer due to maximality\_check=False:

# maximal\_cells()

The maximal cells of this polyhedral complex, in the form of a dictionary: the keys are integers, representing dimension, and the value associated to an integer d is the set of d-maximal cells.

**Warning:** This may give the wrong answer if the polyhedral complex was constructed with maximality\_check set to False.

### **EXAMPLES:**

```
sage: p1 = Polyhedron(vertices=[(1, 1), (0, 0), (1, 2)])
sage: p2 = Polyhedron(vertices=[(1, 2), (0, 0), (0, 2)])
sage: p3 = Polyhedron(vertices=[(1, 2), (0, 2)])
sage: pc = PolyhedralComplex([p1, p2, p3])
sage: len(pc.maximal_cells()[2])
2
sage: 1 in pc.maximal_cells()
False
```

Wrong answer due to maximality\_check=False:

```
sage: pc_invalid = PolyhedralComplex([p1, p2, p3],
....: maximality_check=False)
sage: len(pc_invalid.maximal_cells()[1])
1
```

# maximal\_cells\_sorted()

Return the sorted list of the maximal cells of this polyhedral complex by non-increasing dimensions.

# n\_maximal\_cells(n)

List of maximal cells of dimension n of this polyhedral complex.

#### INPUT:

• n – non-negative integer; the dimension

**Note:** The resulting list need not be sorted. If you want a sorted list of n-cells, use  $_n$ -maximal\_cells\_sorted().

**Warning:** This may give the wrong answer if the polyhedral complex was constructed with maximality\_check set to False.

#### **EXAMPLES:**

```
sage: p1 = Polyhedron(vertices=[(1, 1), (0, 0), (1, 2)])
sage: p2 = Polyhedron(vertices=[(1, 2), (0, 0), (0, 2)])
sage: p3 = Polyhedron(vertices=[(1, 2), (0, 2)])
sage: pc = PolyhedralComplex([p1, p2, p3])
sage: len(pc.n_maximal_cells(2))
2
sage: len(pc.n_maximal_cells(1))
0
```

Wrong answer due to maximality\_check=False:

#### n\_skeleton(n)

The n-skeleton of this polyhedral complex.

The n-skeleton of a polyhedral complex is obtained by discarding all of the cells in dimensions larger than n.

# INPUT:

• n – non-negative integer; the dimension

#### See also:

stratify()

#### plot(\*\*kwds)

Return a plot of the polyhedral complex, if it is of dim at most 3.

#### INPUT:

- explosion\_factor (default: 0) if positive, separate the cells of the complex by extra space. In this case, the following keyword arguments can be passed to exploded\_plot():
  - center (default: None, denoting the origin) the center of explosion
  - sticky\_vertices (default: False) boolean or dict. Whether to draw line segments between shared vertices of the given polyhedra. A dict gives options for sage.plot.line().
  - sticky\_center (default: True) boolean or dict. When center is a vertex of some of the polyhedra, whether to draw line segments connecting the center to the shifted copies of these vertices. A dict gives options for sage.plot.line().
- color (default: None) if "rainbow", assign a different color to every maximal cell; otherwise, passed on to plot().
- other keyword arguments are passed on to plot().

## **EXAMPLES:**

```
sage: p1 = Polyhedron(vertices=[(1, 1), (0, 0), (1, 2)])
sage: p2 = Polyhedron(vertices=[(1, 2), (0, 0), (0, 2)])
sage: p3 = Polyhedron(vertices=[(0, 0), (0, 2), (-1, 1)])
sage: pc1 = PolyhedralComplex([p1, p2, p3, -p1, -p2, -p3])
sage: bb = dict(xmin=-2, xmax=2, ymin=-3, ymax=3, axes=False)
sage: g0 = pc1.plot(color='rainbow', **bb)
                                                                             #_
→optional - sage.plot
sage: g1 = pc1.plot(explosion_factor=0.5, **bb)
                                                                             #__
→optional - sage.plot
sage: g2 = pc1.plot(explosion_factor=1, color='rainbow', alpha=0.5, **bb)
→optional - sage.plot
sage: graphics_array([g0, g1, g2]).show(axes=False)
                                                                             #__
→not tested
sage: pc2 = PolyhedralComplex([polytopes.hypercube(3)])
sage: pc3 = pc2.subdivide(new_vertices=[(0, 0, 0)])
sage: g3 = pc3.plot(explosion_factor=1, color='rainbow',
                                                                             #_
→optional - sage.plot
. . . . :
                    alpha=0.5, axes=False, online=True)
sage: pc4 = pc2.subdivide(make_simplicial=True)
sage: g4 = pc4.plot(explosion_factor=1, center=(1, -1, 1), fill='blue',
                                                                             #. .
→optional - sage.plot
                   wireframe='white', point={'color':'red', 'size':10},
. . . . :
```

```
. . . . :
                    alpha=0.6, online=True)
sage: pc5 = PolyhedralComplex([
              Polyhedron(rays=[[1,0,0], [0,1,0], [0,0,-1]]),
              Polyhedron(rays=[[1,0,0], [0,-1,0], [0,0,-1]]),
              Polyhedron(rays=[[1,0,0], [0,-1,0], [0,0,1]]),
. . . . :
              Polyhedron(rays=[[-1,0,0], [0,-1,0], [0,0,-1]]),
              Polyhedron(rays=[[-1,0,0], [0,-1,0], [0,0,1]]),
              Polyhedron(rays=[[-1,0,0], [0,1,0], [0,0,-1]]),
. . . . :
              Polyhedron(rays=[[-1,0,0], [0,1,0], [0,0,1]])])
sage: g5 = pc5.plot(explosion_factor=0.3, color='rainbow', alpha=0.8,
                                                                                #__
\rightarrowoptional - sage.plot
. . . . :
                     point={'size': 20}, axes=False, online=True)
```

## product(right)

The (Cartesian) product of this polyhedral complex with another one.

#### INPUT:

• right – the other polyhedral complex (the right-hand factor)

#### **OUTPUT:**

• the product self x right

#### **EXAMPLES:**

```
sage: pc = PolyhedralComplex([Polyhedron(vertices=[[0], [1]])])
sage: pc_square = pc.product(pc)
sage: pc_square
Polyhedral complex with 1 maximal cell
sage: next(pc_square.maximal_cell_iterator()).vertices()
(A vertex at (0, 0),
   A vertex at (0, 1),
   A vertex at (1, 0),
   A vertex at (1, 1))
```

# relative\_boundary\_cells()

Return the maximal cells of the relative-boundary sub-complex.

A point P is in the relative boundary of a set S if P is in the closure of S but not in the relative interior of S.

**Warning:** This may give the wrong answer if the polyhedral complex was constructed with maximality\_check set to False.

# **EXAMPLES:**

```
sage: p1 = Polyhedron(vertices=[(1, 1), (0, 0), (1, 2)])
sage: p2 = Polyhedron(vertices=[(1, 2), (0, 0), (0, 2)])
sage: p3 = Polyhedron(vertices=[(1, 2), (0, 2)])
sage: p4 = Polyhedron(vertices=[(2, 2)])
sage: pc = PolyhedralComplex([p1, p2])
sage: rbd_cells = pc.relative_boundary_cells()
sage: len(rbd_cells)
```

```
sage: all(p.dimension() == 1 for p in rbd_cells)
True
sage: pc_lower_dim = PolyhedralComplex([p3])
sage: sorted([p.vertices() for p in pc_lower_dim.relative_boundary_cells()])
[(A vertex at (0, 2),), (A vertex at (1, 2),)]
```

Test on polyhedral complex which is not pure:

```
sage: pc_non_pure = PolyhedralComplex([p1, p3, p4])
sage: (set(pc_non_pure.relative_boundary_cells())
....: == set([f.as_polyhedron() for f in p1.faces(1)] + [p3, p4]))
True
```

Test with maximality\_check == False:

Test unbounded case:

#### remove\_cell(cell, check=False)

Remove cell from self and all the cells that contain cell as a subface.

# INPUT:

- cell a cell of the polyhedral complex
- check boolean (default: False); if True, raise an error if cell is not a cell of this complex

This does not return anything; instead, it **changes** the polyhedral complex.

## **EXAMPLES:**

If you add a cell which is already present, there is no effect:

```
sage: p1 = Polyhedron(vertices=[(1, 1), (0, 0), (1, 2)])
sage: p2 = Polyhedron(vertices=[(1, 2), (0, 0), (0, 2)])
sage: r = Polyhedron(rays=[(1, 0)])
sage: pc = PolyhedralComplex([p1, p2, r])
sage: pc.dimension()
2
sage: pc.remove_cell(Polyhedron(vertices=[(0, 0), (1, 2)]))
sage: pc.dimension()
1
sage: pc
Polyhedral complex with 5 maximal cells
```

```
sage: pc.remove_cell(Polyhedron(vertices=[(1, 2)]))
sage: pc.dimension()
1
sage: pc
Polyhedral complex with 3 maximal cells
sage: pc.remove_cell(Polyhedron(vertices=[(0, 0)]))
sage: pc.dimension()
0
```

## set\_immutable()

Make this polyhedral complex immutable.

# **EXAMPLES:**

```
sage: pc = PolyhedralComplex([Polyhedron(vertices=[[0], [1]])])
sage: pc.is_mutable()
True
sage: pc.set_immutable()
sage: pc.is_mutable()
False
```

## stratify(n)

Return the pure sub-polyhedral complex which is constructed from the n-dimensional maximal cells of this polyhedral complex.

#### See also:

n\_skeleton()

**Warning:** This may give the wrong answer if the polyhedral complex was constructed with maximality\_check set to False.

## **EXAMPLES:**

```
sage: p1 = Polyhedron(vertices=[(1, 1), (0, 0), (1, 2)])
sage: p2 = Polyhedron(vertices=[(1, 2), (0, 0), (0, 2)])
sage: p3 = Polyhedron(vertices=[(1, 2), (0, 2)])
sage: pc = PolyhedralComplex([p1, p2, p3])
sage: pc.stratify(2) == pc
True
sage: pc.stratify(1)
Polyhedral complex with 0 maximal cells
```

Wrong answer due to maximality\_check=False:

```
sage: pc_invalid = PolyhedralComplex([p1, p2, p3],
....: maximality_check=False)
sage: pc_invalid.stratify(1)
Polyhedral complex with 1 maximal cell
```

# subdivide(make\_simplicial=False, new\_vertices=None, new\_rays=None)

Construct a new polyhedral complex by iterative stellar subdivision of self for each new vertex/ray given.

Currently, subdivision is only supported for bounded polyhedral complex or polyhedral fan.

# INPUT:

- make\_simplicial boolean (default: False); if True, the returned polyhedral complex is simplicial
- new\_vertices, new\_rays list (optional); new generators to be added during subdivision

#### **EXAMPLES:**

```
sage: square_vertices = [(1, 1, 1), (-1, 1, 1), (-1, -1, 1), (1, -1, 1)]
sage: pc = PolyhedralComplex([
              Polyhedron(vertices=[(0, 0, 0)] + square_vertices),
. . . . . .
              Polyhedron(vertices=[(0, 0, 2)] + square_vertices)])
. . . . .
sage: pc.is_compact() and not pc.is_simplicial_complex()
sage: subdivided_pc = pc.subdivide(new_vertices=[(0, 0, 1)])
sage: subdivided_pc
Polyhedral complex with 8 maximal cells
sage: subdivided_pc.is_simplicial_complex()
True
sage: simplicial_pc = pc.subdivide(make_simplicial=True)
sage: simplicial_pc
Polyhedral complex with 4 maximal cells
sage: simplicial_pc.is_simplicial_complex()
True
sage: fan = PolyhedralComplex([Polyhedron(rays=square_vertices)])
sage: fan.is_polyhedral_fan() and not fan.is_simplicial_fan()
True
sage: fan.subdivide(new_vertices=[(0, 0, 1)])
Traceback (most recent call last):
ValueError: new vertices cannot be used for subdivision
sage: subdivided_fan = fan.subdivide(new_rays=[(0, 0, 1)])
sage: subdivided_fan
Polyhedral complex with 4 maximal cells
sage: subdivided_fan.is_simplicial_fan()
sage: simplicial_fan = fan.subdivide(make_simplicial=True)
sage: simplicial_fan
Polyhedral complex with 2 maximal cells
sage: simplicial_fan.is_simplicial_fan()
True
sage: halfspace = PolyhedralComplex([Polyhedron(rays=[(0, 0, 1)],
                  lines=[(1, 0, 0), (0, 1, 0)])
sage: halfspace.is_simplicial_fan()
False
sage: subdiv_halfspace = halfspace.subdivide(make_simplicial=True)
sage: subdiv_halfspace
Polyhedral complex with 4 maximal cells
sage: subdiv_halfspace.is_simplicial_fan()
True
```

## union(right)

The union of this polyhedral complex with another one.

#### INPUT:

• right – the other polyhedral complex (the right-hand factor)

## **EXAMPLES:**

```
sage: p1 = Polyhedron(vertices=[(-1, 0), (0, 0), (0, 1)])
sage: p2 = Polyhedron(vertices=[(0, -1), (0, 0), (1, 0)])
sage: p3 = Polyhedron(vertices=[(0, -1), (1, -1), (1, 0)])
sage: pc = PolyhedralComplex([p1]).union(PolyhedralComplex([p3]))
sage: set(pc.maximal_cell_iterator()) == set([p1, p3])
True
sage: pc.union(PolyhedralComplex([p2]))
Polyhedral complex with 3 maximal cells
sage: p4 = Polyhedron(vertices=[(0, -1), (0, 0), (1, 0), (1, -1)])
sage: pc.union(PolyhedralComplex([p4]))
Traceback (most recent call last):
...
ValueError: the given cells are not face-to-face
```

### union\_as\_polyhedron()

Return self as a *Polyhedron* if self is convex.

#### **EXAMPLES:**

```
sage: p1 = Polyhedron(vertices=[(1, 1), (0, 0), (1, 2)])
sage: p2 = Polyhedron(vertices=[(1, 2), (0, 0), (0, 2)])
sage: p3 = Polyhedron(vertices=[(0, 0), (1, 1), (2, 0)])
sage: P = PolyhedralComplex([p1, p2]).union_as_polyhedron()
sage: P.vertices_list()
[[0, 0], [0, 2], [1, 1], [1, 2]]
sage: PolyhedralComplex([p1, p3]).union_as_polyhedron()
Traceback (most recent call last):
...
ValueError: the polyhedral complex is not convex
```

# wedge(right)

The wedge (one-point union) of self with right.

**Todo:** Implement the wedge product of two polyhedral complexes.

# **EXAMPLES:**

```
sage: pc = PolyhedralComplex([Polyhedron(vertices=[[0], [1]])])
sage: pc.wedge(pc)
Traceback (most recent call last):
...
NotImplementedError: wedge is not implemented for polyhedral complex
```

# sage.geometry.polyhedral\_complex.cells\_list\_to\_cells\_dict(cells\_list)

Helper function that returns the dictionary whose keys are the dimensions, and the value associated to an integer d is the set of d-dimensional polyhedra in the given list.

```
sage: p1 = Polyhedron(vertices=[(1, 1), (0, 0), (1, 2)])
sage: p2 = Polyhedron(vertices=[(1, 1), (0, 0)])
sage: p3 = Polyhedron(vertices=[(0, 0)])
sage: p4 = Polyhedron(vertices=[(1, 1)])
sage: sage.geometry.polyhedral_complex.cells_list_to_cells_dict([p1, p2, p3, p4])
{0: {A 0-dimensional polyhedron in ZZ^2 defined as the convex hull of 1 vertex,
    A 0-dimensional polyhedron in ZZ^2 defined as the convex hull of 2 vertices},
1: {A 1-dimensional polyhedron in ZZ^2 defined as the convex hull of 3 vertices}}
```

Return a plot of several polyhedra in one figure with extra space between them.

# INPUT:

- polyhedra an iterable of Polyhedron\_base objects
- center (default: None, denoting the origin) the center of explosion
- explosion\_factor (default: 1) a nonnegative number; translate polyhedra by this factor of the distance from center to their center
- sticky\_vertices (default: False) boolean or dict. Whether to draw line segments between shared vertices of the given polyhedra. A dict gives options for sage.plot.line().
- sticky\_center (default: True) boolean or dict. When center is a vertex of some of the polyhedra, whether to draw line segments connecting the center to the shifted copies of these vertices. A dict gives options for sage.plot.line().
- color (default: None) if "rainbow", assign a different color to every maximal cell and every vertex; otherwise, passed on to plot().
- other keyword arguments are passed on to plot().

# 2.5 Toric geometry

# 2.5.1 Toric lattices

This module was designed as a part of the framework for toric varieties (variety, fano\_variety).

All toric lattices are isomorphic to  $\mathbb{Z}^n$  for some n, but will prevent you from doing "wrong" operations with objects from different lattices.

#### **AUTHORS:**

- Andrey Novoseltsev (2010-05-27): initial version.
- Andrey Novoseltsev (2010-07-30): sublattices and quotients.

#### **EXAMPLES:**

The simplest way to create a toric lattice is to specify its dimension only:

```
sage: N = ToricLattice(3)
sage: N
3-d lattice N
```

While our lattice N is called exactly "N" it is a coincidence: all lattices are called "N" by default:

```
sage: another_name = ToricLattice(3)
sage: another_name
3-d lattice N
```

If fact, the above lattice is exactly the same as before as an object in memory:

```
sage: N is another_name
True
```

There are actually four names associated to a toric lattice and they all must be the same for two lattices to coincide:

```
sage: N, N.dual(), latex(N), latex(N.dual())
(3-d lattice N, 3-d lattice M, N, M)
```

Notice that the lattice dual to N is called "M" which is standard in toric geometry. This happens only if you allow completely automatic handling of names:

```
sage: another_N = ToricLattice(3, "N")
sage: another_N.dual()
3-d lattice N*
sage: N is another_N
False
```

What can you do with toric lattices? Well, their main purpose is to allow creation of elements of toric lattices:

```
sage: n = N([1,2,3])
sage: n
N(1, 2, 3)
sage: M = N.dual()
sage: m = M(1,2,3)
sage: m
M(1, 2, 3)
```

Dual lattices can act on each other:

```
sage: n * m
14
sage: m * n
14
```

You can also add elements of the same lattice or scale them:

```
sage: 2 * n
N(2, 4, 6)
sage: n * 2
N(2, 4, 6)
sage: n + n
N(2, 4, 6)
```

However, you cannot "mix wrong lattices" in your expressions:

```
sage: n + m
Traceback (most recent call last):
...
TypeError: unsupported operand parent(s) for +:
'3-d lattice N' and '3-d lattice M'
sage: n * n
Traceback (most recent call last):
...
TypeError: elements of the same toric lattice cannot be multiplied!
sage: n == m
False
```

Note that n and m are not equal to each other even though they are both "just (1,2,3)." Moreover, you cannot easily convert elements between toric lattices:

```
sage: M(n)
Traceback (most recent call last):
...
TypeError: N(1, 2, 3) cannot be converted to 3-d lattice M!
```

If you really need to consider elements of one lattice as elements of another, you can either use intermediate conversion to "just a vector":

```
sage: ZZ3 = ZZ^3
sage: n_in_M = M(ZZ3(n))
sage: n_in_M
M(1, 2, 3)
sage: n == n_in_M
False
sage: n_in_M == m
True
```

Or you can create a homomorphism from one lattice to any other:

```
sage: h = N.hom(identity_matrix(3), M)
sage: h(n)
M(1, 2, 3)
```

**Warning:** While integer vectors (elements of  $\mathbb{Z}^n$ ) are printed as (1,2,3), in the code (1,2,3) is a tuple, which has nothing to do neither with vectors, nor with toric lattices, so the following is probably not what you want while working with toric geometry objects:

```
sage: (1,2,3) + (1,2,3)
(1, 2, 3, 1, 2, 3)

Instead, use syntax like

sage: N(1,2,3) + N(1,2,3)
N(2, 4, 6)
```

# class sage.geometry.toric\_lattice.ToricLatticeFactory

```
Bases: sage.structure.factory.UniqueFactory
```

Create a lattice for toric geometry objects.

### INPUT:

- rank nonnegative integer, the only mandatory parameter;
- name string;
- dual\_name string;
- latex\_name string;
- latex\_dual\_name string.

#### **OUTPUT:**

· lattice.

A toric lattice is uniquely determined by its rank and associated names. There are four such "associated names" whose meaning should be clear from the names of the corresponding parameters, but the choice of default values is a little bit involved. So here is the full description of the "naming algorithm":

- 1. If no names were given at all, then this lattice will be called "N" and the dual one "M". These are the standard choices in toric geometry.
- 2. If name was given and dual\_name was not, then dual\_name will be name followed by "\*".
- 3. If LaTeX names were not given, they will coincide with the "usual" names, but if dual\_name was constructed automatically, the trailing star will be typeset as a superscript.

### **EXAMPLES:**

Let's start with no names at all and see how automatic names are given:

```
sage: L1 = ToricLattice(3)
sage: L1
3-d lattice N
sage: L1.dual()
3-d lattice M
```

If we give the name "N" explicitly, the dual lattice will be called "N\*":

```
sage: L2 = ToricLattice(3, "N")
sage: L2
3-d lattice N
```

```
sage: L2.dual()
3-d lattice N*
```

However, we can give an explicit name for it too:

```
sage: L3 = ToricLattice(3, "N", "M")
sage: L3
3-d lattice N
sage: L3.dual()
3-d lattice M
```

If you want, you may also give explicit LaTeX names:

```
sage: L4 = ToricLattice(3, "N", "M", r"\mathbb{N}", r"\mathbb{M}")
sage: latex(L4)
\mathbb{N}
sage: latex(L4.dual())
\mathbb{M}
```

While all four lattices above are called "N", only two of them are equal (and are actually the same):

```
sage: L1 == L2
False
sage: L1 == L3
True
sage: L1 is L3
True
sage: L1 == L4
False
```

The reason for this is that L2 and L4 have different names either for dual lattices or for LaTeX typesetting.

**create\_key**(*rank*, *name=None*, *dual\_name=None*, *latex\_name=None*, *latex\_dual\_name=None*)

Create a key that uniquely identifies this toric lattice.

See ToricLattice for documentation.

```
Warning: You probably should not use this function directly.
```

```
create_object(version, key)
```

Create the toric lattice described by key.

See ToricLattice for documentation.

```
Warning: You probably should not use this function directly.
```

```
Bases: sage.geometry.toric\_lattice.ToricLattice\_generic, sage.modules.free\_module.\\ FreeModule\_ambient\_pid
```

Create a toric lattice.

See ToricLattice for documentation.

**Warning:** There should be only one toric lattice with the given rank and associated names. Using this class directly to create toric lattices may lead to unexpected results. Please, use *ToricLattice* to create toric lattices.

# **Element**

```
alias of sage.geometry.toric_lattice_element.ToricLatticeElement
```

# ambient\_module()

Return the ambient module of self.

#### OUTPUT:

• toric lattice.

**Note:** For any ambient toric lattice its ambient module is the lattice itself.

#### **EXAMPLES:**

```
sage: N = ToricLattice(3)
sage: N.ambient_module()
3-d lattice N
sage: N.ambient_module() is N
True
```

# dual()

Return the lattice dual to self.

## **OUTPUT**:

• toric lattice.

### **EXAMPLES:**

```
sage: N = ToricLattice(3)
sage: N
3-d lattice N
sage: M = N.dual()
sage: M
3-d lattice M
sage: M.dual() is N
True
```

Elements of dual lattices can act on each other:

```
sage: n = N(1,2,3)
sage: m = M(4,5,6)
sage: n * m
32
sage: m * n
32
```

```
plot(**options)
```

Plot self.

# INPUT:

• any options for toric plots (see toric\_plotter.options), none are mandatory.

### **OUTPUT**:

• a plot.

#### **EXAMPLES:**

```
sage: N = ToricLattice(3)
sage: N.plot() # optional - sage.plot
Graphics3d Object
```

```
Bases: sage.modules.free_module.FreeModule_generic_pid
```

Abstract base class for toric lattices.

#### **Element**

```
alias of sage.geometry.toric_lattice_element.ToricLatticeElement
```

#### construction()

Return the functorial construction of self.

#### **OUTPUT:**

• None, we do not think of toric lattices as constructed from simpler objects since we do not want to perform arithmetic involving different lattices.

# direct\_sum(other)

Return the direct sum with other.

# INPUT:

• other – a toric lattice or more general module.

#### **OUTPUT**:

The direct sum of self and other as **Z**-modules. If other is a *ToricLattice*, another toric lattice will be returned.

# **EXAMPLES:**

```
sage: K = ToricLattice(3, 'K')
sage: L = ToricLattice(3, 'L')
sage: N = K.direct_sum(L); N
6-d lattice K+L
sage: N, N.dual(), latex(N), latex(N.dual())
(6-d lattice K+L, 6-d lattice K*+L*, K \oplus L, K^* \oplus L^*)
```

With default names:

```
sage: N = ToricLattice(3).direct_sum(ToricLattice(2))
sage: N, N.dual(), latex(N), latex(N.dual())
(5-d lattice N+N, 5-d lattice M+M, N \oplus N, M \oplus M)
```

If other is not a *ToricLattice*, fall back to sum of modules:

```
sage: ToricLattice(3).direct_sum(ZZ^2)
Free module of degree 5 and rank 5 over Integer Ring
Echelon basis matrix:
[1 0 0 0 0]
[0 1 0 0 0]
[0 0 1 0 0]
[0 0 0 1 0]
[0 0 0 0 1]
```

# intersection(other)

Return the intersection of self and other.

#### INPUT:

• other - a toric (sub)lattice.dual

### **OUTPUT**:

• a toric (sub)lattice.

#### **EXAMPLES:**

```
sage: N = ToricLattice(3)
sage: Ns1 = N.submodule([N(2,4,0), N(9,12,0)])
sage: Ns2 = N.submodule([N(1,4,9), N(9,2,0)])
sage: Ns1.intersection(Ns2)
Sublattice <N(54, 12, 0)>
```

Note that if one of the intersecting sublattices is a sublattice of another, no new lattices will be constructed:

```
sage: N.intersection(N) is N
True
sage: Ns1.intersection(N) is Ns1
True
sage: N.intersection(Ns1) is Ns1
True
```

**quotient**(*sub*, *check=True*, *positive\_point=None*, *positive\_dual\_point=None*, \*\*kwds)

Return the quotient of self by the given sublattice sub.

#### INPUT:

- sub sublattice of self;
- check (default: True) whether or not to check that sub is a valid sublattice.

If the quotient is one-dimensional and torsion free, the following two mutually exclusive keyword arguments are also allowed. They decide the sign choice for the (single) generator of the quotient lattice:

- positive\_point a lattice point of self not in the sublattice sub (that is, not zero in the quotient lattice). The quotient generator will be in the same direction as positive\_point.
- positive\_dual\_point a dual lattice point. The quotient generator will be chosen such that its lift has a positive product with positive\_dual\_point. Note: if positive\_dual\_point is not zero on the sublattice sub, then the notion of positivity will depend on the choice of lift!

Further named arguments are passed to the constructor of a toric lattice quotient.

```
sage: N = ToricLattice(3)
sage: Ns = N.submodule([N(2,4,0), N(9,12,0)])
sage: Q = N/Ns
sage: Q
Quotient with torsion of 3-d lattice N
by Sublattice <N(1, 8, 0), N(0, 12, 0)>
```

Attempting to quotient one lattice by a sublattice of another will result in a ValueError:

```
sage: N = ToricLattice(3)
sage: M = ToricLattice(3, name='M')
sage: Ms = M.submodule([M(2,4,0), M(9,12,0)])
sage: N.quotient(Ms)
Traceback (most recent call last):
...
ValueError: M(1, 8, 0) cannot generate a sublattice of
3-d lattice N
```

However, if we forget the sublattice structure, then it is possible to quotient by vector spaces or modules constructed from any sublattice:

```
sage: N = ToricLattice(3)
sage: M = ToricLattice(3, name='M')
sage: Ms = M.submodule([M(2,4,0), M(9,12,0)])
sage: N.quotient(Ms.vector_space())
Quotient with torsion of 3-d lattice N by Sublattice
<N(1, 8, 0), N(0, 12, 0)>
sage: N.quotient(Ms.sparse_module())
Quotient with torsion of 3-d lattice N by Sublattice
<N(1, 8, 0), N(0, 12, 0)>
```

See ToricLattice\_quotient for more examples.

## saturation()

Return the saturation of self.

#### OUTPUT:

• a toric lattice.

# **EXAMPLES:**

```
sage: N = ToricLattice(3)
sage: Ns = N.submodule([(1,2,3), (4,5,6)])
sage: Ns
Sublattice <N(1, 2, 3), N(0, 3, 6)>
sage: Ns_sat = Ns.saturation()
sage: Ns_sat
Sublattice <N(1, 0, -1), N(0, 1, 2)>
sage: Ns_sat is Ns_sat.saturation()
True
```

span(gens, base\_ring=Integer Ring, \*args, \*\*kwds)

Return the span of the given generators.

INPUT:

- gens list of elements of the ambient vector space of self.
- base\_ring (default: **Z**) base ring for the generated module.

#### **OUTPUT**:

· submodule spanned by gens.

**Note:** The output need not be a submodule of self, nor even of the ambient space. It must, however, be contained in the ambient vector space.

See also span\_of\_basis(), submodule(), and submodule\_with\_basis(),

#### **EXAMPLES:**

# span\_of\_basis(basis, base\_ring=Integer Ring, \*args, \*\*kwds)

Return the submodule with the given basis.

## INPUT:

- basis list of elements of the ambient vector space of self.
- base\_ring (default: **Z**) base ring for the generated module.

## **OUTPUT**:

• submodule spanned by basis.

**Note:** The output need not be a submodule of self, nor even of the ambient space. It must, however, be contained in the ambient vector space.

See also span(), submodule(), and submodule\_with\_basis(),

#### **EXAMPLES:**

```
sage: N = ToricLattice(3)
sage: Ns = N.span_of_basis([(1,2,3)])
sage: Ns.span_of_basis([(2,4,0)])
Sublattice <N(2, 4, 0)>
sage: Ns.span_of_basis([(1/5,2/5,0), (1/7,1/7,0)])
Free module of degree 3 and rank 2 over Integer Ring
User basis matrix:
[1/5 2/5 0]
[1/7 1/7 0]
```

Of course the input basis vectors must be linearly independent:

```
sage: Ns.span_of_basis([(1,2,0), (2,4,0)])
Traceback (most recent call last):
...
ValueError: The given basis vectors must be linearly independent.
```

```
Bases: sage.modules.fg_pid.fgp_module.FGP_Module_class
```

Construct the quotient of a toric lattice V by its sublattice W.

# INPUT:

- V ambient toric lattice;
- W sublattice of V;
- check (default: True) whether to check correctness of input or not.

If the quotient is one-dimensional and torsion free, the following two mutually exclusive keyword arguments are also allowed. They decide the sign choice for the (single) generator of the quotient lattice:

- positive\_point a lattice point of self not in the sublattice sub (that is, not zero in the quotient lattice). The quotient generator will be in the same direction as positive\_point.
- positive\_dual\_point a dual lattice point. The quotient generator will be chosen such that its lift has a positive product with positive\_dual\_point. Note: if positive\_dual\_point is not zero on the sublattice sub, then the notion of positivity will depend on the choice of lift!

Further given named arguments are passed to the constructor of an FGP module.

## **OUTPUT:**

• quotient of V by W.

# **EXAMPLES:**

The intended way to get objects of this class is to use quotient() method of toric lattices:

```
sage: N = ToricLattice(3)
sage: sublattice = N.submodule([(1,1,0), (3,2,1)])
sage: Q = N/sublattice
sage: Q
1-d lattice, quotient of 3-d lattice N by Sublattice <N(1, 0, 1), N(0, 1, -1)>
sage: Q.gens()
(N[1, 0, 0],)
```

Here, sublattice happens to be of codimension one in N. If you want to prescribe the sign of the quotient generator, you can do either:

```
sage: Q = N.quotient(sublattice, positive_point=N(0,0,-1)); Q
1-d lattice, quotient of 3-d lattice N by Sublattice <N(1, 0, 1), N(0, 1, -1)>
sage: Q.gens()
(N[1, 0, 0],)
```

or:

```
sage: M = N.dual()
sage: Q = N.quotient(sublattice, positive_dual_point=M(1,0,0)); Q
1-d lattice, quotient of 3-d lattice N by Sublattice <N(1, 0, 1), N(0, 1, -1)>
```

```
sage: Q.gens()
(N[1, 0, 0],)
```

#### Element

alias of ToricLattice\_quotient\_element

### base\_extend(R)

Return the base change of self to the ring R.

#### INPUT:

• R – either Z or Q.

#### OUTPUT:

• self if  $R = \mathbf{Z}$ , quotient of the base extension of the ambient lattice by the base extension of the sublattice if  $R = \mathbf{Q}$ .

#### **EXAMPLES:**

```
sage: N = ToricLattice(3)
sage: Ns = N.submodule([N(2,4,0), N(9,12,0)])
sage: Q = N/Ns
sage: Q.base_extend(ZZ) is Q
True
sage: Q.base_extend(QQ)
Vector space quotient V/W of dimension 1 over Rational Field where
V: Vector space of dimension 3 over Rational Field
W: Vector space of degree 3 and dimension 2 over Rational Field
Basis matrix:
[1 0 0]
[0 1 0]
```

# coordinate\_vector(x, reduce=False)

Return coordinates of x with respect to the optimized representation of self.

#### INPUT:

- x element of self or convertible to self
- reduce (default: False); if True, reduce coefficients modulo invariants

#### **OUTPUT**:

The coordinates as a vector.

#### **EXAMPLES:**

```
sage: N = ToricLattice(3)
sage: Q = N.quotient(N.span([N(1,2,3), N(0,2,1)]), positive_point=N(0,-1,0))
sage: q = Q.gen(0); q
N[0, -1, 0]
sage: q.vector() # indirect test
(1)
sage: Q.coordinate_vector(q)
(1)
```

# dimension()

Return the rank of self.

# **OUTPUT**:

Integer. The dimension of the free part of the quotient.

# **EXAMPLES**:

```
sage: N = ToricLattice(3)
sage: Ns = N.submodule([N(2,4,0), N(9,12,0)])
sage: Q = N/Ns
sage: Q.ngens()
2
sage: Q.rank()
1
sage: Ns = N.submodule([N(1,4,0)])
sage: Q = N/Ns
sage: Q.ngens()
2
sage: Q.ngens()
2
```

# dual()

Return the lattice dual to self.

#### **OUTPUT:**

• a toric lattice quotient.

# **EXAMPLES**:

```
sage: N = ToricLattice(3)
sage: Ns = N.submodule([(1, -1, -1)])
sage: Q = N / Ns
sage: Q.dual()
Sublattice <M(1, 0, 1), M(0, 1, -1)>
```

# gens()

Return the generators of the quotient.

#### **OUTPUT**:

A tuple of *ToricLattice\_quotient\_element* generating the quotient.

# **EXAMPLES:**

```
sage: N = ToricLattice(3)
sage: Q = N.quotient(N.span([N(1,2,3), N(0,2,1)]), positive_point=N(0,-1,0))
sage: Q.gens()
(N[0, -1, 0],)
```

# is\_torsion\_free()

Check if self is torsion-free.

# OUTPUT:

• True is self has no torsion and False otherwise.

```
sage: N = ToricLattice(3)
sage: Ns = N.submodule([N(2,4,0), N(9,12,0)])
sage: Q = N/Ns
sage: Q.is_torsion_free()
False
sage: Ns = N.submodule([N(1,4,0)])
sage: Q = N/Ns
sage: Q.is_torsion_free()
True
```

# rank()

Return the rank of self.

**OUTPUT**:

Integer. The dimension of the free part of the quotient.

# **EXAMPLES:**

```
sage: N = ToricLattice(3)
sage: Ns = N.submodule([N(2,4,0), N(9,12,0)])
sage: Q = N/Ns
sage: Q.ngens()
2
sage: Q.rank()
1
sage: Ns = N.submodule([N(1,4,0)])
sage: Q = N/Ns
sage: Q.ngens()
2
sage: Q.ngens()
2
sage: Q.rank()
```

class sage.geometry.toric\_lattice.ToricLattice\_quotient\_element(parent, x, check=True)

Bases: sage.modules.fg\_pid.fgp\_element.FGP\_Element

Create an element of a toric lattice quotient.

Warning: You probably should not construct such elements explicitly.

# INPUT:

• same as for FGP\_Element.

# OUTPUT:

• element of a toric lattice quotient.

#### set\_immutable()

Make self immutable.

# **OUTPUT**:

• none.

**Note:** Elements of toric lattice quotients are always immutable, so this method does nothing, it is introduced for compatibility purposes only.

### **EXAMPLES:**

```
sage: N = ToricLattice(3)
sage: Ns = N.submodule([N(2,4,0), N(9,12,0)])
sage: Q = N/Ns
sage: Q.0.set_immutable()
```

```
Bases: sage.geometry.toric_lattice.ToricLattice_sublattice_with_basis, sage.modules.free_module.FreeModule_submodule_pid
```

Construct the sublattice of ambient toric lattice generated by gens.

INPUT (same as for FreeModule\_submodule\_pid):

- ambient ambient toric lattice for this sublattice;
- gens list of elements of ambient generating the constructed sublattice;
- see the base class for other available options.

#### **OUTPUT:**

• sublattice of a toric lattice with an automatically chosen basis.

See also ToricLattice\_sublattice\_with\_basis if you want to specify an explicit basis.

# **EXAMPLES:**

The intended way to get objects of this class is to use submodule() method of toric lattices:

```
sage: N = ToricLattice(3)
sage: sublattice = N.submodule([(1,1,0), (3,2,1)])
sage: sublattice.has_user_basis()
False
sage: sublattice.basis()
[
N(1, 0, 1),
N(0, 1, -1)
]
```

For sublattices without user-specified basis, the basis obtained above is the same as the "standard" one:

```
sage: sublattice.echelonized_basis()
[
N(1, 0, 1),
N(0, 1, -1)
]
```

class sage.geometry.toric\_lattice.ToricLattice\_sublattice\_with\_basis(ambient, basis,

check=True, echelonize=False, echelonized\_basis=None, already echelonized=False)

Bases: sage.geometry.toric\_lattice.ToricLattice\_generic, sage.modules.free\_module. FreeModule\_submodule\_with\_basis\_pid

Construct the sublattice of ambient toric lattice with given basis.

INPUT (same as for FreeModule\_submodule\_with\_basis\_pid):

- ambient ambient toric lattice for this sublattice;
- basis list of linearly independent elements of ambient, these elements will be used as the default basis
  of the constructed sublattice;
- see the base class for other available options.

#### **OUTPUT**:

• sublattice of a toric lattice with a user-specified basis.

See also ToricLattice\_sublattice if you do not want to specify an explicit basis.

#### **EXAMPLES:**

The intended way to get objects of this class is to use submodule\_with\_basis() method of toric lattices:

```
sage: N = ToricLattice(3)
sage: sublattice = N.submodule_with_basis([(1,1,0), (3,2,1)])
sage: sublattice.has_user_basis()
True
sage: sublattice.basis()
[
N(1, 1, 0),
N(3, 2, 1)
]
```

Even if you have provided your own basis, you still can access the "standard" one:

```
sage: sublattice.echelonized_basis()
[
N(1, 0, 1),
N(0, 1, -1)
]
```

# dual()

Return the lattice dual to self.

## **OUTPUT**:

a toric lattice quotient.

```
sage: N = ToricLattice(3)
sage: Ns = N.submodule([(1,1,0), (3,2,1)])
sage: Ns.dual()
2-d lattice, quotient of 3-d lattice M by Sublattice <M(1, -1, -1)>
```

```
plot(**options)
    Plot self.
```

#### INPUT:

• any options for toric plots (see toric\_plotter.options), none are mandatory.

# OUTPUT:

• a plot.

#### **EXAMPLES:**

```
sage: N = ToricLattice(3)
sage: sublattice = N.submodule_with_basis([(1,1,0), (3,2,1)])
sage: sublattice.plot() # optional - sage.plot
Graphics3d Object
```

Now we plot both the ambient lattice and its sublattice:

```
sage: N.plot() + sublattice.plot(point_color="red") # optional - sage.plot
Graphics3d Object
```

# sage.geometry.toric\_lattice.is\_ToricLattice(x)

Check if x is a toric lattice.

#### INPUT:

• x -anything.

# **OUTPUT**:

• True if x is a toric lattice and False otherwise.

## **EXAMPLES:**

```
sage: from sage.geometry.toric_lattice import (
...: is_ToricLattice)
sage: is_ToricLattice(1)
False
sage: N = ToricLattice(3)
sage: N
3-d lattice N
sage: is_ToricLattice(N)
True
```

# sage.geometry.toric\_lattice.is\_ToricLatticeQuotient(x)

Check if x is a toric lattice quotient.

#### INPUT:

• x - anything.

# **OUTPUT**:

• True if x is a toric lattice quotient and False otherwise.

# EXAMPLES:

```
sage: is_ToricLatticeQuotient(1)
False
sage: N = ToricLattice(3)
sage: N
3-d lattice N
sage: is_ToricLatticeQuotient(N)
False
sage: Q = N / N.submodule([(1,2,3), (3,2,1)])
sage: Q
Quotient with torsion of 3-d lattice N
by Sublattice <N(1, 2, 3), N(0, 4, 8)>
sage: is_ToricLatticeQuotient(Q)
True
```

# 2.5.2 Convex rational polyhedral cones

This module was designed as a part of framework for toric varieties (variety, fano\_variety). While the emphasis is on strictly convex cones, non-strictly convex cones are supported as well. Work with distinct lattices (in the sense of discrete subgroups spanning vector spaces) is supported. The default lattice is  $ToricLattice\ N$  of the appropriate dimension. The only case when you must specify lattice explicitly is creation of a 0-dimensional cone, where dimension of the ambient space cannot be guessed.

#### **AUTHORS:**

- Andrey Novoseltsev (2010-05-13): initial version.
- Andrey Novoseltsev (2010-06-17): substantial improvement during review by Volker Braun.
- Volker Braun (2010-06-21): various spanned/quotient/dual lattice computations added.
- Volker Braun (2010-12-28): Hilbert basis for cones.
- Andrey Novoseltsev (2012-02-23): switch to PointCollection container.

## **EXAMPLES:**

Use *Cone()* to construct cones:

```
sage: octant = Cone([(1,0,0), (0,1,0), (0,0,1)])
sage: halfspace = Cone([(1,0,0), (0,1,0), (-1,-1,0), (0,0,1)])
sage: positive_xy = Cone([(1,0,0), (0,1,0)])
sage: four_rays = Cone([(1,1,1), (1,-1,1), (-1,-1,1), (-1,1,1)])
```

For all of the cones above we have provided primitive generating rays, but in fact this is not necessary - a cone can be constructed from any collection of rays (from the same space, of course). If there are non-primitive (or even non-integral) rays, they will be replaced with primitive ones. If there are extra rays, they will be discarded. Of course, this means that *Cone()* has to do some work before actually constructing the cone and sometimes it is not desirable, if you know for sure that your input is already "good". In this case you can use options check=False to force *Cone()* to use exactly the directions that you have specified and normalize=False to force it to use exactly the rays that you have specified. However, it is better not to use these possibilities without necessity, since cones are assumed to be represented by a minimal set of primitive generating rays. See *Cone()* for further documentation on construction.

Once you have a cone, you can perform numerous operations on it. The most important ones are, probably, ray accessing methods:

```
sage: rays = halfspace.rays()
sage: rays
N(0, 0, 1),
N(0, 1,0),
N(0, -1, 0),
N(1, 0, 0),
N(-1, 0, 0)
in 3-d lattice N
sage: rays.set()
frozenset({N(-1, 0, 0), N(0, -1, 0), N(0, 0, 1), N(0, 1, 0), N(1, 0, 0)})
sage: rays.matrix()
[0 0 1]
[ 0 1 0]
[0 -1 0]
[ 1 0 0]
[-1 \ 0 \ 0]
sage: rays.column_matrix()
[0 1 - 1 0 0]
[10000]
sage: rays(3)
N(1, 0, 0)
in 3-d lattice N
sage: rays[3]
N(1, 0, 0)
sage: halfspace.ray(3)
N(1, 0, 0)
```

The method *rays()* returns a *PointCollection* with the *i*-th element being the primitive integral generator of the *i*-th ray. It is possible to convert this collection to a matrix with either rows or columns corresponding to these generators. You may also change the default *output\_format()* of all point collections to be such a matrix.

If you want to do something with each ray of a cone, you can write

```
sage: for ray in positive_xy: print(ray)
N(1, 0, 0)
N(0, 1, 0)
```

There are two dimensions associated to each cone - the dimension of the subspace spanned by the cone and the dimension of the space where it lives:

```
sage: positive_xy.dim()
2
sage: positive_xy.lattice_dim()
3
```

You also may be interested in this dimension:

```
sage: dim(positive_xy.linear_subspace())
0
sage: dim(halfspace.linear_subspace())
2
```

Or, perhaps, all you care about is whether it is zero or not:

```
sage: positive_xy.is_strictly_convex()
True
sage: halfspace.is_strictly_convex()
False
```

You can also perform these checks:

```
sage: positive_xy.is_simplicial()
True
sage: four_rays.is_simplicial()
False
sage: positive_xy.is_smooth()
True
```

You can work with subcones that form faces of other cones:

```
sage: face = four_rays.faces(dim=2)[0]
sage: face
2-d face of 3-d cone in 3-d lattice N
sage: face.rays()
N(-1, -1, 1),
N(-1, 1, 1)
in 3-d lattice N
sage: face.ambient_ray_indices()
(2, 3)
sage: four_rays.rays(face.ambient_ray_indices())
N(-1, -1, 1),
N(-1, 1, 1)
in 3-d lattice N
```

If you need to know inclusion relations between faces, you can use

```
sage: L = four_rays.face_lattice()
sage: [len(s) for s in L.level_sets()]
[1, 4, 4, 1]
sage: face = L.level_sets()[2][0]
sage: face.rays()
N(1, 1, 1),
N(1, -1, 1)
in 3-d lattice N
sage: L.hasse_diagram().neighbors_in(face)
[1-d face of 3-d cone in 3-d lattice N,
1-d face of 3-d cone in 3-d lattice N]
```

**Warning:** The order of faces in level sets of the face lattice may differ from the order of faces returned by *faces()*. While the first order is random, the latter one ensures that one-dimensional faces are listed in the same order as generating rays.

When all the functionality provided by cones is not enough, you may want to check if you can do necessary things using polyhedra corresponding to cones:

```
sage: four_rays.polyhedron()
A 3-dimensional polyhedron in ZZ^3 defined as
the convex hull of 1 vertex and 4 rays
```

And of course you are always welcome to suggest new features that should be added to cones!

#### REFERENCES:

• [Ful1993]

sage.geometry.cone.Cone(rays, lattice=None, check=True, normalize=True)
Construct a (not necessarily strictly) convex rational polyhedral cone.

#### **INPUT:**

- rays a list of rays. Each ray should be given as a list or a vector convertible to the rational extension of the given lattice. May also be specified by a *Polyhedron\_base* object;
- lattice ToricLattice,  $\mathbb{Z}^n$ , or any other object that behaves like these. If not specified, an attempt will be made to determine an appropriate toric lattice automatically;
- check by default the input data will be checked for correctness (e.g. that all rays have the same number
  of components) and generating rays will be constructed from rays. If you know that the input is a minimal
  set of generators of a valid cone, you may significantly decrease construction time using check=False
  option;
- normalize you can further speed up construction using normalize=False option. In this case rays
  must be a list of immutable primitive rays in lattice. In general, you should not use this option, it is
  designed for code optimization and does not give as drastic improvement in speed as the previous one.

# **OUTPUT:**

• convex rational polyhedral cone determined by rays.

# EXAMPLES:

Let's define a cone corresponding to the first quadrant of the plane (note, you can even mix objects of different types to represent rays, as long as you let this function to perform all the checks and necessary conversions!):

```
sage: quadrant = Cone([(1,0), [0,1]])
sage: quadrant
2-d cone in 2-d lattice N
sage: quadrant.rays()
N(1, 0),
N(0, 1)
in 2-d lattice N
```

If you give more rays than necessary, the extra ones will be discarded:

```
sage: Cone([(1,0), (0,1), (1,1), (0,1)]).rays()
N(0, 1),
N(1, 0)
in 2-d lattice N
```

However, this work is not done with check=False option, so use it carefully!

```
sage: Cone([(1,0), (0,1), (1,1), (0,1)], check=False).rays()
N(1, 0),
N(0, 1),
```

```
N(1, 1),
N(0, 1)
in 2-d lattice N
```

Even worse things can happen with normalize=False option:

```
sage: Cone([(1,0), (0,1)], check=False, normalize=False)
Traceback (most recent call last):
...
AttributeError: 'tuple' object has no attribute 'parent'
```

You can construct different "not" cones: not full-dimensional, not strictly convex, not containing any rays:

```
sage: one_dimensional_cone = Cone([(1,0)])
sage: one_dimensional_cone.dim()
sage: half_plane = Cone([(1,0), (0,1), (-1,0)])
sage: half_plane.rays()
N(0, 1),
N(1,0),
N(-1, 0)
in 2-d lattice N
sage: half_plane.is_strictly_convex()
False
sage: origin = Cone([(0,0)])
sage: origin.rays()
Empty collection
in 2-d lattice N
sage: origin.dim()
sage: origin.lattice_dim()
```

You may construct the cone above without giving any rays, but in this case you must provide lattice explicitly:

```
sage: origin = Cone([])
Traceback (most recent call last):
...
ValueError: lattice must be given explicitly if there are no rays!
sage: origin = Cone([], lattice=ToricLattice(2))
sage: origin.dim()
0
sage: origin.lattice_dim()
2
sage: origin.lattice()
2-d lattice N
```

However, the trivial cone in n dimensions has a predefined constructor for you to use:

```
sage: origin = cones.trivial(2)
sage: origin.rays()
Empty collection
in 2-d lattice N
```

Of course, you can also provide lattice in other cases:

```
sage: L = ToricLattice(3, "L")
sage: c1 = Cone([(1,0,0),(1,1,1)], lattice=L)
sage: c1.rays()
L(1, 0, 0),
L(1, 1, 1)
in 3-d lattice L
```

Or you can construct cones from rays of a particular lattice:

```
sage: ray1 = L(1,0,0)
sage: ray2 = L(1,1,1)
sage: c2 = Cone([ray1, ray2])
sage: c2.rays()
L(1, 0, 0),
L(1, 1, 1)
in 3-d lattice L
sage: c1 == c2
True
```

When the cone in question is not strictly convex, the standard form for the "generating rays" of the linear subspace is "basis vectors and their negatives", as in the following example:

```
sage: plane = Cone([(1,0), (0,1), (-1,-1)])
sage: plane.rays()
N( 0,  1),
N( 0, -1),
N( 1,  0),
N(-1,  0)
in 2-d lattice N
```

The cone can also be specified by a *Polyhedron\_base*:

```
sage: p = plane.polyhedron()
sage: Cone(p)
2-d cone in 2-d lattice N
sage: Cone(p) == plane
True
```

Bases: sage.geometry.cone.IntegralRayCollection, collections.abc.Container, sage.geometry.convex\_set.ConvexSet\_closed, sage.geometry.abc.ConvexRationalPolyhedralCone

Create a convex rational polyhedral cone.

**Warning:** This class does not perform any checks of correctness of input nor does it convert input into the standard representation. Use *Cone()* to construct cones.

Cones are immutable, but they cache most of the returned values.

INPUT:

The input can be either:

- rays list of immutable primitive vectors in lattice;
- lattice ToricLattice,  $\mathbb{Z}^n$ , or any other object that behaves like these. If None, it will be determined as parent() of the first ray. Of course, this cannot be done if there are no rays, so in this case you must give an appropriate lattice directly.

or (these parameters must be given as keywords):

- ambient ambient structure of this cone, a bigger cone or a fan, this cone must be a face of ambient;
- ambient\_ray\_indices increasing list or tuple of integers, indices of rays of ambient generating this
  cone.

In both cases, the following keyword parameter may be specified in addition:

• PPL – either None (default) or a C\_Polyhedron representing the cone. This serves only to cache the polyhedral data if you know it already. The constructor does not make a copy so the PPL object should not be modified afterwards.

# **OUTPUT**:

· convex rational polyhedral cone.

**Note:** Every cone has its ambient structure. If it was not specified, it is this cone itself.

# Hilbert\_basis()

Return the Hilbert basis of the cone.

Given a strictly convex cone  $C \subset \mathbf{R}^d$ , the Hilbert basis of C is the set of all irreducible elements in the semigroup  $C \cap \mathbf{Z}^d$ . It is the unique minimal generating set over  $\mathbf{Z}$  for the integral points  $C \cap \mathbf{Z}^d$ .

If the cone C is not strictly convex, this method finds the (unique) minimal set of lattice points that need to be added to the defining rays of the cone to generate the whole semigroup  $C \cap \mathbf{Z}^d$ . But because the rays of the cone are not unique nor necessarily minimal in this case, neither is the returned generating set (consisting of the rays plus additional generators).

See also <code>semigroup\_generators()</code> if you are not interested in a minimal set of generators.

# **OUTPUT**:

• a PointCollection. The rays of self are the first self.nrays() entries.

### **EXAMPLES:**

The following command ensures that the output ordering in the examples below is independent of TOP-COM, you don't have to use it:

```
sage: PointConfiguration.set_engine('internal')
```

We start with a simple case of a non-smooth 2-dimensional cone:

```
sage: Cone([ (1,0), (1,2) ]).Hilbert_basis()
N(1, 0),
N(1, 2),
N(1, 1)
in 2-d lattice N
```

Two more complicated example from GAP/toric:

```
sage: Cone([[1,0],[3,4]]).dual().Hilbert_basis()
M(0, 1),
M(4, -3),
M(1, 0),
M(2, -1),
M(3, -2)
in 2-d lattice M
sage: cone = Cone([[1,2,3,4],[0,1,0,7],[3,1,0,2],[0,0,1,0]]).dual()
sage: cone.Hilbert_basis()
                                  # long time
M(10, -7, 0, 1),
M(-5, 21, 0, -3),
M(0, -2,
          0.
               1),
M(15, -63, 25,
               9),
M(2, -3, 0,
               1),
M(1, -4, 1,
               1),
M(4,
      -4,
           0,
               1),
      3,
M(-1,
          0,
               0),
M(1, -5, 2,
              1).
M(3, -5,
          1,
               1),
M(6,
     -5,
           0.
              1),
M(3, -13,
          5, 2),
M(2, -6, 2,
              1),
M(5, -6,
          1,
               1),
M(8,
     -6, 0,
              1).
M( 0,
      1,
          0,
               0),
M(-2,
       8, 0, -1),
M(10, -42, 17,
M( 7, -28, 11,
               4),
M(5, -21, 9,
               3),
M(6, -21, 8,
               3),
M(5, -14, 5,
               2),
M( 2,
     -7,
          3,
              1),
M(4, -7, 2, 1),
M(7,
      -7, 1, 1),
M( 0,
       0,
          1, 0),
       0,
          0, 0),
M(1,
       7, 0, -1),
M(-1,
      14, 0, -2)
M(-3,
in 4-d lattice M
```

Not a strictly convex cone:

```
sage: wedge = Cone([ (1,0,0), (1,2,0), (0,0,1), (0,0,-1) ])
sage: sorted(wedge.semigroup_generators())
[N(0, 0, -1), N(0, 0, 1), N(1, 0, 0), N(1, 1, 0), N(1, 2, 0)]
sage: wedge.Hilbert_basis()
N(1, 2, 0),
N(1, 0, 0),
N(0, 0, 1),
N(0, 0, -1),
N(1, 1, 0)
in 3-d lattice N
```

Not full-dimensional cones are ok, too (see trac ticket #11312):

```
sage: Cone([(1,1,0), (-1,1,0)]).Hilbert_basis()
N( 1, 1, 0),
N(-1, 1, 0),
N( 0, 1, 0)
in 3-d lattice N
```

#### ALGORITHM:

The primal Normaliz algorithm, see [Normaliz].

Hilbert\_coefficients(point, solver, verbose=None, integrality\_tolerance=0)

Return the expansion coefficients of point with respect to *Hilbert\_basis()*.

### INPUT:

- point a *lattice()* point in the cone, or something that can be converted to a point. For example, a list or tuple of integers.
- solver (default: None) Specify a Mixed Integer Linear Programming (MILP) solver to be used. If set to None, the default one is used. For more information on MILP solvers and which default solver is used, see the method solve of the class MixedIntegerLinearProgram.
- verbose integer (default: 0). Sets the level of verbosity of the LP solver. Set to 0 by default, which means quiet.
- integrality\_tolerance parameter for use with MILP solvers over an inexact base ring; see MixedIntegerLinearProgram.get\_values().

#### **OUTPUT:**

A Z-vector of length len(self.Hilbert\_basis()) with nonnegative components.

**Note:** Since the Hilbert basis elements are not necessarily linearly independent, the expansion coefficients are not unique. However, this method will always return the same expansion coefficients when invoked with the same argument.

# **EXAMPLES:**

```
sage: cone = Cone([(1,0),(0,1)])
sage: cone.rays()
N(1, 0),
N(0, 1)
in 2-d lattice N
sage: cone.Hilbert_coefficients([3,2])
(3, 2)
```

A more complicated example:

```
sage: N = ToricLattice(2)
sage: cone = Cone([N(1,0),N(1,2)])
sage: cone.Hilbert_basis()
N(1, 0),
N(1, 2),
N(1, 1)
in 2-d lattice N
sage: cone.Hilbert_coefficients( N(1,1) )
(0, 0, 1)
```

The cone need not be strictly convex:

```
sage: N = ToricLattice(3)
sage: cone = Cone([N(1,0,0),N(1,2,0),N(0,0,1),N(0,0,-1)])
sage: cone.Hilbert_basis()
N(1, 2, 0),
N(1, 0, 0),
N(0, 0, 1),
N(0, 0, -1),
N(1, 1, 0)
in 3-d lattice N
sage: cone.Hilbert_coefficients( N(1,1,3) )
(0, 0, 3, 0, 1)
```

# Z\_operators\_gens()

Compute minimal generators of the Z-operators on this cone.

The Z-operators on a cone generalize the Z-matrices over the nonnegative orthant. They are simply negations of the *cross\_positive\_operators\_gens()*.

### OUTPUT:

A list of n-by-n matrices where n is the ambient dimension of this cone. Each matrix L in the list has the property that  $s(L(x)) \leq 0$  whenever (x,s) is an element of this cone's  $discrete\_complementarity\_set()$ .

The returned matrices generate the cone of Z-operators on this cone; that is,

- Any nonnegative linear combination of the returned matrices is a Z-operator on this cone.
- Every Z-operator on this cone is some nonnegative linear combination of the returned matrices.

#### See also

cross\_positive\_operators\_gens(), lyapunov\_like\_basis(), positive\_operators\_gens()

## **REFERENCES:**

- [BP1994]
- [Or2018b]

# adjacent()

Return faces adjacent to self in the ambient face lattice.

Two distinct faces  $F_1$  and  $F_2$  of the same face lattice are **adjacent** if all of the following conditions hold:

- $F_1$  and  $F_2$  have the same dimension d;
- $F_1$  and  $F_2$  share a facet of dimension d-1;
- $F_1$  and  $F_2$  are facets of some face of dimension d+1, unless d is the dimension of the ambient structure.

# **OUTPUT**:

• tuple of cones.

### **EXAMPLES:**

```
sage: octant = Cone([(1,0,0), (0,1,0), (0,0,1)])
sage: octant.adjacent()
()
sage: one_face = octant.faces(1)[0]
```

```
sage: len(one_face.adjacent())
2
sage: one_face.adjacent()[1]
1-d face of 3-d cone in 3-d lattice N
```

Things are a little bit subtle with fans, as we illustrate below.

First, we create a fan from two cones in the plane:

The second generating cone is adjacent to this one. Now we create the same fan, but embedded into the 3-dimensional space:

The result is as before, since we still have:

```
sage: fan.dim()
2
```

Now we add another cone to make the fan 3-dimensional:

Since now cone has smaller dimension than fan, it and its adjacent cones must be facets of a bigger one, but since cone in this example is generating, it is not contained in any other.

#### ambient()

Return the ambient structure of self.

# **OUTPUT**:

• cone or fan containing self as a face.

# **EXAMPLES:**

```
sage: cone = Cone([(1,2,3), (4,6,5), (9,8,7)])
sage: cone.ambient()
3-d cone in 3-d lattice N
sage: cone.ambient() is cone
True
sage: face = cone.faces(1)[0]
```

```
sage: face
1-d face of 3-d cone in 3-d lattice N
sage: face.ambient()
3-d cone in 3-d lattice N
sage: face.ambient() is cone
True
```

# ambient\_ray\_indices()

Return indices of rays of the ambient structure generating self.

### OUTPUT:

• increasing tuple of integers.

### **EXAMPLES:**

```
sage: quadrant = Cone([(1,0), (0,1)])
sage: quadrant.ambient_ray_indices()
(0, 1)
sage: quadrant.facets()[1].ambient_ray_indices()
(1,)
```

# an\_affine\_basis()

Return points in self that form a basis for the affine hull.

### **EXAMPLES:**

```
sage: quadrant = Cone([(1,0), (0,1)])
sage: quadrant.an_affine_basis()
[(0, 0), (1, 0), (0, 1)]
sage: ray = Cone([(1, 1)])
sage: ray.an_affine_basis()
[(0, 0), (1, 1)]
sage: line = Cone([(1,0), (-1,0)])
sage: line.an_affine_basis()
[(1, 0), (0, 0)]
```

### cartesian\_product(other, lattice=None)

Return the Cartesian product of self with other.

# INPUT:

- other a cone;
- lattice (optional) the ambient lattice for the Cartesian product cone. By default, the direct sum of the ambient lattices of self and other is constructed.

# **OUTPUT**:

• a cone.

# **EXAMPLES:**

```
sage: c = Cone([(1,)])
sage: c.cartesian_product(c)
2-d cone in 2-d lattice N+N
sage: _.rays()
```

```
N+N(1, 0),
N+N(0, 1)
in 2-d lattice N+N
```

### contains(\*args)

Check if a given point is contained in self.

#### INPUT:

 anything. An attempt will be made to convert all arguments into a single element of the ambient space of self. If it fails, False will be returned.

# **OUTPUT**:

• True if the given point is contained in self, False otherwise.

### **EXAMPLES:**

```
sage: c = Cone([(1,0), (0,1)])
sage: c.contains(c.lattice()(1,0))
True
sage: c.contains((1,0))
True
sage: c.contains((1,1))
True
sage: c.contains(1,1)
sage: c.contains((-1,0))
False
sage: c.contains(c.dual_lattice()(1,0)) #random output (warning)
sage: c.contains(c.dual_lattice()(1,0))
False
sage: c.contains(1)
sage: c.contains(1/2, sqrt(3))
True
sage: c.contains(-1/2, sqrt(3))
False
```

# cross\_positive\_operators\_gens()

Compute minimal generators of the cross-positive operators on this cone.

Any positive operator P on this cone will have  $s(P(x)) \ge 0$  whenever x is an element of this cone and s is an element of its dual. By contrast, the cross-positive operators need only satisfy that property on the  $discrete\_complementarity\_set()$ ; that is, when x and s are "cross" (orthogonal).

The cross-positive operators (on some fixed cone) themselves form a closed convex cone. This method computes and returns the generators of that cone as a list of matrices.

Cross-positive operators are also called exponentially-positive, since they become positive operators when exponentiated. Other equivalent names are resolvent-positive, essentially-positive, and quasimonotone.

# **OUTPUT**:

A list of n-by-n matrices where n is the ambient dimension of this cone. Each matrix L in the list has the property that  $s(L(x)) \geq 0$  whenever (x,s) is an element of this cone's  $discrete\_complementarity\_set()$ .

The returned matrices generate the cone of cross-positive operators on this cone; that is,

- Any nonnegative linear combination of the returned matrices is cross-positive on this cone.
- Every cross-positive operator on this cone is some nonnegative linear combination of the returned matrices.

### See also:

```
lyapunov_like_basis(), positive_operators_gens(), Z_operators_gens()
```

### REFERENCES:

- [SV1970]
- [Or2018b]

#### **EXAMPLES:**

Cross-positive operators on the nonnegative orthant are negations of Z-matrices; that is, matrices whose off-diagonal elements are nonnegative:

The trivial cone in a trivial space has no cross-positive operators:

```
sage: K = cones.trivial(0)
sage: K.cross_positive_operators_gens()
[]
```

Every operator is a cross-positive operator on the ambient vector space:

```
sage: K = Cone([(1,),(-1,)])
sage: K.is_full_space()
True
sage: K.cross_positive_operators_gens()
[[1], [-1]]

sage: K = Cone([(1,0),(-1,0),(0,1),(0,-1)])
sage: K.is_full_space()
True
sage: K.cross_positive_operators_gens()
[
[1 0] [-1 0] [0 1] [0 -1] [0 0] [0 0] [0 0] [0 0]
[0 0], [0 0], [0 0], [0 0], [1 0], [-1 0], [0 1], [0 -1]
]
```

A non-obvious application is to find the cross-positive operators on the right half-plane [Or2018b]:

```
sage: K = Cone([(1,0),(0,1),(0,-1)])
sage: K.cross_positive_operators_gens()
[
[1 0] [-1 0] [0 0] [0 0] [0 0] [0 0]
[0 0], [0 0], [1 0], [-1 0], [0 1], [0 -1]
]
```

Cross-positive operators on a subspace are Lyapunov-like and vice-versa:

## discrete\_complementarity\_set()

Compute a discrete complementarity set of this cone.

A discrete complementarity set of a cone is the set of all orthogonal pairs (x, s) where x is in some fixed generating set of the cone, and s is in some fixed generating set of its dual. The generators chosen for this cone and its dual are simply their rays().

### **OUTPUT**:

A tuple of pairs (x, s) such that,

- x and s are nonzero.
- s(x) is zero.
- x is one of this cone's rays().
- s is one of the rays() of this cone's dual().

## REFERENCES:

• [Or2017]

## **EXAMPLES:**

Pairs of standard basis elements form a discrete complementarity set for the nonnegative orthant:

```
sage: K = cones.nonnegative_orthant(2)
sage: K.discrete_complementarity_set()
((N(1, 0), M(0, 1)), (N(0, 1), M(1, 0)))
```

If a cone consists of a single ray, then the second components of a discrete complementarity set for that cone should generate the orthogonal complement of the ray:

```
sage: K = Cone([(1,0)])
sage: K.discrete_complementarity_set()
((N(1, 0), M(0, 1)), (N(1, 0), M(0, -1)))
sage: K = Cone([(1,0,0)])
sage: K.discrete_complementarity_set()
((N(1, 0, 0), M(0, 1, 0)),
```

```
(N(1, 0, 0), M(0, -1, 0)),
(N(1, 0, 0), M(0, 0, 1)),
(N(1, 0, 0), M(0, 0, -1)))
```

When a cone is the entire space, its dual is the trivial cone, so the only discrete complementarity set for it is empty:

```
sage: K = Cone([(1,0),(-1,0),(0,1),(0,-1)])
sage: K.is_full_space()
True
sage: K.discrete_complementarity_set()
()
```

Likewise for trivial cones, whose duals are the entire space:

```
sage: cones.trivial(0).discrete_complementarity_set()
()
```

### dual()

Return the dual cone of self.

**OUTPUT**:

· cone.

**EXAMPLES:** 

```
sage: cone = Cone([(1,0), (-1,3)])
sage: cone.dual().rays()
M(0, 1),
M(3, 1)
in 2-d lattice M
```

Now let's look at a more complicated case:

```
sage: cone = Cone([(-2,-1,2), (4,1,0), (-4,-1,-5), (4,1,5)])
sage: cone.is_strictly_convex()
False
sage: cone.dim()
3
sage: cone.dual().rays()
M(7, -18, -2),
M(1, -4, 0)
in 3-d lattice M
sage: cone.dual().dual() is cone
True
```

We correctly handle the degenerate cases:

```
sage: N = ToricLattice(2)
sage: Cone([], lattice=N).dual().rays() # empty cone
M( 1,  0),
M(-1,  0),
M( 0,  1),
```

```
M(0, -1)
in 2-d lattice M
sage: Cone([(1,0)], lattice=N).dual().rays() # ray in 2d
M(1, 0),
M(0, 1),
M(0, -1)
in 2-d lattice M
sage: Cone([(1,0),(-1,0)], lattice=N).dual().rays() # line in 2d
M(0, 1),
M(0, -1)
in 2-d lattice M
sage: Cone([(1,0),(0,1)], lattice=N).dual().rays() # strictly convex cone
M(0, 1),
M(1, 0)
in 2-d lattice M
sage: Cone([(1,0),(-1,0),(0,1)], lattice=N).dual().rays() # half space
M(0, 1)
in 2-d lattice M
sage: Cone([(1,0),(0,1),(-1,-1)], lattice=N).dual().rays() # whole space
Empty collection
in 2-d lattice M
```

### embed(cone)

Return the cone equivalent to the given one, but sitting in self as a face.

You may need to use this method before calling methods of cone that depend on the ambient structure, such as <code>ambient\_ray\_indices()</code> or <code>facet\_of()</code>. The cone returned by this method will have <code>self</code> as ambient. If <code>cone</code> does not represent a valid cone of <code>self</code>, <code>ValueError</code> exception is raised.

**Note:** This method is very quick if self is already the ambient structure of cone, so you can use without extra checks and performance hit even if cone is likely to sit in self but in principle may not.

# INPUT:

• cone – a cone.

### **OUTPUT**:

• a cone, equivalent to cone but sitting inside self.

### **EXAMPLES:**

Let's take a 3-d cone on 4 rays:

```
sage: c = Cone([(1,0,1), (0,1,1), (-1,0,1), (0,-1,1)])
```

Then any ray generates a 1-d face of this cone, but if you construct such a face directly, it will not "sit" inside the cone:

```
sage: ray = Cone([(0,-1,1)])
sage: ray
1-d cone in 3-d lattice N
sage: ray.ambient_ray_indices()
(0,)
```

```
sage: ray.adjacent()
()
sage: ray.ambient()
1-d cone in 3-d lattice N
```

If we want to operate with this ray as a face of the cone, we need to embed it first:

```
sage: e_ray = c.embed(ray)
sage: e_ray
1-d face of 3-d cone in 3-d lattice N
sage: e_ray.rays()
N(0, -1, 1)
in 3-d lattice N
sage: e_ray is ray
False
sage: e_ray.is_equivalent(ray)
sage: e_ray.ambient_ray_indices()
(3,)
sage: e_ray.adjacent()
(1-d face of 3-d cone in 3-d lattice N,
1-d face of 3-d cone in 3-d lattice N)
sage: e_ray.ambient()
3-d cone in 3-d lattice N
```

Not every cone can be embedded into a fixed ambient cone:

```
sage: c.embed(Cone([(0,0,1)]))
Traceback (most recent call last):
...
ValueError: 1-d cone in 3-d lattice N is not a face
of 3-d cone in 3-d lattice N!
sage: c.embed(Cone([(1,0,1), (-1,0,1)]))
Traceback (most recent call last):
...
ValueError: 2-d cone in 3-d lattice N is not a face
of 3-d cone in 3-d lattice N!
```

# face\_lattice()

Return the face lattice of self.

This lattice will have the origin as the bottom (we do not include the empty set as a face) and this cone itself as the top.

# OUTPUT:

• finite poset of cones.

# **EXAMPLES:**

Let's take a look at the face lattice of the first quadrant:

```
sage: quadrant = Cone([(1,0), (0,1)])
sage: L = quadrant.face_lattice()
```

```
sage: L
Finite lattice containing 4 elements with distinguished linear extension
```

To see all faces arranged by dimension, you can do this:

```
sage: for level in L.level_sets(): print(level)
[0-d face of 2-d cone in 2-d lattice N]
[1-d face of 2-d cone in 2-d lattice N,
  1-d face of 2-d cone in 2-d lattice N]
[2-d cone in 2-d lattice N]
```

For a particular face you can look at its actual rays...

```
sage: face = L.level_sets()[1][0]
sage: face.rays()
N(1, 0)
in 2-d lattice N
```

... or you can see the index of the ray of the original cone that corresponds to the above one:

```
sage: face.ambient_ray_indices()
(0,)
sage: quadrant.ray(0)
N(1, 0)
```

An alternative to extracting faces from the face lattice is to use faces() method:

```
sage: face is quadrant.faces(dim=1)[0]
True
```

The advantage of working with the face lattice directly is that you can (relatively easily) get faces that are related to the given one:

```
sage: face = L.level_sets()[1][0]
sage: D = L.hasse_diagram()
sage: sorted(D.neighbors(face))
[0-d face of 2-d cone in 2-d lattice N,
2-d cone in 2-d lattice N]
```

However, you can achieve some of this functionality using facets(), facet\_of(), and adjacent() methods:

```
sage: face = quadrant.faces(1)[0]
sage: face
1-d face of 2-d cone in 2-d lattice N
sage: face.rays()
N(1, 0)
in 2-d lattice N
sage: face.facets()
(0-d face of 2-d cone in 2-d lattice N,)
sage: face.facet_of()
(2-d cone in 2-d lattice N,)
sage: face.adjacent()
```

```
(1-d face of 2-d cone in 2-d lattice N,)
sage: face.adjacent()[0].rays()
N(0, 1)
in 2-d lattice N
```

Note that if cone is a face of supercone, then the face lattice of cone consists of (appropriate) faces of supercone:

```
sage: supercone = Cone([(1,2,3,4), (5,6,7,8),
                        (1,2,4,8), (1,3,9,7)])
sage: supercone.face_lattice()
Finite lattice containing 16 elements with distinguished linear extension
sage: supercone.face_lattice().top()
4-d cone in 4-d lattice N
sage: cone = supercone.facets()[0]
sage: cone
3-d face of 4-d cone in 4-d lattice N
sage: cone.face_lattice()
Finite poset containing 8 elements with distinguished linear extension
sage: cone.face_lattice().bottom()
0-d face of 4-d cone in 4-d lattice N
sage: cone.face_lattice().top()
3-d face of 4-d cone in 4-d lattice N
sage: cone.face_lattice().top() == cone
True
```

faces(dim=None, codim=None)

Return faces of self of specified (co)dimension.

#### INPUT:

- dim integer, dimension of the requested faces;
- codim integer, codimension of the requested faces.

Note: You can specify at most one parameter. If you don't give any, then all faces will be returned.

### **OUTPUT**:

- if either dim or codim is given, the output will be a tuple of *cones*;
- if neither dim nor codim is given, the output will be the tuple of tuples as above, giving faces of all existing dimensions. If you care about inclusion relations between faces, consider using face\_lattice() or adjacent(), facet\_of(), and facets().

### **EXAMPLES:**

Let's take a look at the faces of the first quadrant:

```
sage: quadrant = Cone([(1,0), (0,1)])
sage: quadrant.faces()
((0-d face of 2-d cone in 2-d lattice N,),
  (1-d face of 2-d cone in 2-d lattice N,
  1-d face of 2-d cone in 2-d lattice N),
  (2-d cone in 2-d lattice N,))
```

```
sage: quadrant.faces(dim=1)
(1-d face of 2-d cone in 2-d lattice N,
  1-d face of 2-d cone in 2-d lattice N)
sage: face = quadrant.faces(dim=1)[0]
```

Now you can look at the actual rays of this face...

```
sage: face.rays()
N(1, 0)
in 2-d lattice N
```

... or you can see indices of the rays of the original cone that correspond to the above ray:

```
sage: face.ambient_ray_indices()
(0,)
sage: quadrant.ray(0)
N(1, 0)
```

Note that it is OK to ask for faces of too small or high dimension:

```
sage: quadrant.faces(-1)
()
sage: quadrant.faces(3)
()
```

In the case of non-strictly convex cones even faces of small non-negative dimension may be missing:

```
sage: halfplane = Cone([(1,0), (0,1), (-1,0)])
sage: halfplane.faces(0)
()
sage: halfplane.faces()
((1-d face of 2-d cone in 2-d lattice N,),
    (2-d cone in 2-d lattice N,))
sage: plane = Cone([(1,0), (0,1), (-1,-1)])
sage: plane.faces(1)
()
sage: plane.faces()
((2-d cone in 2-d lattice N,),)
```

# facet\_normals()

Return inward normals to facets of self.

#### Note:

- 1. For a not full-dimensional cone facet normals will specify hyperplanes whose intersections with the space spanned by self give facets of self.
- 2. For a not strictly convex cone facet normals will be orthogonal to the linear subspace of self, i.e. they always will be elements of the dual cone of self.
- 3. The order of normals is random, but consistent with facets().

# OUTPUT:

• a PointCollection.

If the ambient lattice() of self is a toric lattice, the facet normals will be elements of the dual lattice. If it is a general lattice (like  $ZZ^n$ ) that does not have a dual() method, the facet normals will be returned as integral vectors.

# **EXAMPLES:**

```
sage: cone = Cone([(1,0), (-1,3)])
sage: cone.facet_normals()
M(0, 1),
M(3, 1)
in 2-d lattice M
```

Now let's look at a more complicated case:

```
sage: cone = Cone([(-2,-1,2), (4,1,0), (-4,-1,-5), (4,1,5)])
sage: cone.is_strictly_convex()
False
sage: cone.dim()
3
sage: cone.linear_subspace().dimension()
1
sage: lsg = (QQ^3)(cone.linear_subspace().gen(0)); lsg
(1, 1/4, 5/4)
sage: cone.facet_normals()
M(7, -18, -2),
M(1, -4, 0)
in 3-d lattice M
sage: [lsg*normal for normal in cone.facet_normals()]
[0, 0]
```

A lattice that does not have a dual() method:

```
sage: Cone([(1,1),(0,1)], lattice=ZZ^2).facet_normals()
(-1, 1),
( 1, 0)
in Ambient free module of rank 2
over the principal ideal domain Integer Ring
```

We correctly handle the degenerate cases:

```
sage: N = ToricLattice(2)
sage: Cone([], lattice=N).facet_normals() # empty cone
Empty collection
in 2-d lattice M
sage: Cone([(1,0)], lattice=N).facet_normals() # ray in 2d
M(1, 0)
in 2-d lattice M
sage: Cone([(1,0),(-1,0)], lattice=N).facet_normals() # line in 2d
Empty collection
in 2-d lattice M
sage: Cone([(1,0),(0,1)], lattice=N).facet_normals() # strictly convex cone
M(0, 1),
M(1, 0)
in 2-d lattice M
sage: Cone([(1,0),(-1,0),(0,1)], lattice=N).facet_normals() # half space
```

```
M(0, 1)
in 2-d lattice M
sage: Cone([(1,0),(0,1),(-1,-1)], lattice=N).facet_normals() # whole space
Empty collection
in 2-d lattice M
```

## facet\_of()

Return cones of the ambient face lattice having self as a facet.

#### **OUTPUT**:

• tuple of cones.

# **EXAMPLES**:

```
sage: octant = Cone([(1,0,0), (0,1,0), (0,0,1)])
sage: octant.facet_of()
()
sage: one_face = octant.faces(1)[0]
sage: len(one_face.facet_of())
2
sage: one_face.facet_of()[1]
2-d face of 3-d cone in 3-d lattice N
```

While fan is the top element of its own cone lattice, which is a variant of a face lattice, we do not refer to cones as its facets:

```
sage: fan = Fan([octant])
sage: fan.generating_cone(0).facet_of()
()
```

Subcones of generating cones work as before:

```
sage: one_cone = fan(1)[0]
sage: len(one_cone.facet_of())
2
```

### facets()

Return facets (faces of codimension 1) of self.

## OUTPUT:

• tuple of cones.

# **EXAMPLES:**

```
sage: quadrant = Cone([(1,0), (0,1)])
sage: quadrant.facets()
(1-d face of 2-d cone in 2-d lattice N,
  1-d face of 2-d cone in 2-d lattice N)
```

# incidence\_matrix()

Return the incidence matrix.

**Note:** The columns correspond to facets/facet normals in the order of facet\_normals(), the rows cor-

374

respond to the rays in the order of rays().

#### **EXAMPLES:**

```
sage: octant = Cone([(1,0,0), (0,1,0), (0,0,1)])
sage: octant.incidence_matrix()
[0 1 1]
[1 0 1]
[1 1 0]

sage: halfspace = Cone([(1,0,0), (0,1,0), (-1,-1,0), (0,0,1)])
sage: halfspace.incidence_matrix()
[0]
[1]
[1]
[1]
```

### interior()

Return the interior of self.

#### **OUTPUT:**

• either self, an empty polyhedron, or an instance of *RelativeInterior*.

### **EXAMPLES:**

```
sage: c = Cone([(1,0,0), (0,1,0)]); c
2-d cone in 3-d lattice N
sage: c.interior()
The empty polyhedron in ZZ^3
sage: origin = cones.trivial(2); origin
0-d cone in 2-d lattice N
sage: origin interior()
The empty polyhedron in ZZ^2
sage: K = cones.nonnegative_orthant(2); K
2-d cone in 2-d lattice N
sage: K.interior()
Relative interior of 2-d cone in 2-d lattice N
sage: K2 = Cone([(1,0),(-1,0),(0,1),(0,-1)]); K2
2-d cone in 2-d lattice N
sage: K2.interior() is K2
True
```

# interior\_contains(\*args)

Check if a given point is contained in the interior of self.

For a cone of strictly lower-dimension than the ambient space, the interior is always empty. You probably want to use  $relative\_interior\_contains()$  in this case.

# INPUT:

 anything. An attempt will be made to convert all arguments into a single element of the ambient space of self. If it fails, False will be returned.

## **OUTPUT**:

• True if the given point is contained in the interior of self, False otherwise.

## **EXAMPLES**:

```
sage: c = Cone([(1,0), (0,1)])
sage: c.contains((1,1))
True
sage: c.interior_contains((1,1))
True
sage: c.contains((1,0))
True
sage: c.interior_contains((1,0))
False
```

#### intersection(other)

Compute the intersection of two cones.

# INPUT:

• other - cone.

#### **OUTPUT:**

· cone.

Raises ValueError if the ambient space dimensions are not compatible.

### **EXAMPLES:**

```
sage: cone1 = Cone([(1,0), (-1, 3)])
sage: cone2 = Cone([(-1,0), (2, 5)])
sage: cone1.intersection(cone2).rays()
N(-1, 3),
N( 2, 5)
in 2-d lattice N
```

It is OK to intersect cones living in sublattices of the same ambient lattice:

```
sage: N = cone1.lattice()
sage: Ns = N.submodule([(1,1)])
sage: cone3 = Cone([(1,1)], lattice=Ns)
sage: I = cone1.intersection(cone3)
sage: I.rays()
N(1, 1)
in Sublattice <N(1, 1)>
sage: I.lattice()
Sublattice <N(1, 1)>
```

But you cannot intersect cones from incompatible lattices without explicit conversion:

```
sage: cone1.intersection(cone1.dual())
Traceback (most recent call last):
...
ValueError: 2-d lattice N and 2-d lattice M
have different ambient lattices!
sage: cone1.intersection(Cone(cone1.dual().rays(), N)).rays()
```

```
N(3, 1),
N(0, 1)
in 2-d lattice N
```

## is\_compact()

Checks if the cone has no rays.

### **OUTPUT**:

• True if the cone has no rays, False otherwise.

#### **EXAMPLES**:

```
sage: c0 = cones.trivial(3)
sage: c0.is_trivial()
True
sage: c0.nrays()
0
```

#### is\_empty()

Return whether self is the empty set.

Because a cone always contains the origin, this method returns False.

#### **EXAMPLES:**

```
sage: trivial_cone = cones.trivial(3)
sage: trivial_cone.is_empty()
False
```

# is\_equivalent(other)

Check if self is "mathematically" the same as other.

# INPUT:

• other - cone.

### OUTPUT:

• True if self and other define the same cones as sets of points in the same lattice, False otherwise.

There are three different equivalences between cones  $C_1$  and  $C_2$  in the same lattice:

- 1. They have the same generating rays in the same order. This is tested by C1 = C2.
- 2. They describe the same sets of points. This is tested by C1.is\_equivalent(C2).
- 3. They are in the same orbit of  $GL(n, \mathbf{Z})$  (and, therefore, correspond to isomorphic affine toric varieties). This is tested by C1.is\_isomorphic(C2).

# **EXAMPLES**:

```
sage: cone1 = Cone([(1,0), (-1, 3)])
sage: cone2 = Cone([(-1,3), (1, 0)])
sage: cone1.rays()
N( 1, 0),
N(-1, 3)
in 2-d lattice N
sage: cone2.rays()
```

```
N(-1, 3),
N( 1, 0)
in 2-d lattice N
sage: cone1 == cone2
False
sage: cone1.is_equivalent(cone2)
True
```

# is\_face\_of(cone)

Check if self forms a face of another cone.

### INPUT:

• cone - cone.

### OUTPUT:

• True if self is a face of cone, False otherwise.

### **EXAMPLES:**

```
sage: quadrant = Cone([(1,0), (0,1)])
sage: cone1 = Cone([(1,0)])
sage: cone2 = Cone([(1,2)])
sage: quadrant.is_face_of(quadrant)
True
sage: cone1.is_face_of(quadrant)
True
sage: cone2.is_face_of(quadrant)
False
```

Being a face means more than just saturating a facet inequality:

```
sage: octant = Cone([(1,0,0), (0,1,0), (0,0,1)])
sage: cone = Cone([(2,1,0),(1,2,0)])
sage: cone.is_face_of(octant)
False
```

# is\_full\_dimensional()

Check if this cone is solid.

A cone is said to be solid if it has nonempty interior. That is, if its extreme rays span the entire ambient space.

An alias is is\_full\_dimensional().

#### **OUTPUT**:

True if this cone is solid, and False otherwise.

# See also:

is\_proper()

### **EXAMPLES:**

The nonnegative orthant is always solid:

```
sage: quadrant = cones.nonnegative_orthant(2)
sage: quadrant.is_solid()
True
sage: octant = Cone([(1,0,0), (0,1,0), (0,0,1)])
sage: octant.is_solid()
True
```

However, if we embed the two-dimensional nonnegative quadrant into three-dimensional space, then the resulting cone no longer has interior, so it is not solid:

```
sage: quadrant = Cone([(1,0,0), (0,1,0)])
sage: quadrant.is_solid()
False
```

## is\_full\_space()

Check if this cone is equal to its ambient vector space.

An alias is is\_universe().

**OUTPUT**:

True if this cone equals its entire ambient vector space and False otherwise.

**EXAMPLES:** 

A single ray in two dimensions is not equal to the entire space:

```
sage: K = Cone([(1,0)])
sage: K.is_full_space()
False
```

Neither is the nonnegative orthant:

```
sage: K = cones.nonnegative_orthant(2)
sage: K.is_full_space()
False
```

The right half-space contains a vector subspace, but it is still not equal to the entire space:

```
sage: K = Cone([(1,0),(-1,0),(0,1)])
sage: K.is_full_space()
False
```

However, if we allow conic combinations of both axes, then the resulting cone is the entire two-dimensional space:

```
sage: K = Cone([(1,0),(-1,0),(0,1),(0,-1)])
sage: K.is_full_space()
True
```

# is\_isomorphic(other)

Check if self is in the same  $GL(n, \mathbf{Z})$ -orbit as other.

INPUT:

• other - cone.

**OUTPUT**:

• True if self and other are in the same  $GL(n, \mathbf{Z})$ -orbit, False otherwise.

There are three different equivalences between cones  $C_1$  and  $C_2$  in the same lattice:

- 1. They have the same generating rays in the same order. This is tested by C1 = C2.
- 2. They describe the same sets of points. This is tested by C1.is\_equivalent(C2).
- 3. They are in the same orbit of  $GL(n, \mathbf{Z})$  (and, therefore, correspond to isomorphic affine toric varieties). This is tested by C1.is\_isomorphic(C2).

# **EXAMPLES:**

```
sage: cone1 = Cone([(1,0), (0, 3)])
sage: m = matrix(ZZ, [(1, -5), (-1, 4)]) # a GL(2,ZZ)-matrix
sage: cone2 = Cone( m*r for r in cone1.rays() )
sage: cone1.is_isomorphic(cone2)
True

sage: cone1 = Cone([(1,0), (0, 3)])
sage: cone2 = Cone([(-1,3), (1, 0)])
sage: cone1.is_isomorphic(cone2)
False
```

## is\_proper()

Check if this cone is proper.

A cone is said to be proper if it is closed, convex, solid, and contains no lines. This cone is assumed to be closed and convex; therefore it is proper if it is solid and contains no lines.

## **OUTPUT**:

True if this cone is proper, and False otherwise.

# See also:

```
is_strictly_convex(), is_solid()
```

#### **EXAMPLES:**

The nonnegative orthant is always proper:

```
sage: quadrant = cones.nonnegative_orthant(2)
sage: quadrant.is_proper()
True
sage: octant = Cone([(1,0,0), (0,1,0), (0,0,1)])
sage: octant.is_proper()
True
```

However, if we embed the two-dimensional nonnegative quadrant into three-dimensional space, then the resulting cone no longer has interior, so it is not solid, and thus not proper:

```
sage: quadrant = Cone([(1,0,0), (0,1,0)])
sage: quadrant.is_proper()
False
```

Likewise, a half-space contains at least one line, so it is not proper:

```
sage: halfspace = Cone([(1,0),(0,1),(-1,0)])
sage: halfspace.is_proper()
False
```

# is\_relatively\_open()

Return whether self is relatively open.

OUTPUT:

Boolean.

**EXAMPLES:** 

```
sage: K = cones.nonnegative_orthant(3)
sage: K.is_relatively_open()
False

sage: K1 = Cone([(1,0), (-1,0)]); K1
1-d cone in 2-d lattice N
sage: K1.is_relatively_open()
True
```

## is\_simplicial()

Check if self is simplicial.

A cone is called **simplicial** if primitive vectors along its generating rays form a part of a *rational* basis of the ambient space.

### **OUTPUT**:

• True if self is simplicial, False otherwise.

# **EXAMPLES:**

```
sage: cone1 = Cone([(1,0), (0, 3)])
sage: cone2 = Cone([(1,0), (0, 3), (-1,-1)])
sage: cone1.is_simplicial()
True
sage: cone2.is_simplicial()
False
```

# is\_smooth()

Check if self is smooth.

A cone is called **smooth** if primitive vectors along its generating rays form a part of an *integral* basis of the ambient space. Equivalently, they generate the whole lattice on the linear subspace spanned by the rays.

# OUTPUT:

• True if self is smooth. False otherwise.

### **EXAMPLES:**

```
sage: cone1 = Cone([(1,0), (0, 1)])
sage: cone2 = Cone([(1,0), (-1, 3)])
sage: cone1.is_smooth()
True
sage: cone2.is_smooth()
False
```

The following cones are the same up to a  $SL(2, \mathbf{Z})$  coordinate transformation:

```
sage: Cone([(1,0,0), (2,1,-1)]).is_smooth()
True
sage: Cone([(1,0,0), (2,1,1)]).is_smooth()
True
sage: Cone([(1,0,0), (2,1,2)]).is_smooth()
True
```

### is\_solid()

Check if this cone is solid.

A cone is said to be solid if it has nonempty interior. That is, if its extreme rays span the entire ambient space.

An alias is is\_full\_dimensional().

### **OUTPUT:**

True if this cone is solid, and False otherwise.

#### See also:

```
is_proper()
```

## **EXAMPLES:**

The nonnegative orthant is always solid:

```
sage: quadrant = cones.nonnegative_orthant(2)
sage: quadrant.is_solid()
True
sage: octant = Cone([(1,0,0), (0,1,0), (0,0,1)])
sage: octant.is_solid()
True
```

However, if we embed the two-dimensional nonnegative quadrant into three-dimensional space, then the resulting cone no longer has interior, so it is not solid:

```
sage: quadrant = Cone([(1,0,0), (0,1,0)])
sage: quadrant.is_solid()
False
```

# is\_strictly\_convex()

Check if self is strictly convex.

A cone is called **strictly convex** if it does not contain any lines.

### **OUTPUT**:

• True if self is strictly convex, False otherwise.

### **EXAMPLES:**

```
sage: cone1 = Cone([(1,0), (0, 1)])
sage: cone2 = Cone([(1,0), (-1, 0)])
sage: cone1.is_strictly_convex()
True
sage: cone2.is_strictly_convex()
False
```

## is\_trivial()

Checks if the cone has no rays.

#### **OUTPUT:**

• True if the cone has no rays, False otherwise.

### **EXAMPLES:**

```
sage: c0 = cones.trivial(3)
sage: c0.is_trivial()
True
sage: c0.nrays()
0
```

# is\_universe()

Check if this cone is equal to its ambient vector space.

```
An alias is is_universe().
```

# **OUTPUT**:

True if this cone equals its entire ambient vector space and False otherwise.

#### **EXAMPLES:**

A single ray in two dimensions is not equal to the entire space:

```
sage: K = Cone([(1,0)])
sage: K.is_full_space()
False
```

Neither is the nonnegative orthant:

```
sage: K = cones.nonnegative_orthant(2)
sage: K.is_full_space()
False
```

The right half-space contains a vector subspace, but it is still not equal to the entire space:

```
sage: K = Cone([(1,0),(-1,0),(0,1)])
sage: K.is_full_space()
False
```

However, if we allow conic combinations of both axes, then the resulting cone is the entire two-dimensional space:

```
sage: K = Cone([(1,0),(-1,0),(0,1),(0,-1)])
sage: K.is_full_space()
True
```

# lineality()

Return the lineality of this cone.

The lineality of a cone is the dimension of the largest linear subspace contained in that cone.

# **OUTPUT**:

A nonnegative integer; the dimension of the largest subspace contained within this cone.

REFERENCES:

• [Roc1970]

# **EXAMPLES:**

The lineality of the nonnegative orthant is zero, since it clearly contains no lines:

```
sage: K = cones.nonnegative_orthant(3)
sage: K.lineality()
0
```

However, if we add another ray so that the entire x-axis belongs to the cone, then the resulting cone will have lineality one:

```
sage: K = Cone([(1,0,0), (-1,0,0), (0,1,0), (0,0,1)])
sage: K.lineality()
1
```

If our cone is all of  $\mathbb{R}^2$ , then its lineality is equal to the dimension of the ambient space (i.e. two):

```
sage: K = Cone([(1,0), (-1,0), (0,1), (0,-1)])
sage: K.is_full_space()
True
sage: K.lineality()
2
sage: K.lattice_dim()
2
```

Per the definition, the lineality of the trivial cone in a trivial space is zero:

```
sage: K = cones.trivial(0)
sage: K.lineality()
0
```

### linear\_subspace()

Return the largest linear subspace contained inside of self.

# OUTPUT:

• subspace of the ambient space of self.

## **EXAMPLES:**

```
sage: halfplane = Cone([(1,0), (0,1), (-1,0)])
sage: halfplane.linear_subspace()
Vector space of degree 2 and dimension 1 over Rational Field
Basis matrix:
[1 0]
```

# lines()

Return lines generating the linear subspace of self.

### **OUTPUT**:

• tuple of primitive vectors in the lattice of self giving directions of lines that span the linear subspace of self. These lines are arbitrary, but fixed. If you do not care about the order, see also line\_set().

# **EXAMPLES:**

```
sage: halfplane = Cone([(1,0), (0,1), (-1,0)])
sage: halfplane.lines()
N(1, 0)
in 2-d lattice N
sage: fullplane = Cone([(1,0), (0,1), (-1,-1)])
sage: fullplane.lines()
N(0, 1),
N(1, 0)
in 2-d lattice N
```

## lyapunov\_like\_basis()

Compute a basis of Lyapunov-like transformations on this cone.

A linear transformation L is said to be Lyapunov-like on this cone if L(x) and s are orthogonal for every pair (x,s) in its  $discrete\_complementarity\_set()$ . The set of all such transformations forms a vector space, namely the Lie algebra of the automorphism group of this cone.

## **OUTPUT**:

A list of matrices forming a basis for the space of all Lyapunov-like transformations on this cone.

#### See also:

```
cross_positive_operators_gens(), positive_operators_gens(), Z_operators_gens()
```

# REFERENCES:

- [Or2017]
- [RNPA2011]

# **EXAMPLES:**

Every transformation is Lyapunov-like on the trivial cone:

```
sage: K = cones.trivial(2)
sage: M = MatrixSpace(K.lattice().base_field(), K.lattice_dim())
sage: list(M.basis()) == K.lyapunov_like_basis()
True
```

And by duality, every transformation is Lyapunov-like on the ambient space:

```
sage: K = Cone([(1,0), (-1,0), (0,1), (0,-1)])
sage: K.is_full_space()
True
sage: M = MatrixSpace(K.lattice().base_field(), K.lattice_dim())
sage: list(M.basis()) == K.lyapunov_like_basis()
True
```

However, in a trivial space, there are no non-trivial linear maps, so there can be no Lyapunov-like basis:

```
sage: K = cones.trivial(0)
sage: K.lyapunov_like_basis()
[]
```

The Lyapunov-like transformations on the nonnegative orthant are diagonal matrices:

```
sage: K = cones.nonnegative_orthant(1)
sage: K.lyapunov_like_basis()
[[1]]

sage: K = cones.nonnegative_orthant(2)
sage: K.lyapunov_like_basis()
[
[1 0] [0 0]
[0 0], [0 1]
]

sage: K = cones.nonnegative_orthant(3)
sage: K.lyapunov_like_basis()
[
[1 0 0] [0 0 0] [0 0 0]
[0 0 0] [0 1 0] [0 0 0]
[0 0 0], [0 0 0], [0 0 1]
]
```

Only the identity matrix is Lyapunov-like on the pyramids defined by the one- and infinity-norms [RNPA2011]:

```
sage: l31 = Cone([(1,0,1), (0,-1,1), (-1,0,1), (0,1,1)])
sage: l31.lyapunov_like_basis()
[
[1 0 0]
[0 1 0]
[0 0 1]
]

sage: l3infty = Cone([(0,1,1), (1,0,1), (0,-1,1), (-1,0,1)])
sage: l3infty.lyapunov_like_basis()
[
[1 0 0]
[0 1 0]
[0 0 1]
]
```

# lyapunov\_rank()

Compute the Lyapunov rank of this cone.

The Lyapunov rank of a cone is the dimension of the space of its Lyapunov-like transformations — that is, the length of a *lyapunov\_like\_basis()*. Equivalently, the Lyapunov rank is the dimension of the Lie algebra of the automorphism group of the cone.

# **OUTPUT**:

A nonnegative integer representing the Lyapunov rank of this cone.

If the ambient space is trivial, then the Lyapunov rank will be zero. On the other hand, if the dimension of the ambient vector space is n > 0, then the resulting Lyapunov rank will be between 1 and  $n^2$  inclusive. If this cone  $is\_proper()$ , then that upper bound reduces from  $n^2$  to n. A Lyapunov rank of n-1 is not possible (by Lemma 6 [Or2017]) in either case.

# ALGORITHM:

Algorithm 3 [Or2017] is used. Every closed convex cone is isomorphic to a Cartesian product of a proper

cone, a subspace, and a trivial cone. The Lyapunov ranks of the subspace and trivial cone are easy to compute. Essentially, we "peel off" those easy parts of the cone and compute their Lyapunov ranks separately. We then compute the rank of the proper cone by counting a <code>lyapunov\_like\_basis()</code> for it. Summing the individual ranks gives the Lyapunov rank of the original cone.

### REFERENCES:

- [GT2014]
- [Or2017]
- [RNPA2011]

### **EXAMPLES:**

The Lyapunov rank of the nonnegative orthant is the same as the dimension of the ambient space [RNPA2011]:

```
sage: positives = cones.nonnegative_orthant(1)
sage: positives.lyapunov_rank()

sage: quadrant = cones.nonnegative_orthant(2)
sage: quadrant.lyapunov_rank()

sage: octant = cones.nonnegative_orthant(3)
sage: octant.lyapunov_rank()
```

A vector space of dimension n has Lyapunov rank  $n^2$  [Or2017]:

```
sage: Q5 = VectorSpace(QQ, 5)
sage: gs = Q5.basis() + [ -r for r in Q5.basis() ]
sage: K = Cone(gs)
sage: K.lyapunov_rank()
25
```

A pyramid in three dimensions has Lyapunov rank one [RNPA2011]:

```
sage: 131 = Cone([(1,0,1), (0,-1,1), (-1,0,1), (0,1,1)])
sage: 131.lyapunov_rank()
1
sage: 13infty = Cone([(0,1,1), (1,0,1), (0,-1,1), (-1,0,1)])
sage: 13infty.lyapunov_rank()
1
```

A ray in n dimensions has Lyapunov rank  $n^2 - n + 1$  [Or2017]:

```
sage: K = Cone([(1,0,0,0,0)])
sage: K.lyapunov_rank()
21
sage: K.lattice_dim()**2 - K.lattice_dim() + 1
21
```

A subspace of dimension m in an n-dimensional ambient space has Lyapunov rank  $n^2-m(n-m)$  [Or2017]:

```
sage: e1 = vector(QQ, [1,0,0,0,0])
sage: e2 = vector(QQ, [0,1,0,0,0])
sage: z = (0,0,0,0,0)
sage: K = Cone([e1, -e1, e2, -e2, z, z, z])
sage: K.lyapunov_rank()
19
sage: K.lattice_dim()**2 - K.dim()*K.codim()
19
```

Lyapunov rank is additive on a product of proper cones [RNPA2011]:

```
sage: 131 = Cone([(1,0,1), (0,-1,1), (-1,0,1), (0,1,1)])
sage: octant = Cone([(1,0,0), (0,1,0), (0,0,1)])
sage: K = 131.cartesian_product(octant)
sage: K.lyapunov_rank()
4
sage: 131.lyapunov_rank() + octant.lyapunov_rank()
4
```

Two linearly-isomorphic cones have the same Lyapunov rank [RNPA2011]. A cone linearly-isomorphic to the nonnegative octant will have Lyapunov rank 3:

```
sage: K = Cone([(1,2,3), (-1,1,0), (1,0,6)])
sage: K.lyapunov_rank()
3
```

Lyapunov rank is invariant under *dual()* [RNPA2011]:

```
sage: K = Cone([(2,2,4), (-1,9,0), (2,0,6)])
sage: K.lyapunov_rank() == K.dual().lyapunov_rank()
True
```

### orthogonal\_sublattice(\*args, \*\*kwds)

The sublattice (in the dual lattice) orthogonal to the sublattice spanned by the cone.

Let  $M = self.dual\_lattice()$  be the lattice dual to the ambient lattice of the given cone  $\sigma$ . Then, in the notation of [Ful1993], this method returns the sublattice

$$M(\sigma) \stackrel{\mathrm{def}}{=} \sigma^{\perp} \cap M \subset M$$

# INPUT:

• either nothing or something that can be turned into an element of this lattice.

#### OUTPUT:

• if no arguments were given, a toric sublattice, otherwise the corresponding element of it.

# **EXAMPLES:**

```
sage: c = Cone([(1,1,1), (1,-1,1), (-1,-1,1), (-1,1,1)])
sage: c.orthogonal_sublattice()
Sublattice <>
sage: c12 = Cone([(1,1,1), (1,-1,1)])
sage: c12.sublattice()
Sublattice <N(1, 1, 1), N(0, -1, 0)>
```

```
sage: c12.orthogonal_sublattice()
Sublattice <M(1, 0, -1)>
```

### plot(\*\*options)

Plot self.

### INPUT:

• any options for toric plots (see toric\_plotter.options), none are mandatory.

#### **OUTPUT**:

• a plot.

# **EXAMPLES:**

```
sage: quadrant = Cone([(1,0), (0,1)])
sage: quadrant.plot() # optional - sage.plot
Graphics object consisting of 9 graphics primitives
```

#### polyhedron()

Return the polyhedron associated to self.

Mathematically this polyhedron is the same as self.

### **OUTPUT**:

Polyhedron\_base.

### **EXAMPLES:**

```
sage: quadrant = Cone([(1,0), (0,1)])
sage: quadrant.polyhedron()
A 2-dimensional polyhedron in ZZ^2 defined as the convex hull
of 1 vertex and 2 rays
sage: line = Cone([(1,0), (-1,0)])
sage: line.polyhedron()
A 1-dimensional polyhedron in ZZ^2 defined as the convex hull
of 1 vertex and 1 line
```

Here is an example of a trivial cone (see trac ticket #10237):

```
sage: origin = Cone([], lattice=ZZ^2)
sage: origin.polyhedron()
A 0-dimensional polyhedron in ZZ^2 defined as the convex hull
of 1 vertex
```

# positive\_operators\_gens(K2=None)

Compute minimal generators of the positive operators on this cone.

A linear operator on a cone is positive if the image of the cone under the operator is a subset of the cone. This concept can be extended to two cones: the image of the first cone under a positive operator is a subset of the second cone, which may live in a different space.

The positive operators (on one or two fixed cones) themselves form a closed convex cone. This method computes and returns the generators of that cone as a list of matrices.

INPUT:

 K2 – (default: self) the codomain cone; the image of this cone under the returned generators is a subset of K2.

#### **OUTPUT:**

A list of m-by-n matrices where m is the ambient dimension of K2 and n is the ambient dimension of this cone. Each matrix P in the list has the property that P(x) is an element of K2 whenever x is an element of this cone.

The returned matrices generate the cone of positive operators from this cone to K2; that is,

- Any nonnegative linear combination of the returned matrices sends elements of this cone to K2.
- Every positive operator on this cone (with respect to K2) is some nonnegative linear combination of the returned matrices.

### ALGORITHM:

Computing positive operators directly is difficult, but computing their dual is straightforward using the generators of Berman and Gaiha. We construct the dual of the positive operators, and then return the dual of that, which is guaranteed to be the desired positive operators because everything is closed, convex, and polyhedral.

#### See also:

```
cross_positive_operators_gens(), lyapunov_like_basis(), Z_operators_gens()
```

### REFERENCES:

- [BG1972]
- [BP1994]
- [Or2018b]

# **EXAMPLES:**

Positive operators on the nonnegative orthant are nonnegative matrices:

```
sage: K = Cone([(1,)])
sage: K.positive_operators_gens()
[[1]]

sage: K = Cone([(1,0),(0,1)])
sage: K.positive_operators_gens()
[
[1 0] [0 1] [0 0] [0 0]
[0 0], [0 0], [1 0], [0 1]
]
```

The trivial cone in a trivial space has no positive operators:

```
sage: K = cones.trivial(0)
sage: K.positive_operators_gens()
[]
```

Every operator is positive on the trivial cone:

```
sage: K = cones.trivial(1)
sage: K.positive_operators_gens()
[[1], [-1]]
```

```
sage: K = cones.trivial(2)
sage: K.is_trivial()
True
sage: K.positive_operators_gens()
[
[1 0] [-1 0] [0 1] [ 0 -1] [0 0] [ 0 0] [ 0 0] [ 0 0]
[0 0], [ 0 0], [ 0 0], [ 0 0], [ 1 0], [-1 0], [ 0 1], [ 0 -1]
]
```

Every operator is positive on the ambient vector space:

```
sage: K = Cone([(1,),(-1,)])
sage: K.is_full_space()
True
sage: K.positive_operators_gens()
[[1], [-1]]

sage: K = Cone([(1,0),(-1,0),(0,1),(0,-1)])
sage: K.is_full_space()
True
sage: K.positive_operators_gens()
[
[1 0] [-1 0] [0 1] [0 -1] [0 0] [0 0] [0 0] [0 0]
[0 0], [0 0], [0 0], [0 0], [1 0], [-1 0], [0 1], [0 -1]
]
```

A non-obvious application is to find the positive operators on the right half-plane [Or2018b]:

```
sage: K = Cone([(1,0),(0,1),(0,-1)])
sage: K.positive_operators_gens()
[
[1 0] [0 0] [0 0] [0 0] [0 0]
[0 0], [1 0], [-1 0], [0 1], [ 0 -1]
]
```

## random\_element(ring=Integer Ring)

Return a random element of this cone.

All elements of a convex cone can be represented as a nonnegative linear combination of its generators. A random element is thus constructed by assigning random nonnegative weights to the generators of this cone. By default, these weights are integral and the resulting random element will live in the same lattice as the cone.

The random nonnegative weights are chosen from ring which defaults to ZZ. When ring is not ZZ, the random element returned will be a vector. Only the rings ZZ and QQ are currently supported.

# INPUT:

• ring – (default: ZZ) the ring from which the random generator weights are chosen; either ZZ or QQ.

### **OUTPUT:**

Either a lattice element or vector contained in both this cone and its ambient vector space. If ring is ZZ, a lattice element is returned; otherwise a vector is returned. If ring is neither ZZ nor QQ, then a NotImplementedError is raised.

## **EXAMPLES:**

The trivial element () is always returned in a trivial space:

```
sage: K = cones.trivial(0)
sage: K.random_element()
N()
sage: K.random_element(ring=QQ)
()
```

A random element of the trivial cone in a nontrivial space is zero:

```
sage: K = cones.trivial(3)
sage: K.random_element()
N(0, 0, 0)
sage: K.random_element(ring=QQ)
(0, 0, 0)
```

A random element of the nonnegative orthant should have all components nonnegative:

```
sage: K = cones.nonnegative_orthant(3)
sage: all( x >= 0 for x in K.random_element() )
True
sage: all( x >= 0 for x in K.random_element(ring=QQ) )
True
```

If ring is not ZZ or QQ, an error is raised:

```
sage: K = Cone([(1,0),(0,1)])
sage: K.random_element(ring=RR)
Traceback (most recent call last):
...
NotImplementedError: ring must be either ZZ or QQ.
```

### relative\_interior()

Return the relative interior of self.

## OUTPUT:

• either self or an instance of RelativeInterior.

#### **EXAMPLES:**

```
sage: c = Cone([(1,0,0), (0,1,0)]); c
2-d cone in 3-d lattice N
sage: c.relative_interior()
Relative interior of 2-d cone in 3-d lattice N

sage: origin = cones.trivial(2); origin
0-d cone in 2-d lattice N
sage: origin.relative_interior() is origin
True

sage: K1 = Cone([(1,0), (-1,0)]); K1
1-d cone in 2-d lattice N
sage: K1.relative_interior() is K1
```

```
True
sage: K2 = Cone([(1,0),(-1,0),(0,1),(0,-1)]); K2
2-d cone in 2-d lattice N
sage: K2.relative_interior() is K2
True
```

# relative\_interior\_contains(\*args)

Check if a given point is contained in the relative interior of self.

For a full-dimensional cone the relative interior is simply the interior, so this method will do the same check as *interior\_contains()*. For a strictly lower-dimensional cone, the relative interior is the cone without its facets.

### INPUT:

 anything. An attempt will be made to convert all arguments into a single element of the ambient space of self. If it fails, False will be returned.

### **OUTPUT**:

• True if the given point is contained in the relative interior of self, False otherwise.

#### **EXAMPLES:**

```
sage: c = Cone([(1,0,0), (0,1,0)])
sage: c.contains((1,1,0))
True
sage: c.relative_interior_contains((1,1,0))
True
sage: c.interior_contains((1,1,0))
False
sage: c.contains((1,0,0))
True
sage: c.relative_interior_contains((1,0,0))
False
sage: c.relative_interior_contains((1,0,0))
False
sage: c.interior_contains((1,0,0))
```

# relative\_orthogonal\_quotient(supercone)

The quotient of the dual spanned lattice by the dual of the supercone's spanned lattice.

In the notation of [Ful1993], if supercone =  $\rho > \sigma$  = self is a cone that contains  $\sigma$  as a face, then  $M(\rho)$  = supercone.orthogonal\_sublattice() is a saturated sublattice of  $M(\sigma)$  = self. orthogonal\_sublattice(). This method returns the quotient lattice. The lifts of the quotient generators are  $\dim(\rho) - \dim(\sigma)$  linearly independent M-lattice lattice points that, together with  $M(\rho)$ , generate  $M(\sigma)$ .

### **OUTPUT**:

• toric lattice quotient.

If we call the output Mrho, then

- Mrho.cover() == self.orthogonal\_sublattice(), and
- Mrho.relations() == supercone.orthogonal\_sublattice().

#### Note:

- $M(\sigma)/M(\rho)$  has no torsion since the sublattice  $M(\rho)$  is saturated.
- In the codimension one case, (a lift of) the generator of  $M(\sigma)/M(\rho)$  is chosen to be positive on  $\sigma$ .

#### **EXAMPLES:**

```
sage: rho = Cone([(1,1,1,3),(1,-1,1,3),(-1,-1,1,3),(-1,1,1,3)])
sage: rho.orthogonal_sublattice()
Sublattice <M(0, 0, 3, -1)>
sage: sigma = rho.facets()[1]
sage: sigma.orthogonal_sublattice()
Sublattice <M(0, 1, 1, 0), M(0, 0, 3, -1)>
sage: sigma.is_face_of(rho)
True
sage: Q = sigma.relative_orthogonal_quotient(rho); Q
1-d lattice, quotient
of Sublattice <M(0, 1, 1, 0), M(0, 0, 3, -1)>
by Sublattice <M(0, 0, 3, -1)>
sage: Q.gens()
(M[0, 1, 1, 0],)
```

### Different codimension:

```
sage: rho = Cone([[1,-1,1,3],[-1,-1,1,3]])
sage: sigma = rho.facets()[0]
sage: sigma.orthogonal_sublattice()
Sublattice <M(1, 0, 2, -1), M(0, 1, 1, 0), M(0, 0, 3, -1)>
sage: rho.orthogonal_sublattice()
Sublattice <M(0, 1, 1, 0), M(0, 0, 3, -1)>
sage: sigma.relative_orthogonal_quotient(rho).gens()
(M[-1, 0, -2, 1],)
```

Sign choice in the codimension one case:

```
sage: sigma1 = Cone([(1, 2, 3), (1, -1, 1), (-1, 1, 1), (-1, -1, 1)]) # 3d
sage: sigma2 = Cone([(1, 1, -1), (1, 2, 3), (1, -1, 1), (1, -1, -1)]) # 3d
sage: rho = sigma1.intersection(sigma2)
sage: rho.relative_orthogonal_quotient(sigma1).gens()
(M[-5, -2, 3],)
sage: rho.relative_orthogonal_quotient(sigma2).gens()
(M[5, 2, -3],)
```

### relative\_quotient(subcone)

The quotient of the spanned lattice by the lattice spanned by a subcone.

In the notation of [Ful1993], let N be the ambient lattice and  $N_{\sigma}$  the sublattice spanned by the given cone  $\sigma$ . If  $\rho < \sigma$  is a subcone, then  $N_{\rho} = \text{rho.sublattice}$  is a saturated sublattice of  $N_{\sigma} = \text{self.}$  sublattice(). This method returns the quotient lattice. The lifts of the quotient generators are  $\dim(\sigma) - \dim(\rho)$  linearly independent primitive lattice points that, together with  $N_{\rho}$ , generate  $N_{\sigma}$ .

## **OUTPUT**:

• toric lattice quotient.

#### Note:

- The quotient  $N_{\sigma}/N_{\rho}$  of spanned sublattices has no torsion since the sublattice  $N_{\rho}$  is saturated.
- In the codimension one case, the generator of  $N_{\sigma}/N_{\rho}$  is chosen to be in the same direction as the image  $\sigma/N_{\rho}$

#### **EXAMPLES:**

```
sage: sigma = Cone([(1,1,1,3),(1,-1,1,3),(-1,-1,1,3),(-1,1,1,3)])
sage: rho = Cone([(-1, -1, 1, 3), (-1, 1, 1, 3)])
sage: sigma.sublattice()
Sublattice <N(1, 1, 1, 3), N(0, -1, 0, 0), N(-1, -1, 0, 0)>
sage: rho.sublattice()
Sublattice <N(-1, -1, 1, 3), N(0, 1, 0, 0)>
sage: sigma.relative_quotient(rho)
1-d lattice, quotient
of Sublattice <N(1, 1, 1, 3), N(0, -1, 0, 0), N(-1, -1, 0, 0)>
by Sublattice <N(1, 0, -1, -3), N(0, 1, 0, 0)>
sage: sigma.relative_quotient(rho).gens()
(N[1, 0, 0, 0],)
```

More complicated example:

Sign choice in the codimension one case:

```
sage: sigma1 = Cone([(1, 2, 3), (1, -1, 1), (-1, 1, 1), (-1, -1, 1)]) # 3d
sage: sigma2 = Cone([(1, 1, -1), (1, 2, 3), (1, -1, 1), (1, -1, -1)]) # 3d
sage: rho = sigma1.intersection(sigma2)
sage: rho.sublattice()
Sublattice <N(1, -1, 1), N(1, 2, 3)>
sage: sigma1.relative_quotient(rho)
1-d lattice, quotient
of Sublattice <N(1, 2, 3), N(1, -1, 1), N(-1, -1, -2)>
by Sublattice <N(1, 2, 3), N(0, 3, 2)>
sage: sigma1.relative_quotient(rho).gens()
(N[-1, -1, -2],)
sage: sigma2.relative_quotient(rho).gens()
(N[0, 2, 1],)
```

#### semigroup\_generators()

Return generators for the semigroup of lattice points of self.

#### **OUTPUT:**

• a PointCollection of lattice points generating the semigroup of lattice points contained in self.

**Note:** No attempt is made to return a minimal set of generators, see *Hilbert\_basis()* for that.

### **EXAMPLES:**

The following command ensures that the output ordering in the examples below is independent of TOP-COM, you don't have to use it:

```
sage: PointConfiguration.set_engine('internal')
```

We start with a simple case of a non-smooth 2-dimensional cone:

```
sage: Cone([ (1,0), (1,2) ]).semigroup_generators()
N(1, 1),
N(1, 0),
N(1, 2)
in 2-d lattice N
```

A non-simplicial cone works, too:

```
sage: cone = Cone([(3,0,-1), (1,-1,0), (0,1,0), (0,0,1)])
sage: sorted(cone.semigroup_generators())
[N(0, 0, 1), N(0, 1, 0), N(1, -1, 0), N(1, 0, 0), N(3, 0, -1)]
```

GAP's toric package thinks this is challenging:

```
sage: cone = Cone([[1,2,3,4],[0,1,0,7],[3,1,0,2],[0,0,1,0]]).dual()
sage: len( cone.semigroup_generators() )
2806
```

The cone need not be strictly convex:

```
sage: halfplane = Cone([(1,0),(2,1),(-1,0)])
sage: sorted(halfplane.semigroup_generators())
[N(-1, 0), N(0, 1), N(1, 0)]
sage: line = Cone([(1,1,1),(-1,-1,-1)])
sage: sorted(line.semigroup_generators())
[N(-1, -1, -1), N(1, 1, 1)]
sage: wedge = Cone([ (1,0,0), (1,2,0), (0,0,1), (0,0,-1) ])
sage: sorted(wedge.semigroup_generators())
[N(0, 0, -1), N(0, 0, 1), N(1, 0, 0), N(1, 1, 0), N(1, 2, 0)]
```

Nor does it have to be full-dimensional (see trac ticket #11312):

```
sage: Cone([(1,1,0), (-1,1,0)]).semigroup_generators()
N( 0, 1, 0),
N( 1, 1, 0),
N(-1, 1, 0)
in 3-d lattice N
```

Neither full-dimensional nor simplicial:

#### ALGORITHM:

If the cone is not simplicial, it is first triangulated. Each simplicial subcone has the integral points of the spaned parallelotope as generators. This is the first step of the primal Normaliz algorithm, see [Normaliz]. For each simplicial cone (of dimension d), the integral points of the open parallelotope

$$par\langle x_1,\ldots,x_d\rangle = \mathbf{Z}^n \cap \{q_1x_1 + \cdots + q_dx_d: \ 0 \le q_i < 1\}$$

are then computed [BK2001].

Finally, the union of the generators of all simplicial subcones is returned.

### solid\_restriction()

Return a solid representation of this cone in terms of a basis of its *sublattice()*.

We define the **solid restriction** of a cone to be a representation of that cone in a basis of its own sublattice. Since a cone's sublattice is just large enough to hold the cone (by definition), the resulting solid restriction  $is\_solid()$ . For convenience, the solid restriction lives in a new lattice (of the appropriate dimension) and not actually in the sublattice object returned by sublattice().

### **OUTPUT**:

A solid cone in a new lattice having the same dimension as this cone's *sublattice()*.

### **EXAMPLES:**

The nonnegative quadrant in the plane is left after we take its solid restriction in space:

```
sage: K = Cone([(1,0,0), (0,1,0)])
sage: K.solid_restriction().rays()
N(0, 1),
N(1, 0)
in 2-d lattice N
```

The solid restriction of a single ray has the same representation regardless of the ambient space:

```
sage: K = Cone([(1,0)])
sage: K.solid_restriction().rays()
N(1)
in 1-d lattice N
sage: K = Cone([(1,1,1)])
```

(continues on next page)

```
sage: K.solid_restriction().rays()
N(1)
in 1-d lattice N
```

The solid restriction of the trivial cone lives in a trivial space:

```
sage: K = cones.trivial(0)
sage: K.solid_restriction()
0-d cone in 0-d lattice N
sage: K = cones.trivial(4)
sage: K.solid_restriction()
0-d cone in 0-d lattice N
```

The solid restriction of a solid cone is itself:

```
sage: K = Cone([(1,1),(1,2)])
sage: K.solid_restriction() is K
True
```

### strict\_quotient()

Return the quotient of self by the linear subspace.

We define the **strict quotient** of a cone to be the image of this cone in the quotient of the ambient space by the linear subspace of the cone, i.e. it is the "complementary part" to the linear subspace.

#### **OUTPUT:**

· cone.

### **EXAMPLES:**

```
sage: halfplane = Cone([(1,0), (0,1), (-1,0)])
sage: ssc = halfplane.strict_quotient()
sage: ssc
1-d cone in 1-d lattice N
sage: ssc.rays()
N(1)
in 1-d lattice N
sage: line = Cone([(1,0), (-1,0)])
sage: ssc = line.strict_quotient()
sage: ssc
0-d cone in 1-d lattice N
sage: ssc.rays()
Empty collection
in 1-d lattice N
```

The quotient of the trivial cone is trivial:

```
sage: K = cones.trivial(0)
sage: K.strict_quotient()
0-d cone in 0-d lattice N
sage: K = Cone([(0,0,0,0)])
sage: K.strict_quotient()
0-d cone in 4-d lattice N
```

```
sublattice(*args, **kwds)
```

The sublattice spanned by the cone.

Let  $\sigma$  be the given cone and N = self.lattice() the ambient lattice. Then, in the notation of [Ful1993], this method returns the sublattice

$$N_{\sigma} \stackrel{\text{def}}{=} span(N \cap \sigma)$$

## INPUT:

• either nothing or something that can be turned into an element of this lattice.

### **OUTPUT**:

• if no arguments were given, a toric sublattice, otherwise the corresponding element of it.

### Note:

- The sublattice spanned by the cone is the saturation of the sublattice generated by the rays of the cone.
- If you only need a Q-basis, you may want to try the basis() method on the result of rays().
- The returned lattice points are usually not rays of the cone. In fact, for a non-smooth cone the rays do not generate the sublattice  $N_{\sigma}$ , but only a finite index sublattice.

#### **EXAMPLES:**

```
sage: cone = Cone([(1, 1, 1), (1, -1, 1), (-1, -1, 1), (-1, 1, 1)])
sage: cone.rays().basis()
N( 1,  1,  1),
N( 1,  -1,  1),
N(-1, -1,  1)
in 3-d lattice N
sage: cone.rays().basis().matrix().det()
-4
sage: cone.sublattice()
Sublattice <N(1, 1, 1), N(0, -1, 0), N(-1, -1, 0)>
sage: matrix( cone.sublattice().gens() ).det()
-1
```

### Another example:

```
sage: c = Cone([(1,2,3), (4,-5,1)])
sage: c
2-d cone in 3-d lattice N
sage: c.rays()
N(1, 2, 3),
N(4, -5, 1)
in 3-d lattice N
sage: c.sublattice()
Sublattice <N(4, -5, 1), N(1, 2, 3)>
sage: c.sublattice(5, -3, 4)
N(5, -3, 4)
sage: c.sublattice(1, 0, 0)
Traceback (most recent call last):
...
TypeError: element [1, 0, 0] is not in free module
```

## sublattice\_complement(\*args, \*\*kwds)

A complement of the sublattice spanned by the cone.

In other words, *sublattice()* and *sublattice\_complement()* together form a **Z**-basis for the ambient *lattice()*.

In the notation of [Ful1993], let  $\sigma$  be the given cone and  $N=\mathtt{self.lattice}$ () the ambient lattice. Then this method returns

$$N(\sigma) \stackrel{\text{def}}{=} N/N_{\sigma}$$

lifted (non-canonically) to a sublattice of N.

# INPUT:

• either nothing or something that can be turned into an element of this lattice.

#### OUTPUT

• if no arguments were given, a toric sublattice, otherwise the corresponding element of it.

## **EXAMPLES:**

```
sage: C2_Z2 = Cone([(1,0),(1,2)]) # C^2/Z_2
sage: c1, c2 = C2_Z2.facets()
sage: c2.sublattice()
Sublattice <N(1, 2)>
sage: c2.sublattice_complement()
Sublattice <N(0, 1)>
```

A more complicated example:

```
sage: c = Cone([(1,2,3), (4,-5,1)])
sage: c.sublattice()
Sublattice <N(4, -5, 1), N(1, 2, 3)>
sage: c.sublattice_complement()
Sublattice <N(2, -3, 0)>
sage: m = matrix( c.sublattice().gens() + c.sublattice_complement().gens() )
sage: m
[ 4 -5   1]
[ 1   2   3]
[ 2 -3   0]
sage: m.det()
-1
```

### sublattice\_quotient(\*args, \*\*kwds)

The quotient of the ambient lattice by the sublattice spanned by the cone.

# INPUT:

• either nothing or something that can be turned into an element of this lattice.

### OUTPUT:

• if no arguments were given, a *quotient of a toric lattice*, otherwise the corresponding element of it.

# **EXAMPLES:**

```
sage: C2_Z2 = Cone([(1,0),(1,2)]) # C^2/Z_2
sage: c1, c2 = C2_Z2.facets()
sage: c2.sublattice_quotient()
1-d lattice, quotient of 2-d lattice N by Sublattice <N(1, 2)>
sage: N = C2_Z2.lattice()
sage: n = N(1,1)
sage: n_bar = c2.sublattice_quotient(n); n_bar
N[1, 1]
sage: n_bar.lift()
N(1, 1)
sage: vector(n_bar)
(-1)
```

# class sage.geometry.cone.IntegralRayCollection(rays, lattice)

 $Bases: \verb|sage.structure.sage_object.Sage0bject|, \verb|collections.abc.Hashable|, \verb|collections.abc.Hasha$ 

Create a collection of integral rays.

**Warning:** No correctness check or normalization is performed on the input data. This class is designed for internal operations and you probably should not use it directly.

This is a base class for convex rational polyhedral cones and fans.

Ray collections are immutable, but they cache most of the returned values.

### INPUT:

- rays list of immutable vectors in lattice;
- lattice *ToricLattice*,  $\mathbb{Z}^n$ , or any other object that behaves like these. If None, it will be determined as parent() of the first ray. Of course, this cannot be done if there are no rays, so in this case you must give an appropriate lattice directly. Note that None is *not* the default value you always *must* give this argument explicitly, even if it is None.

### **OUTPUT**:

• collection of given integral rays.

#### ambient\_dim()

Return the dimension of the ambient lattice of self.

An alias is ambient\_dim().

### **OUTPUT**:

• integer.

### **EXAMPLES:**

```
sage: c = Cone([(1,0)])
sage: c.lattice_dim()
2
sage: c.dim()
1
```

# ambient\_vector\_space(base\_field=None)

Return the ambient vector space.

It is the ambient lattice (lattice()) tensored with a field.

### INPUT:

• base\_field - (default: the rationals) a field.

### **EXAMPLES:**

```
sage: c = Cone([(1,0)])
sage: c.ambient_vector_space()
Vector space of dimension 2 over Rational Field
sage: c.ambient_vector_space(AA)
Vector space of dimension 2 over Algebraic Real Field
```

## cartesian\_product(other, lattice=None)

Return the Cartesian product of self with other.

#### INPUT:

- other an IntegralRayCollection;
- lattice (optional) the ambient lattice for the result. By default, the direct sum of the ambient lattices of self and other is constructed.

### **OUTPUT**:

• an IntegralRayCollection.

By the Cartesian product of ray collections  $(r_0, \ldots, r_{n-1})$  and  $(s_0, \ldots, s_{m-1})$  we understand the ray collection of the form  $((r_0, 0), \ldots, (r_{n-1}, 0), (0, s_0), \ldots, (0, s_{m-1}))$ , which is suitable for Cartesian products of cones and fans. The ray order is guaranteed to be as described.

### **EXAMPLES:**

```
sage: c = Cone([(1,)])
sage: c.cartesian_product(c)  # indirect doctest
2-d cone in 2-d lattice N+N
sage: _.rays()
N+N(1, 0),
N+N(0, 1)
in 2-d lattice N+N
```

### codim()

Return the codimension of self.

The codimension of a collection of rays (of a cone/fan) is the difference between the dimension of the ambient space and the dimension of the subspace spanned by those rays (of the cone/fan).

### **OUTPUT:**

A nonnegative integer representing the codimension of self.

# See also:

```
dim(), lattice_dim()
```

### **EXAMPLES:**

The codimension of the nonnegative orthant is zero, since the span of its generators equals the entire ambient space:

```
sage: K = cones.nonnegative_orthant(3)
sage: K.codim()
0
```

However, if we remove a ray so that the entire cone is contained within the x-y plane, then the resulting cone will have codimension one, because the z-axis is perpendicular to every element of the cone:

```
sage: K = Cone([(1,0,0), (0,1,0)])
sage: K.codim()
1
```

If our cone is all of  $\mathbb{R}^2$ , then its codimension is zero:

```
sage: K = Cone([(1,0), (-1,0), (0,1), (0,-1)])
sage: K.is_full_space()
True
sage: K.codim()
0
```

And if the cone is trivial in any space, then its codimension is equal to the dimension of the ambient space:

```
sage: K = cones.trivial(0)
sage: K.lattice_dim()
0
sage: K.codim()
0
sage: K = cones.trivial(1)
sage: K.lattice_dim()
1
sage: K.codim()
1
sage: K = cones.trivial(2)
sage: K.lattice_dim()
2
sage: K.codim()
2
```

## codimension()

Return the codimension of self.

The codimension of a collection of rays (of a cone/fan) is the difference between the dimension of the ambient space and the dimension of the subspace spanned by those rays (of the cone/fan).

# **OUTPUT**:

A nonnegative integer representing the codimension of self.

#### See also:

```
dim(), lattice_dim()
```

# **EXAMPLES:**

The codimension of the nonnegative orthant is zero, since the span of its generators equals the entire ambient space:

```
sage: K = cones.nonnegative_orthant(3)
sage: K.codim()

0
```

However, if we remove a ray so that the entire cone is contained within the x-y plane, then the resulting cone will have codimension one, because the z-axis is perpendicular to every element of the cone:

```
sage: K = Cone([(1,0,0), (0,1,0)])
sage: K.codim()
1
```

If our cone is all of  $\mathbb{R}^2$ , then its codimension is zero:

```
sage: K = Cone([(1,0), (-1,0), (0,1), (0,-1)])
sage: K.is_full_space()
True
sage: K.codim()
0
```

And if the cone is trivial in any space, then its codimension is equal to the dimension of the ambient space:

```
sage: K = cones.trivial(0)
sage: K.lattice_dim()
0
sage: K.codim()
0
sage: K = cones.trivial(1)
sage: K.lattice_dim()
1
sage: K.codim()
1
sage: K = cones.trivial(2)
sage: K.lattice_dim()
2
sage: K.codim()
2
```

# dim()

Return the dimension of the subspace spanned by rays of self.

**OUTPUT**:

• integer.

**EXAMPLES:** 

```
sage: c = Cone([(1,0)])
sage: c.lattice_dim()
2
sage: c.dim()
1
```

# dual\_lattice()

Return the dual of the ambient lattice of self.

## **OUTPUT**:

• lattice. If possible (that is, if *lattice()* has a dual() method), the dual lattice is returned. Otherwise,  $\mathbf{Z}^n$  is returned, where n is the dimension of *lattice()*.

### **EXAMPLES**:

```
sage: c = Cone([(1,0)])
sage: c.dual_lattice()
2-d lattice M
sage: Cone([], ZZ^3).dual_lattice()
Ambient free module of rank 3
over the principal ideal domain Integer Ring
```

# lattice()

Return the ambient lattice of self.

#### **OUTPUT**:

· lattice.

# **EXAMPLES:**

```
sage: c = Cone([(1,0)])
sage: c.lattice()
2-d lattice N
sage: Cone([], ZZ^3).lattice()
Ambient free module of rank 3
over the principal ideal domain Integer Ring
```

### lattice\_dim()

Return the dimension of the ambient lattice of self.

An alias is ambient\_dim().

# OUTPUT:

• integer.

### **EXAMPLES**:

```
sage: c = Cone([(1,0)])
sage: c.lattice_dim()
2
sage: c.dim()
1
```

## nrays()

Return the number of rays of self.

### **OUTPUT**:

• integer.

# **EXAMPLES**:

```
sage: c = Cone([(1,0), (0,1)])
sage: c.nrays()
2
```

```
plot(**options)
```

Plot self.

#### INPUT:

• any options for toric plots (see toric\_plotter.options), none are mandatory.

## OUTPUT:

• a plot.

## **EXAMPLES:**

```
sage: quadrant = Cone([(1,0), (0,1)])
sage: quadrant.plot() # optional - sage.plot
Graphics object consisting of 9 graphics primitives
```

### ray(n)

Return the n-th ray of self.

## INPUT:

• n – integer, an index of a ray of self. Enumeration of rays starts with zero.

### **OUTPUT**:

• ray, an element of the lattice of self.

### **EXAMPLES:**

```
sage: c = Cone([(1,0), (0,1)])
sage: c.ray(0)
N(1, 0)
```

## rays(\*args)

Return (some of the) rays of self.

# INPUT:

 ray\_list – a list of integers, the indices of the requested rays. If not specified, all rays of self will be returned.

### **OUTPUT**:

• a PointCollection of primitive integral ray generators.

# **EXAMPLES:**

```
sage: c = Cone([(1,0), (0,1), (-1, 0)])
sage: c.rays()
N( 0, 1),
N( 1, 0),
N(-1, 0)
in 2-d lattice N
sage: c.rays([0, 2])
N( 0, 1),
N(-1, 0)
in 2-d lattice N
```

You can also give ray indices directly, without packing them into a list:

```
sage: c.rays(0, 2)
N( 0, 1),
N(-1, 0)
in 2-d lattice N
```

### span(base\_ring=None)

Return the span of self.

### INPUT:

• base\_ring - (default: from lattice) the base ring to use for the generated module.

### **OUTPUT**:

A module spanned by the generators of self.

### **EXAMPLES:**

The span of a single ray is a one-dimensional sublattice:

```
sage: K1 = Cone([(1,)])
sage: K1.span()
Sublattice <N(1)>
sage: K2 = Cone([(1,0)])
sage: K2.span()
Sublattice <N(1, 0)>
```

The span of the nonnegative orthant is the entire ambient lattice:

```
sage: K = cones.nonnegative_orthant(3)
sage: K.span() == K.lattice()
True
```

By specifying a base\_ring, we can obtain a vector space:

```
sage: K = Cone([(1,0,0),(0,1,0),(0,0,1)])
sage: K.span(base_ring=QQ)
Vector space of degree 3 and dimension 3 over Rational Field
Basis matrix:
[1 0 0]
[0 1 0]
[0 0 1]
```

### sage.geometry.cone.classify\_cone\_2d(ray0, ray1, check=True)

Return (d, k) classifying the lattice cone spanned by the two rays.

## INPUT:

- ray0, ray1 two primitive integer vectors. The generators of the two rays generating the two-dimensional cone.
- check boolean (default: True). Whether to check the input rays for consistency.

## **OUTPUT**:

A pair (d, k) of integers classifying the cone up to  $GL(2, \mathbf{Z})$  equivalence. See Proposition 10.1.1 of [CLS2011] for the definition. We return the unique (d, k) with minimal k, see Proposition 10.1.3 of [CLS2011].

#### **EXAMPLES:**

```
sage: ray0 = vector([1,0])
sage: ray1 = vector([2,3])
sage: from sage.geometry.cone import classify_cone_2d
sage: classify_cone_2d(ray0, ray1)
(3, 2)

sage: ray0 = vector([2,4,5])
sage: ray1 = vector([5,19,11])
sage: classify_cone_2d(ray0, ray1)
(3, 1)

sage: m = matrix(ZZ, [(19, -14, -115), (-2, 5, 25), (43, -42, -298)])
sage: m.det() # check that it is in GL(3,ZZ)
-1
sage: classify_cone_2d(m*ray0, m*ray1)
(3, 1)
```

# sage.geometry.cone.integral\_length(v)

Compute the integral length of a given rational vector.

## INPUT:

• v – any object which can be converted to a list of rationals

#### OUTPUT:

Rational number r such that v = r \* u, where u is the primitive integral vector in the direction of v.

## **EXAMPLES:**

```
sage: from sage.geometry.cone import integral_length
sage: integral_length([1, 2, 4])
1
sage: integral_length([2, 2, 4])
2
sage: integral_length([2/3, 2, 4])
2/3
```

## sage.geometry.cone.is\_Cone(x)

Check if x is a cone.

### INPUT:

• x – anything.

### **OUTPUT:**

• True if x is a cone and False otherwise.

# **EXAMPLES:**

```
sage: from sage.geometry.cone import is_Cone
sage: is_Cone(1)
False
sage: quadrant = Cone([(1,0), (0,1)])
sage: quadrant
2-d cone in 2-d lattice N
```

(continues on next page)

```
sage: is_Cone(quadrant)
True
```

sage.geometry.cone.normalize\_rays(rays, lattice)

Normalize a list of rational rays: make them primitive and immutable.

### INPUT:

- rays list of rays which can be converted to the rational extension of lattice;
- lattice ToricLattice,  $\mathbb{Z}^n$ , or any other object that behaves like these. If None, an attempt will be made to determine an appropriate toric lattice automatically.

### **OUTPUT:**

list of immutable primitive vectors of the lattice in the same directions as original rays.

#### **EXAMPLES:**

```
sage: from sage.geometry.cone import normalize_rays
sage: normalize_rays([(0, 1), (0, 2), (3, 2), (5/7, 10/3)], None)
[N(0, 1), N(0, 1), N(3, 2), N(3, 14)]
sage: L = ToricLattice(2, "L")
sage: normalize_rays([(0, 1), (0, 2), (3, 2), (5/7, 10/3)], L.dual())
[L^*(0, 1), L^*(0, 1), L^*(3, 2), L^*(3, 14)]
sage: ray_in_L = L(0,1)
sage: normalize_rays([ray_in_L, (0, 2), (3, 2), (5/7, 10/3)], None)
[L(0, 1), L(0, 1), L(3, 2), L(3, 14)]
sage: normalize_rays([(0, 1), (0, 2), (3, 2), (5/7, 10/3)], ZZ^2)
[(0, 1), (0, 1), (3, 2), (3, 14)]
sage: normalize_rays([(0, 1), (0, 2), (3, 2), (5/7, 10/3)], ZZ^3)
Traceback (most recent call last):
TypeError: cannot convert (0, 1) to
Vector space of dimension 3 over Rational Field!
sage: normalize_rays([], ZZ^3)
```

Generate a random convex rational polyhedral cone.

Lower and upper bounds may be provided for both the dimension of the ambient space and the number of generating rays of the cone. If a lower bound is left unspecified, it defaults to zero. Unspecified upper bounds will be chosen randomly, unless you set solid, in which case they are chosen a little more wisely.

You may specify the ambient lattice for the returned cone. In that case, the min\_ambient\_dim and max\_ambient\_dim parameters are ignored.

You may also request that the returned cone be strictly convex (or not). Likewise you may request that it be (non-)solid.

**Warning:** If you request a large number of rays in a low-dimensional space, you might be waiting for a while. For example, in three dimensions, it is possible to obtain an octagon raised up to height one (all z-coordinates equal to one). But in practice, we usually generate the entire three-dimensional space with six

rays before we get to the eight rays needed for an octagon. We therefore have to throw the cone out and start over from scratch. This process repeats until we get lucky.

We also refrain from "adjusting" the min/max parameters given to us when a (non-)strictly convex or (non-)solid cone is requested. This means that it may take a long time to generate such a cone if the parameters are chosen unwisely.

For example, you may want to set min\_rays close to min\_ambient\_dim if you desire a solid cone. Or, if you desire a non-strictly-convex cone, then they all contain at least two generating rays. So that might be a good candidate for min\_rays.

### INPUT:

- lattice (default: random) A ToricLattice object in which the returned cone will live. By default a new lattice will be constructed with a randomly-chosen rank (subject to min\_ambient\_dim and max ambient dim).
- min\_ambient\_dim (default: zero) A nonnegative integer representing the minimum dimension of the ambient lattice.
- max\_ambient\_dim (default: random) A nonnegative integer representing the maximum dimension of the ambient lattice.
- min\_rays (default: zero) A nonnegative integer representing the minimum number of generating rays of the cone.
- max\_rays (default: random) A nonnegative integer representing the maximum number of generating rays of the cone.
- strictly\_convex (default: random) Whether or not to make the returned cone strictly convex. Specify True for a strictly convex cone, False for a non-strictly-convex cone, or None if you don't care.
- solid (default: random) Whether or not to make the returned cone solid. Specify True for a solid cone, False for a non-solid cone, or None if you don't care.

### **OUTPUT**:

A new, randomly generated cone.

A ValueError will be thrown under the following conditions:

- Any of min\_ambient\_dim, max\_ambient\_dim, min\_rays, or max\_rays are negative.
- max\_ambient\_dim is less than min\_ambient\_dim.
- max\_rays is less than min\_rays.
- Both max\_ambient\_dim and lattice are specified.
- min\_rays is greater than four but max\_ambient\_dim is less than three.
- min\_rays is greater than four but lattice has dimension less than three.
- min\_rays is greater than two but max\_ambient\_dim is less than two.
- min\_rays is greater than two but lattice has dimension less than two.
- min\_rays is positive but max\_ambient\_dim is zero.
- min\_rays is positive but lattice has dimension zero.
- A trivial lattice is supplied and a non-strictly-convex cone is requested.
- A non-strictly-convex cone is requested but max\_rays is less than two.

- A solid cone is requested but max\_rays is less than min\_ambient\_dim.
- A solid cone is requested but max\_rays is less than the dimension of lattice.
- A non-solid cone is requested but max\_ambient\_dim is zero.
- A non-solid cone is requested but lattice has dimension zero.
- A non-solid cone is requested but min\_rays is so large that it guarantees a solid cone.

#### ALGORITHM:

First, a lattice is determined from min\_ambient\_dim and max\_ambient\_dim (or from the supplied lattice).

Then, lattice elements are generated one at a time and added to a cone. This continues until either the cone meets the user's requirements, or the cone is equal to the entire space (at which point it is futile to generate more).

We check whether or not the resulting cone meets the user's requirements; if it does, it is returned. If not, we throw it away and start over. This process repeats indefinitely until an appropriate cone is generated.

### **EXAMPLES:**

Generate a trivial cone in a trivial space:

```
sage: random_cone(max_ambient_dim=0, max_rays=0)
0-d cone in 0-d lattice N
```

We can predict the ambient dimension when min\_ambient\_dim == max\_ambient\_dim:

```
sage: K = random_cone(min_ambient_dim=4, max_ambient_dim=4)
sage: K.lattice_dim()
4
```

Likewise for the number of rays when min\_rays == max\_rays:

```
sage: K = random_cone(min_rays=3, max_rays=3)
sage: K.nrays()
3
```

If we specify a lattice, then the returned cone will live in it:

```
sage: L = ToricLattice(5, "L")
sage: K = random_cone(lattice=L)
sage: K.lattice() is L
True
```

We can also request a strictly convex cone:

Or one that isn't strictly convex:

An example with all parameters set:

# 2.5.3 Catalog of common polyhedral convex cones

This module provides shortcut functions, grouped under the globally-available cones prefix, to create some common cones:

- The nonnegative orthant,
- The rearrangement cone of order p,
- The Schur cone,
- · The trivial cone.

At the moment, only convex rational polyhedral cones are supported—specifically, those cones that can be built using the <code>Cone()</code> constructor. As a result, each shortcut method can be passed either an ambient dimension <code>ambient\_dim</code>, or a toric <code>lattice</code> (from which the dimension can be inferred) to determine the ambient space.

Here are some typical usage examples:

```
sage: cones.nonnegative_orthant(2).rays()
N(1, 0),
N(0, 1)
in 2-d lattice N
```

```
sage: cones.rearrangement(2,2).rays()
N( 1,  0),
N( 1, -1),
N(-1,  1)
in 2-d lattice N
```

```
sage: cones.schur(3).rays()
N(1, -1, 0),
N(0, 1, -1)
in 3-d lattice N
```

```
sage: cones.trivial(3).rays()
Empty collection
in 3-d lattice N
```

To specify some other lattice, pass it as an argument to the function:

```
sage: K = cones.nonnegative_orthant(3)
sage: cones.schur(lattice=K.dual().lattice())
2-d cone in 3-d lattice M
```

For more information about these cones, see the documentation for the individual functions and the references therein.

```
sage.geometry.cone_catalog.nonnegative_orthant(ambient_dim=None, lattice=None)
```

The nonnegative orthant in ambient\_dim dimensions, or living in lattice.

The nonnegative orthant consists of all componentwise-nonnegative vectors. It is the convex-conic hull of the standard basis.

## INPUT:

- ambient\_dim a nonnegative integer (default: None); the dimension of the ambient space
- lattice a toric lattice (default: None); the lattice in which the cone will live

If ambient\_dim is omitted, then it will be inferred from the rank of lattice. If the lattice is omitted, then the default lattice of rank ambient\_dim will be used.

A ValueError is raised if neither ambient\_dim nor lattice are specified. It is also a ValueError to specify both ambient\_dim and lattice unless the rank of lattice is equal to ambient\_dim.

### **OUTPUT:**

A *ConvexRationalPolyhedralCone* living in lattice and having ambient\_dim standard basis vectors as its generators. Each generating ray has the integer ring as its base ring.

A ValueError can be raised if the inputs are incompatible or insufficient. See the INPUT documentation for details.

# REFERENCES:

• Chapter 2 in [BV2009] (Examples 2.4, 2.14, and 2.23 in particular)

### **EXAMPLES:**

```
sage: cones.nonnegative_orthant(3).rays()
N(1, 0, 0),
N(0, 1, 0),
N(0, 0, 1)
in 3-d lattice N
```

sage.geometry.cone\_catalog.rearrangement(p, ambient\_dim=None, lattice=None)

The rearrangement cone of order p in ambient\_dim dimensions, or living in lattice.

The rearrangement cone of order p in ambient\_dim dimensions consists of all vectors of length ambient\_dim whose smallest p components sum to a nonnegative number.

For example, the rearrangement cone of order one has its single smallest component nonnegative. This implies that all components are nonnegative, and that therefore the rearrangement cone of order one is the nonnegative orthant in its ambient space.

When p and ambient\_dim are equal, all components of the cone's elements must sum to a nonnegative number. In other words, the rearrangement cone of order ambient\_dim is a half-space.

### INPUT:

- $\bullet$  p a nonnegative integer; the number of components to "rearrange", between 1 and ambient\_diminclusive
- ambient\_dim a nonnegative integer (default: None); the dimension of the ambient space

• lattice – a toric lattice (default: None); the lattice in which the cone will live

If ambient\_dim is omitted, then it will be inferred from the rank of lattice. If the lattice is omitted, then the default lattice of rank ambient\_dim will be used.

A ValueError is raised if neither ambient\_dim nor lattice are specified. It is also a ValueError to specify both ambient\_dim and lattice unless the rank of lattice is equal to ambient\_dim.

It is also a ValueError to specify a non-integer p.

#### **OUTPUT:**

A *ConvexRationalPolyhedralCone* representing the rearrangement cone of order p living in lattice, with ambient dimension ambient\_dim. Each generating ray has the integer ring as its base ring.

A ValueError can be raised if the inputs are incompatible or insufficient. See the INPUT documentation for details.

### ALGORITHM:

Suppose that the ambient space is of dimension n. The extreme directions of the rearrangement cone for  $1 \le p \le n-1$  are given by [Jeong2017] Theorem 5.2.3. When  $2 \le p \le n-2$  (that is, if we ignore p=1 and p=n-1), they consist of

- the standard basis  $\{e_1, e_2, \dots, e_n\}$  for the ambient space, and
- the *n* vectors  $(1, 1, ..., 1)^T pe_i$  for i = 1, 2, ..., n.

Special cases are then given for p=1 and p=n-1 in the theorem. However in SageMath we don't need conically-independent extreme directions. We only need a generating set, because the *Cone()* function will eliminate any redundant generators. And one can easily verify that the special-case extreme directions for p=1 and p=n-1 are contained in the conic hull of the 2n generators just described. The half space resulting from p=n is also covered by this set of generators, so for all valid p we simply take the conic hull of those 2n vectors.

### **REFERENCES:**

- [GJ2016], Section 4
- [HS2010], Example 2.21
- [Jeong2017], Section 5.2

#### **EXAMPLES:**

The rearrangement cones of order one are nonnegative orthants:

```
sage: orthant = cones.nonnegative_orthant(6)
sage: cones.rearrangement(1,6).is_equivalent(orthant)
True
```

When p and ambient\_dim are equal, the rearrangement cone is a half-space, so we expect its lineality to be one less than ambient\_dim because it will contain a hyperplane but is not the entire space:

```
sage: cones.rearrangement(5,5).lineality()
4
```

Jeong's Proposition 5.2.1 [Jeong2017] states that all rearrangement cones are proper when p is less than ambient\_dim:

Jeong's Corollary 5.2.4 [Jeong2017] states that if p = n - 1 in an *n*-dimensional ambient space, then the Lyapunov rank of the rearrangement cone is n, and that for all other p > 1 its Lyapunov rank is one:

sage.geometry.cone\_catalog.schur(ambient\_dim=None, lattice=None)

The Schur cone in ambient\_dim dimensions, or living in lattice.

The Schur cone in n dimensions induces the majorization ordering on the ambient space. If  $\{e_1, e_2, \dots, e_n\}$  is the standard basis for the space, then its generators are  $\{e_i - e_{i+1} \mid 1 \le i \le n-1\}$ . Its dual is the downward monotonic cone.

### INPUT:

- ambient\_dim a nonnegative integer (default: None); the dimension of the ambient space
- lattice a toric lattice (default: None); the lattice in which the cone will live

If ambient\_dim is omitted, then it will be inferred from the rank of lattice. If the lattice is omitted, then the default lattice of rank ambient dim will be used.

A ValueError is raised if neither ambient\_dim nor lattice are specified. It is also a ValueError to specify both ambient\_dim and lattice unless the rank of lattice is equal to ambient\_dim.

# OUTPUT:

A *ConvexRationalPolyhedralCone* representing the Schur cone living in lattice, with ambient dimension ambient\_dim. Each generating ray has the integer ring as its base ring.

A ValueError can be raised if the inputs are incompatible or insufficient. See the INPUT documentation for details.

# REFERENCES:

- [GS2010], Section 3.1
- [IS2005], Example 7.3
- [SS2016], Example 7.4

## **EXAMPLES:**

Verify the claim [SS2016] that the maximal angle between any two generators of the Schur cone and the non-negative orthant in dimension five is  $(3/4) \pi$ :

```
sage: P = cones.schur(5)
sage: Q = cones.nonnegative_orthant(5)
sage: G = ( g.change_ring(QQbar).normalized() for g in P )
sage: H = ( h.change_ring(QQbar).normalized() for h in Q )
sage: actual = max(arccos(u.inner_product(v)) for u in G for v in H)
sage: expected = 3*pi/4
```

(continues on next page)

```
sage: abs(actual - expected).n() < 1e-12
True</pre>
```

The dual of the Schur cone is the "downward monotonic cone" [GS2010], whose elements' entries are in non-increasing order:

```
sage: ambient_dim = ZZ.random_element(10)
sage: K = cones.schur(ambient_dim).dual()
sage: x = K.random_element()
sage: all( x[i] >= x[i+1] for i in range(ambient_dim-1) )
True
```

sage.geometry.cone\_catalog.trivial(ambient\_dim=None, lattice=None)

The trivial cone with no nonzero generators in ambient\_dim dimensions, or living in lattice.

## INPUT:

- ambient\_dim a nonnegative integer (default: None); the dimension of the ambient space
- lattice a toric lattice (default: None); the lattice in which the cone will live

If ambient\_dim is omitted, then it will be inferred from the rank of lattice. If the lattice is omitted, then the default lattice of rank ambient\_dim will be used.

A ValueError is raised if neither ambient\_dim nor lattice are specified. It is also a ValueError to specify both ambient\_dim and lattice unless the rank of lattice is equal to ambient\_dim.

### **OUTPUT:**

A *ConvexRationalPolyhedralCone* representing the trivial cone with no nonzero generators living in lattice, with ambient dimension ambient\_dim.

A ValueError can be raised if the inputs are incompatible or insufficient. See the INPUT documentation for details.

### **EXAMPLES:**

Construct the trivial cone, containing only the origin, in three dimensions:

```
sage: cones.trivial(3)
0-d cone in 3-d lattice N
```

If a lattice is given, the trivial cone will live in that lattice:

```
sage: L = ToricLattice(3, 'M')
sage: cones.trivial(3, lattice=L)
0-d cone in 3-d lattice M
```

# 2.5.4 Rational polyhedral fans

This module was designed as a part of the framework for toric varieties (variety, fano\_variety). While the emphasis is on complete full-dimensional fans, arbitrary fans are supported. Work with distinct lattices. The default lattice is *ToricLattice N* of the appropriate dimension. The only case when you must specify lattice explicitly is creation of a 0-dimensional fan, where dimension of the ambient space cannot be guessed.

A **rational polyhedral fan** is a *finite* collection of *strictly* convex rational polyhedral cones, such that the intersection of any two cones of the fan is a face of each of them and each face of each cone is also a cone of the fan.

### **AUTHORS:**

- Andrey Novoseltsev (2010-05-15): initial version.
- Andrey Novoseltsev (2010-06-17): substantial improvement during review by Volker Braun.

#### **EXAMPLES:**

Use Fan() to construct fans "explicitly":

In addition to giving such lists of cones and rays you can also create cones first using Cone() and then combine them into a fan. See the documentation of Fan() for details.

In 2 dimensions there is a unique maximal fan determined by rays, and you can use Fan2d() to construct it:

```
sage: fan2d = Fan2d(rays=[(1,0), (0,1), (-1,0)])
sage: fan2d.is_equivalent(fan)
True
```

But keep in mind that in higher dimensions the cone data is essential and cannot be omitted. Instead of building a fan from scratch, for this tutorial we will use an easy way to get two fans associated to *lattice polytopes*: FaceFan() and NormalFan():

```
sage: fan1 = FaceFan(lattice_polytope.cross_polytope(3))
sage: fan2 = NormalFan(lattice_polytope.cross_polytope(3))
```

Given such "automatic" fans, you may wonder what are their rays and cones:

```
sage: fan1.rays()
M( 1,  0,  0),
M( 0,  1,  0),
M( 0,  0,  1),
M(-1,  0,  0),
M( 0,  -1,  0),
M( 0,  0,  -1)
in 3-d lattice M
sage: fan1.generating_cones()
(3-d cone of Rational polyhedral fan in 3-d lattice M,
3-d cone of Rational polyhedral fan in 3-d lattice M,
3-d cone of Rational polyhedral fan in 3-d lattice M,
3-d cone of Rational polyhedral fan in 3-d lattice M,
3-d cone of Rational polyhedral fan in 3-d lattice M,
3-d cone of Rational polyhedral fan in 3-d lattice M,
```

(continues on next page)

```
3-d cone of Rational polyhedral fan in 3-d lattice M,
3-d cone of Rational polyhedral fan in 3-d lattice M,
3-d cone of Rational polyhedral fan in 3-d lattice M)
```

The last output is not very illuminating. Let's try to improve it:

```
sage: for cone in fan1: print(cone.rays())
M(0, 1, 0),
M(0, 0, 1),
M(-1, 0, 0)
in 3-d lattice M
M(0, 0, 1),
M(-1, 0, 0),
M(0, -1, 0)
in 3-d lattice M
M(-1, 0, 0),
M(0, -1, 0),
M(0, 0, -1)
in 3-d lattice M
M(0, 1, 0),
M(-1, 0, 0),
M(0, 0, -1)
in 3-d lattice M
M(1, 0, 0),
M(0, 1, 0),
M(0, 0, -1)
in 3-d lattice M
M(1, 0, 0),
M(0, 1, 0),
M(0, 0, 1)
in 3-d lattice M
M(1, 0, 0),
M(0, 0, 1),
M(0, -1, 0)
in 3-d lattice M
M(1, 0, 0),
M(0, -1, 0),
M(0, 0, -1)
in 3-d lattice M
```

You can also do

```
sage: for cone in fan1: print(cone.ambient_ray_indices())
(1, 2, 3)
(2, 3, 4)
(3, 4, 5)
(1, 3, 5)
(0, 1, 5)
(0, 1, 2)
(0, 2, 4)
(0, 4, 5)
```

to see indices of rays of the fan corresponding to each cone.

While the above cycles were over "cones in fan", it is obvious that we did not get ALL the cones: every face of every cone in a fan must also be in the fan, but all of the above cones were of dimension three. The reason for this behaviour is that in many cases it is enough to work with generating cones of the fan, i.e. cones which are not faces of bigger cones. When you do need to work with lower dimensional cones, you can easily get access to them using *cones*():

```
sage: [cone.ambient_ray_indices() for cone in fan1.cones(2)]
[(0, 1), (0, 2), (1, 2), (1, 3), (2, 3), (0, 4),
  (2, 4), (3, 4), (1, 5), (3, 5), (4, 5), (0, 5)]
```

In fact, you do not have to type .cones:

```
sage: [cone.ambient_ray_indices() for cone in fan1(2)]
[(0, 1), (0, 2), (1, 2), (1, 3), (2, 3), (0, 4),
  (2, 4), (3, 4), (1, 5), (3, 5), (4, 5), (0, 5)]
```

You may also need to know the inclusion relations between all of the cones of the fan. In this case check out cone\_lattice():

```
sage: L = fan1.cone_lattice()
sage: L
Finite lattice containing 28 elements with distinguished linear extension
sage: L.bottom()
0-d cone of Rational polyhedral fan in 3-d lattice M
sage: L.top()
Rational polyhedral fan in 3-d lattice M
sage: cone = L.level_sets()[2][0]
sage: cone
2-d cone of Rational polyhedral fan in 3-d lattice M
sage: sorted(L.hasse_diagram().neighbors(cone))
[1-d cone of Rational polyhedral fan in 3-d lattice M,
1-d cone of Rational polyhedral fan in 3-d lattice M,
3-d cone of Rational polyhedral fan in 3-d lattice M,
3-d cone of Rational polyhedral fan in 3-d lattice M,
3-d cone of Rational polyhedral fan in 3-d lattice M,
```

You can check how "good" a fan is:

```
sage: fan1.is_complete()
True
sage: fan1.is_simplicial()
True
sage: fan1.is_smooth()
True
```

The face fan of the octahedron is really good! Time to remember that we have also constructed its normal fan:

```
sage: fan2.is_complete()
True
sage: fan2.is_simplicial()
False
sage: fan2.is_smooth()
False
```

This one does have some "problems," but we can fix them:

```
sage: fan3 = fan2.make_simplicial()
sage: fan3.is_simplicial()
True
sage: fan3.is_smooth()
False
```

Note that we had to save the result of *make\_simplicial()* in a new fan. Fans in Sage are immutable, so any operation that does change them constructs a new fan.

We can also make fan3 smooth, but it will take a bit more work:

Let's see how "different" are fan2 and fan4:

Smoothness does not come for free!

Please take a look at the rest of the available functions below and their complete descriptions. If you need any features that are missing, feel free to suggest them. (Or implement them on your own and submit a patch to Sage for inclusion!)

```
class sage.geometry.fan.Cone_of_fan(ambient, ambient_ray_indices)
    Bases: sage.geometry.cone.ConvexRationalPolyhedralCone
```

Construct a cone belonging to a fan.

**Warning:** This class does not check that the input defines a valid cone of a fan. You must not construct objects of this class directly.

In addition to all of the properties of "regular" cones, such cones know their relation to the fan.

INPUT:

• ambient – fan whose cone is constructed;

ambient\_ray\_indices – increasing list or tuple of integers, indices of rays of ambient generating this
cone.

#### **OUTPUT**:

• cone of ambient.

### **EXAMPLES**:

The intended way to get objects of this class is the following:

### star\_generator\_indices()

Return indices of generating cones of the "ambient fan" containing self.

### OUTPUT:

• increasing tuple of integers.

#### **EXAMPLES**:

### star\_generators()

Return indices of generating cones of the "ambient fan" containing self.

# OUTPUT:

• increasing tuple of integers.

### **EXAMPLES:**

```
sage: P1xP1 = toric_varieties.P1xP1()  # optional -
    palp
sage: cone = P1xP1.fan().generating_cone(0)  # optional -
    palp
sage: cone.star_generators()  # optional -
    palp
(2-d cone of Rational polyhedral fan in 2-d lattice N,)
```

### sage.geometry.fan.FaceFan(polytope, lattice=None)

Construct the face fan of the given rational polytope.

### INPUT:

- polytope a *polytope* over **Q** or a *lattice polytope*. A (not necessarily full-dimensional) polytope containing the origin in its relative interior.
- lattice ToricLattice,  $\mathbb{Z}^n$ , or any other object that behaves like these. If not specified, an attempt will be made to determine an appropriate toric lattice automatically.

#### OUTPUT:

• rational polyhedral fan.

See also NormalFan().

### **EXAMPLES:**

Let's construct the fan corresponding to the product of two projective lines:

```
sage: diamond = lattice_polytope.cross_polytope(2)
sage: P1xP1 = FaceFan(diamond)
sage: P1xP1.rays()
M(1, 0),
M(0, 1),
M(-1, 0),
M(0, -1)
in 2-d lattice M
sage: for cone in P1xP1: print(cone.rays())
M(-1, 0).
M(0, -1)
in 2-d lattice M
M(0, 1),
M(-1, 0)
in 2-d lattice M
M(1, 0),
M(0, 1)
in 2-d lattice M
M(1, 0),
M(0, -1)
in 2-d lattice M
```

**Note:** Approximate time to construct a fan consisting of n cones is  $n^2/5$  seconds. That is half an hour for 100 cones. This time can be significantly reduced in the future, but it is still likely to be  $\sim n^2$  (with, say, /500 instead of /5). If you know that your input does form a valid fan, use check=False option to skip consistency checks.

### INPUT:

- cones list of either *Cone* objects or lists of integers interpreted as indices of generating rays
  in rays. These must be only **maximal** cones of the fan, unless discard\_faces=True or
  allow\_arrangement=True option is specified;
- rays list of rays given as list or vectors convertible to the rational extension of lattice. If cones are given by *Cone* objects rays may be determined automatically. You still may give them explicitly to ensure a particular order of rays in the fan. In this case you must list all rays that appear in cones. You can give

"extra" ones if it is convenient (e.g. if you have a big list of rays for several fans), but all "extra" rays will be discarded;

- lattice ToricLattice,  $\mathbb{Z}^n$ , or any other object that behaves like these. If not specified, an attempt will be made to determine an appropriate toric lattice automatically;
- check by default the input data will be checked for correctness (e.g. that intersection of any two given
  cones is a face of each), unless allow\_arrangement=True option is specified. If you know for sure that
  the input is correct, you may significantly decrease construction time using check=False option;
- normalize you can further speed up construction using normalize=False option. In this case cones
  must be a list of sorted tuples and rays must be immutable primitive vectors in lattice. In general, you
  should not use this option, it is designed for code optimization and does not give as drastic improvement in
  speed as the previous one;
- is\_complete every fan can determine on its own if it is complete or not, however it can take quite a bit of time for "big" fans with many generating cones. On the other hand, in some situations it is known in advance that a certain fan is complete. In this case you can pass is\_complete=True option to speed up some computations. You may also pass is\_complete=False option, although it is less likely to be beneficial. Of course, passing a wrong value can compromise the integrity of data structures of the fan and lead to wrong results, so you should be very careful if you decide to use this option;
- virtual\_rays (optional, computed automatically if needed) a list of ray generators to be used for virtual\_rays();
- discard\_faces by default, the fan constructor expects the list of **maximal** cones, unless allow\_arrangement=True option is specified. If you provide "extra" ones and leave allow\_arrangement=False (default) and check=True (default), an exception will be raised. If you provide "extra" cones and set allow\_arrangement=False (default) and check=False, you may get wrong results as assumptions on internal data structures will be invalid. If you want the fan constructor to select the maximal cones from the given input, you may provide discard\_faces=True option (it works both for check=True and check=False).
- allow\_arrangement by default (allow\_arrangement=False), the fan constructor expects that the intersection of any two given cones is a face of each. If allow\_arrangement=True option is specified, then construct a rational polyhedralfan from the cone arrangement, so that the union of the cones in the polyhedral fan equals to the union of the given cones, and each given cone is the union of some cones in the polyhedral fan.

### **OUTPUT**:

• a fan.

#### See also:

In 2 dimensions you can cyclically order the rays. Hence the rays determine a unique maximal fan without having to specify the cones, and you can use Fan2d() to construct this fan from just the rays.

## EXAMPLES:

Let's construct a fan corresponding to the projective plane in several ways:

```
sage: cone1 = Cone([(1,0), (0,1)])
sage: cone2 = Cone([(0,1), (-1,-1)])
sage: cone3 = Cone([(-1,-1), (1,0)])
sage: P2 = Fan([cone1, cone2, cone2])
Traceback (most recent call last):
...
ValueError: you have provided 3 cones, but only 2 of them are maximal!
```

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```
Use discard_faces=True if you indeed need to construct a fan from these cones.
```

Oops! There was a typo and cone2 was listed twice as a generating cone of the fan. If it was intentional (e.g. the list of cones was generated automatically and it is possible that it contains repetitions or faces of other cones), use discard\_faces=True option:

```
sage: P2 = Fan([cone1, cone2, cone2], discard_faces=True)
sage: P2.ngenerating_cones()
2
```

However, in this case it was definitely a typo, since the fan of  $\mathbb{P}^2$  has 3 maximal cones:

```
sage: P2 = Fan([cone1, cone2, cone3])
sage: P2.ngenerating_cones()
3
```

Looks better. An alternative way is

```
sage: rays = [(1,0), (0,1), (-1,-1)]
sage: cones = [(0,1), (1,2), (2,0)]
sage: P2a = Fan(cones, rays)
sage: P2a.ngenerating_cones()
3
sage: P2 == P2a
False
```

That may seem wrong, but it is not:

```
sage: P2.is_equivalent(P2a)
True
```

See is\_equivalent() for details.

Yet another way to construct this fan is

```
sage: P2b = Fan(cones, rays, check=False)
sage: P2b.ngenerating_cones()
3
sage: P2a == P2b
True
```

If you try the above examples, you are likely to notice the difference in speed, so when you are sure that everything is correct, it is a good idea to use check=False option. On the other hand, it is usually **NOT** a good idea to use normalize=False option:

```
sage: P2c = Fan(cones, rays, check=False, normalize=False)
Traceback (most recent call last):
...
AttributeError: 'tuple' object has no attribute 'parent'
```

Yet another way is to use functions FaceFan() and NormalFan() to construct fans from lattice polytopes.

We have not yet used lattice argument, since if was determined automatically:

```
sage: P2.lattice()
2-d lattice N
sage: P2b.lattice()
2-d lattice N
```

However, it is necessary to specify it explicitly if you want to construct a fan without rays or cones:

```
sage: Fan([], [])
Traceback (most recent call last):
...
ValueError: you must specify the lattice
when you construct a fan without rays and cones!
sage: F = Fan([], [], lattice=ToricLattice(2, "L"))
sage: F
Rational polyhedral fan in 2-d lattice L
sage: F.lattice_dim()
2
sage: F.dim()
0
```

In the following examples, we test the allow\_arrangement=True option. See trac ticket #25122.

The intersection of the two cones is not a face of each. Therefore, they do not belong to the same rational polyhedral fan:

```
sage: c1 = Cone([(-2,-1,1), (-2,1,1), (2,1,1), (2,-1,1)])
sage: c2 = Cone([(-1,-2,1), (-1,2,1), (1,2,1), (1,-2,1)])
sage: c1.intersection(c2).is_face_of(c1)
False
sage: c1.intersection(c2).is_face_of(c2)
False
sage: Fan([c1, c2])
Traceback (most recent call last):
...
ValueError: these cones cannot belong to the same fan!
...
```

Let's construct the fan using allow\_arrangement=True option:

```
sage: fan = Fan([c1, c2], allow_arrangement=True)
sage: fan.ngenerating_cones()
5
```

Another example where cone c2 is inside cone c1:

```
sage: c1 = Cone([(4, 0, 0), (0, 4, 0), (0, 0, 4)])
sage: c2 = Cone([(2, 1, 1), (1, 2, 1), (1, 1, 2)])
sage: fan = Fan([c1, c2], allow_arrangement=True)
sage: fan.ngenerating_cones()
7
sage: fan.plot() # optional - sage.plot
Graphics3d Object
```

Cones of different dimension:

```
sage: c1 = Cone([(1,0),(0,1)])
sage: c2 = Cone([(2,1)])
sage: c3 = Cone([(-1,-2)])
sage: fan = Fan([c1, c2, c3], allow_arrangement=True)
sage: for cone in sorted(fan.generating_cones()): print(sorted(cone.rays()))
[N(-1, -2)]
[N(0, 1), N(1, 2)]
[N(1, 0), N(2, 1)]
[N(1, 2), N(2, 1)]
```

### A 3-d cone and a 1-d cone:

```
sage: c3 = Cone([[0, 1, 1], [1, 0, 1], [0, -1, 1], [-1, 0, 1]])
sage: c1 = Cone([[0, 0, 1]])
sage: fan1 = Fan([c1, c3], allow_arrangement=True)
sage: fan1.plot() # optional - sage.plot
Graphics3d Object
```

#### A 3-d cone and two 2-d cones:

```
sage: c2v = Cone([[0, 1, 1], [0, -1, 1]])
sage: c2h = Cone([[1, 0, 1], [-1, 0, 1]])
sage: fan2 = Fan([c2v, c2h, c3], allow_arrangement=True)
sage: fan2.is_simplicial()
True
sage: fan2.is_equivalent(fan1)
True
```

## sage.geometry.fan.Fan2d(rays, lattice=None)

Construct the maximal 2-d fan with given rays.

In two dimensions we can uniquely construct a fan from just rays, just by cyclically ordering the rays and constructing as many cones as possible. This is why we implement a special constructor for this case.

### INPUT:

- rays list of rays given as list or vectors convertible to the rational extension of lattice. Duplicate rays are removed without changing the ordering of the remaining rays.
- lattice ToricLattice,  $\mathbb{Z}^n$ , or any other object that behaves like these. If not specified, an attempt will be made to determine an appropriate toric lattice automatically.

# EXAMPLES:

```
sage: Fan2d([(0,1), (1,0)])
Rational polyhedral fan in 2-d lattice N
sage: Fan2d([], lattice=ToricLattice(2, 'myN'))
Rational polyhedral fan in 2-d lattice myN
```

The ray order is as specified, even if it is not the cyclic order:

```
sage: fan1 = Fan2d([(0,1), (1,0)])
sage: fan1.rays()
N(0, 1),
N(1, 0)
in 2-d lattice N
```

(continues on next page)

```
sage: fan2 = Fan2d([(1,0), (0,1)])
sage: fan2.rays()
N(1, 0),
N(0, 1)
in 2-d lattice N

sage: fan1 == fan2, fan1.is_equivalent(fan2)
(False, True)

sage: fan = Fan2d([(1,1), (-1,-1), (1,-1), (-1,1)])
sage: [ cone.ambient_ray_indices() for cone in fan ]
[(2, 1), (1, 3), (3, 0), (0, 2)]
sage: fan.is_complete()
True
```

### sage.geometry.fan.NormalFan(polytope, lattice=None)

Construct the normal fan of the given rational polytope.

This returns the inner normal fan. For the outer normal fan, use NormalFan(-P).

#### INPUT:

- polytope a full-dimensional polytope over  $\mathbf{Q}$  or:class:latticepolytope  $< sage.geometry.lattice_polytope.LatticePolytopeClass>$ .
- lattice ToricLattice,  $\mathbb{Z}^n$ , or any other object that behaves like these. If not specified, an attempt will be made to determine an appropriate toric lattice automatically.

## **OUTPUT**:

• rational polyhedral fan.

See also FaceFan().

### **EXAMPLES:**

Let's construct the fan corresponding to the product of two projective lines:

```
sage: square = LatticePolytope([(1,1), (-1,1), (-1,-1), (1,-1)])
sage: P1xP1 = NormalFan(square)
sage: P1xP1.rays()
N(1, 0),
N(0, 1),
N(-1, 0),
N(0, -1)
in 2-d lattice N
sage: for cone in P1xP1: print(cone.rays())
N(-1, 0),
N(0, -1)
in 2-d lattice N
N(1, 0),
N(0, -1)
in 2-d lattice N
N(1, 0),
N(0, 1)
in 2-d lattice N
```

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```
N(0,1),
N(-1, 0)
in 2-d lattice N
sage: cuboctahed = polytopes.cuboctahedron()
sage: NormalFan(cuboctahed)
Rational polyhedral fan in 3-d lattice N
```

**class** sage.geometry.fan.**RationalPolyhedralFan**(cones, rays, lattice, is\_complete=None, *virtual\_rays=None*)

Bases: sage.geometry.cone.IntegralRayCollection, collections.abc.Callable, collections. abc.Container

Create a rational polyhedral fan.

Warning: This class does not perform any checks of correctness of input nor does it convert input into the standard representation. Use Fan() to construct fans from "raw data" or FaceFan() and NormalFan() to get fans associated to polytopes.

Fans are immutable, but they cache most of the returned values.

#### INPUT:

- cones list of generating cones of the fan, each cone given as a list of indices of its generating rays in
- rays list of immutable primitive vectors in lattice consisting of exactly the rays of the fan (i.e. no "extra" ones);
- lattice ToricLattice,  $\mathbb{Z}^n$ , or any other object that behaves like these. If None, it will be determined as parent() of the first ray. Of course, this cannot be done if there are no rays, so in this case you must give an appropriate lattice directly;
- is\_complete if given, must be True or False depending on whether this fan is complete or not. By default, it will be determined automatically if necessary;
- virtual\_rays if given, must be a list of immutable primitive vectors in lattice, see virtual\_rays() for details. By default, it will be determined automatically if necessary.

# **OUTPUT:**

• rational polyhedral fan.

### Gale\_transform()

Return the Gale transform of self.

**OUTPUT**:

A matrix over ZZ.

#### **EXAMPLES:**

```
sage: fan = toric_varieties.P1xP1().fan()
                                                                         # optional -
sage: fan.Gale_transform()
                                                                         # optional -
→ palp
[1 1 0 0 -2]
                                                                      (continues on next page)
```

```
[ 0 0 1 1 -2]
sage: _.base_ring() # optional -

→ palp
Integer Ring
```

# Stanley\_Reisner\_ideal(ring)

Return the Stanley-Reisner ideal.

### INPUT:

• A polynomial ring in self.nrays() variables.

### **OUTPUT**:

• The Stanley-Reisner ideal in the given polynomial ring.

### **EXAMPLES:**

```
sage: fan = Fan([[0,1,3],[3,4],[2,0],[1,2,4]], [(-3, -2, 1), (0, 0, 1), (3, -2, _{\rightarrow}1), (-1, -1, 1), (1, -1, 1)])

sage: fan.Stanley_Reisner_ideal( PolynomialRing(QQ,5,'A, B, C, D, E') )

Ideal (A*E, C*D, A*B*C, B*D*E) of Multivariate Polynomial Ring in A, B, C, D, E _{\rightarrow}0 over Rational Field
```

### cartesian\_product(other, lattice=None)

Return the Cartesian product of self with other.

#### INPUT:

- other a rational polyhedral fan;
- lattice (optional) the ambient lattice for the Cartesian product fan. By default, the direct sum of the ambient lattices of self and other is constructed.

## **OUTPUT**:

• a fan whose cones are all pairwise Cartesian products of the cones of self and other.

#### **EXAMPLES:**

```
sage: K = ToricLattice(1, 'K')
sage: fan1 = Fan([[0],[1]],[(1,),(-1,)], lattice=K)
sage: L = ToricLattice(2, 'L')
sage: fan2 = Fan(rays=[(1,0),(0,1),(-1,-1)],
...: cones=[[0,1],[1,2],[2,0]], lattice=L)
sage: fan1.cartesian_product(fan2)
Rational polyhedral fan in 3-d lattice K+L
sage: _.ngenerating_cones()
```

# common\_refinement(other)

Return the common refinement of this fan and other.

#### INPUT:

• other – a fan in the same lattice() and with the same support as this fan

# **OUTPUT**:

• a fan

### **EXAMPLES:**

Refining a fan with itself gives itself:

```
sage: F0 = Fan2d([(1,0),(0,1),(-1,0),(0,-1)])
sage: F0.common_refinement(F0) == F0
True
```

A more complex example with complete fans:

```
sage: F1 = Fan([[0],[1]],[(1,),(-1,)])
sage: F2 = Fan2d([(1,0),(1,1),(0,1),(-1,0),(0,-1)])
sage: F3 = F2.cartesian_product(F1)
sage: F4 = F1.cartesian_product(F2)
sage: FF = F3.common_refinement(F4)
sage: F3.ngenerating_cones()
10
sage: F4.ngenerating_cones()
10
sage: FF.ngenerating_cones()
```

An example with two non-complete fans with the same support:

```
sage: F5 = Fan2d([(1,0),(1,2),(0,1)])
sage: F6 = Fan2d([(1,0),(2,1),(0,1)])
sage: F5.common_refinement(F6).ngenerating_cones()
3
```

Both fans must live in the same lattice:

```
sage: F0.common_refinement(F1)
Traceback (most recent call last):
...
ValueError: the fans are not in the same lattice
```

# complex(base\_ring=Integer Ring, extended=False)

Return the chain complex of the fan.

To a d-dimensional fan  $\Sigma$ , one can canonically associate a chain complex  $K^{\bullet}$ 

$$0 \longrightarrow \mathbf{Z}^{\Sigma(d)} \longrightarrow \mathbf{Z}^{\Sigma(d-1)} \longrightarrow \cdots \longrightarrow \mathbf{Z}^{\Sigma(0)} \longrightarrow 0$$

where the leftmost non-zero entry is in degree 0 and the rightmost entry in degree d. See [Kly1990], eq. (3.2). This complex computes the homology of  $|\Sigma| \subset N_{\mathbf{R}}$  with arbitrary support,

$$H_i(K) = H_{d-i}(|\Sigma|, \mathbf{Z})_{\text{non-cpct}}$$

For a complete fan, this is just the non-compactly supported homology of  $\mathbf{R}^d$ . In this case,  $H_0(K) = \mathbf{Z}$  and 0 in all non-zero degrees.

For a complete fan, there is an extended chain complex

$$0 \longrightarrow \mathbf{Z} \longrightarrow \mathbf{Z}^{\Sigma(d)} \longrightarrow \mathbf{Z}^{\Sigma(d-1)} \longrightarrow \cdots \longrightarrow \mathbf{Z}^{\Sigma(0)} \longrightarrow 0$$

where we take the first  $\mathbf{Z}$  term to be in degree -1. This complex is an exact sequence, that is, all homology groups vanish.

The orientation of each cone is chosen as in *oriented\_boundary()*.

#### INPUT:

- extended Boolean (default:False). Whether to construct the extended complex, that is, including the **Z**-term at degree -1 or not.
- base\_ring A ring (default: ZZ). The ring to use instead of **Z**.

#### OUTPUT:

The complex associated to the fan as a ChainComplex. Raises a ValueError if the extended complex is requested for a non-complete fan.

### **EXAMPLES**:

```
sage: fan = toric_varieties.P(3).fan()
                                                                              #_
→optional - palp
sage: K_normal = fan.complex(); K_normal
                                                                              #_
→optional - palp
Chain complex with at most 4 nonzero terms over Integer Ring
sage: K_normal.homology()
→optional - palp
{0: Z, 1: 0, 2: 0, 3: 0}
sage: K_extended = fan.complex(extended=True); K_extended
                                                                              #_
→optional - palp
Chain complex with at most 5 nonzero terms over Integer Ring
sage: K_extended.homology()
                                                                              #__
→optional - palp
\{-1: 0, 0: 0, 1: 0, 2: 0, 3: 0\}
```

Homology computations are much faster over **Q** if you do not care about the torsion coefficients:

The extended complex is only defined for complete fans:

```
sage: fan = Fan([ Cone([(1,0)]) ])
sage: fan.is_complete()
False
sage: fan.complex(extended=True)
Traceback (most recent call last):
...
ValueError: The extended complex is only defined for complete fans!
```

The definition of the complex does not refer to the ambient space of the fan, so it does not distinguish a fan from the same fan embedded in a subspace:

```
sage: K1 = Fan([Cone([(-1,)]), Cone([(1,)])]).complex()
sage: K2 = Fan([Cone([(-1,0,0)]), Cone([(1,0,0)])]).complex()
sage: K1 == K2
True
```

Things get more complicated for non-complete fans:

### cone\_containing(\*points)

Return the smallest cone of self containing all given points.

### INPUT:

• either one or more indices of rays of self, or one or more objects representing points of the ambient space of self, or a list of such objects (you CANNOT give a list of indices).

#### **OUTPUT**:

• A cone of fan whose ambient fan is self.

**Note:** We think of the origin as of the smallest cone containing no rays at all. If there is no ray in self that contains all rays, a ValueError exception will be raised.

# **EXAMPLES:**

```
sage: cone1 = Cone([(0,-1), (1,0)])
sage: cone2 = Cone([(1,0), (0,1)])
sage: f = Fan([cone1, cone2])
sage: f.ravs()
N(0, -1),
N(0, 1),
N(1, 0)
in 2-d lattice N
sage: f.cone_containing(0) # ray index
1-d cone of Rational polyhedral fan in 2-d lattice N
sage: f.cone_containing(0, 1) # ray indices
Traceback (most recent call last):
ValueError: there is no cone in
Rational polyhedral fan in 2-d lattice N
containing all of the given rays! Ray indices: [0, 1]
sage: f.cone_containing(0, 2) # ray indices
```

(continues on next page)

```
2-d cone of Rational polyhedral fan in 2-d lattice N
sage: f.cone_containing((0,1)) # point
1-d cone of Rational polyhedral fan in 2-d lattice N
sage: f.cone_containing([(0,1)]) # point
1-d cone of Rational polyhedral fan in 2-d lattice N
sage: f.cone_containing((1,1))
2-d cone of Rational polyhedral fan in 2-d lattice N
sage: f.cone_containing((1,1), (1,0))
2-d cone of Rational polyhedral fan in 2-d lattice N
sage: f.cone_containing()
0-d cone of Rational polyhedral fan in 2-d lattice N
sage: f.cone_containing((0,0))
0-d cone of Rational polyhedral fan in 2-d lattice N
sage: f.cone_containing((-1,1))
Traceback (most recent call last):
ValueError: there is no cone in
Rational polyhedral fan in 2-d lattice N
containing all of the given points! Points: [N(-1, 1)]
```

### cone\_lattice()

Return the cone lattice of self.

This lattice will have the origin as the bottom (we do not include the empty set as a cone) and the fan itself as the top.

# **OUTPUT**:

• finite poset <sage.combinat.posets.posets.FinitePoset of *cones of fan*, behaving like "regular" cones, but also containing the information about their relation to this fan, namely, the contained rays and containing generating cones. The top of the lattice will be this fan itself (*which is not a cone of fan*).

See also *cones()*.

# **EXAMPLES:**

Cone lattices can be computed for arbitrary fans:

```
sage: cone1 = Cone([(1,0), (0,1)])
sage: cone2 = Cone([(-1,0)])
sage: fan = Fan([cone1, cone2])
sage: fan.rays()
N(-1, 0),
N( 0, 1),
N( 1, 0)
in 2-d lattice N
sage: for cone in fan: print(cone.ambient_ray_indices())
(1, 2)
(0,)
sage: L = fan.cone_lattice()
sage: L
Finite poset containing 6 elements with distinguished linear extension
```

These 6 elements are the origin, three rays, one two-dimensional cone, and the fan itself. Since we do add the fan itself as the largest face, you should be a little bit careful with this last element:

```
sage: for face in L: print(face.ambient_ray_indices())
Traceback (most recent call last):
...
AttributeError: 'RationalPolyhedralFan'
object has no attribute 'ambient_ray_indices'
sage: L.top()
Rational polyhedral fan in 2-d lattice N
```

For example, you can do

```
sage: for 1 in L.level_sets()[:-1]:
....:    print([f.ambient_ray_indices() for f in 1])
[()]
[(0,), (1,), (2,)]
[(1, 2)]
```

If the fan is complete, its cone lattice is atomic and coatomic and can (and will!) be computed in a much more efficient way, but the interface is exactly the same:

Let's also consider the cone lattice of a fan generated by a single cone:

```
sage: fan = Fan([cone1])
sage: L = fan.cone_lattice()
sage: L
Finite poset containing 5 elements with distinguished linear extension
```

Here these 5 elements correspond to the origin, two rays, one generating cone of dimension two, and the whole fan. While this single cone "is" the whole fan, it is consistent and convenient to distinguish them in the cone lattice.

cones(dim=None, codim=None)

Return the specified cones of self.

#### INPUT:

- dim dimension of the requested cones;
- codim codimension of the requested cones.

**Note:** You can specify at most one input parameter.

# **OUTPUT**:

• tuple of cones of self of the specified (co)dimension, if either dim or codim is given. Otherwise tuple of such tuples for all existing dimensions.

# **EXAMPLES:**

```
sage: cone1 = Cone([(1,0), (0,1)])
sage: cone2 = Cone([(-1,0)])
sage: fan = Fan([cone1, cone2])
sage: fan(dim=0)
(0-d cone of Rational polyhedral fan in 2-d lattice N,)
sage: fan(codim=2)
(0-d cone of Rational polyhedral fan in 2-d lattice N,)
sage: for cone in fan.cones(1): cone.ray(0)
N(-1, 0)
N(0, 1)
N(1, 0)
sage: fan.cones(2)
(2-d cone of Rational polyhedral fan in 2-d lattice N,)
```

You cannot specify both dimension and codimension, even if they "agree":

```
sage: fan(dim=1, codim=1)
Traceback (most recent call last):
...
ValueError: dimension and codimension
cannot be specified together!
```

But it is OK to ask for cones of too high or low (co)dimension:

```
sage: fan(-1)
()
sage: fan(3)
()
sage: fan(codim=4)
()
```

## contains(cone)

Check if a given cone is equivalent to a cone of the fan.

## INPUT:

cone – anything.

### **OUTPUT**:

• False if cone is not a cone or if cone is not equivalent to a cone of the fan. True otherwise.

**Note:** Recall that a fan is a (finite) collection of cones. A cone is contained in a fan if it is equivalent to one of the cones of the fan. In particular, it is possible that all rays of the cone are in the fan, but the cone itself is not

If you want to know whether a point is in the support of the fan, you should use support\_contains().

# **EXAMPLES:**

We first construct a simple fan:

```
sage: cone1 = Cone([(0,-1), (1,0)])
sage: cone2 = Cone([(1,0), (0,1)])
sage: f = Fan([cone1, cone2])
```

Now we check if some cones are in this fan. First, we make sure that the order of rays of the input cone does not matter (check=False option ensures that rays of these cones will be listed exactly as they are given):

```
sage: f.contains(Cone([(1,0), (0,1)], check=False))
True
sage: f.contains(Cone([(0,1), (1,0)], check=False))
True
```

Now we check that a non-generating cone is in our fan:

```
sage: f.contains(Cone([(1,0)]))
True
sage: Cone([(1,0)]) in f # equivalent to the previous command
True
```

Finally, we test some cones which are not in this fan:

```
sage: f.contains(Cone([(1,1)]))
False
sage: f.contains(Cone([(1,0), (-0,1)]))
True
```

A point is not a cone:

```
sage: n = f.lattice()(1,1); n
N(1, 1)
sage: f.contains(n)
False
```

### embed(cone)

Return the cone equivalent to the given one, but sitting in self.

You may need to use this method before calling methods of cone that depend on the ambient structure, such as *ambient\_ray\_indices()* or *facet\_of()*. The cone returned by this method will have self as ambient. If cone does not represent a valid cone of self, ValueError exception is raised.

**Note:** This method is very quick if self is already the ambient structure of cone, so you can use without extra checks and performance hit even if cone is likely to sit in self but in principle may not.

## INPUT:

• cone – a cone.

# **OUTPUT**:

• a cone of fan, equivalent to cone but sitting inside self.

#### **EXAMPLES:**

Let's take a 3-d fan generated by a cone on 4 rays:

```
sage: f = Fan([Cone([(1,0,1), (0,1,1), (-1,0,1), (0,-1,1)])])
```

Then any ray generates a 1-d cone of this fan, but if you construct such a cone directly, it will not "sit" inside the fan:

```
sage: ray = Cone([(0,-1,1)])
sage: ray
1-d cone in 3-d lattice N
sage: ray.ambient_ray_indices()
(0,)
sage: ray.adjacent()
()
sage: ray.ambient()
1-d cone in 3-d lattice N
```

If we want to operate with this ray as a part of the fan, we need to embed it first:

```
sage: e_ray = f.embed(ray)
sage: e_ray
1-d cone of Rational polyhedral fan in 3-d lattice N
sage: e_ray.rays()
N(0, -1, 1)
in 3-d lattice N
sage: e_ray is ray
False
sage: e_ray.is_equivalent(ray)
True
sage: e_ray.ambient_ray_indices()
(3,)
sage: e_ray.adjacent()
(1-d cone of Rational polyhedral fan in 3-d lattice N,
1-d cone of Rational polyhedral fan in 3-d lattice N)
sage: e_ray.ambient()
Rational polyhedral fan in 3-d lattice N
```

Not every cone can be embedded into a fixed fan:

```
sage: f.embed(Cone([(0,0,1)]))
Traceback (most recent call last):
...
ValueError: 1-d cone in 3-d lattice N does not belong
to Rational polyhedral fan in 3-d lattice N!
sage: f.embed(Cone([(1,0,1), (-1,0,1)]))
Traceback (most recent call last):
...
ValueError: 2-d cone in 3-d lattice N does not belong
to Rational polyhedral fan in 3-d lattice N!
```

# generating\_cone(n)

Return the n-th generating cone of self.

INPUT:

• n – integer, the index of a generating cone.

OUTPUT:

• cone of fan.

### **EXAMPLES:**

# generating\_cones()

Return generating cones of self.

# **OUTPUT**:

• tuple of cones of fan.

### **EXAMPLES**:

# is\_complete()

Check if self is complete.

A rational polyhedral fan is *complete* if its cones fill the whole space.

### **OUTPUT**:

• True if self is complete and False otherwise.

# EXAMPLES:

## is\_equivalent(other)

Check if self is "mathematically" the same as other.

### INPUT:

• other - fan.

### **OUTPUT**:

• True if self and other define the same fans as collections of equivalent cones in the same lattice, False otherwise.

There are three different equivalences between fans  $F_1$  and  $F_2$  in the same lattice:

- 1. They have the same rays in the same order and the same generating cones in the same order. This is tested by F1 == F2.
- 2. They have the same rays and the same generating cones without taking into account any order. This is tested by F1.is\_equivalent(F2).
- 3. They are in the same orbit of  $GL(n, \mathbf{Z})$  (and, therefore, correspond to isomorphic toric varieties). This is tested by F1.is\_isomorphic(F2).

Note that *virtual\_rays()* are included into consideration for all of the above equivalences.

#### **EXAMPLES:**

```
sage: fan1 = Fan(cones=[(0,1), (1,2)],
. . . . :
                  rays=[(1,0), (0,1), (-1,-1)],
                  check=False)
. . . . :
sage: fan2 = Fan(cones=[(2,1), (0,2)],
                  rays=[(1,0), (-1,-1), (0,1)],
. . . . . .
                  check=False)
. . . . .
sage: fan3 = Fan(cones=[(0,1), (1,2)],
                  rays=[(1,0), (0,1), (-1,1)],
                  check=False)
. . . . :
sage: fan1 == fan2
False
sage: fan1.is_equivalent(fan2)
True
sage: fan1 == fan3
False
sage: fan1.is_equivalent(fan3)
False
```

# is\_isomorphic(other)

Check if self is in the same  $GL(n, \mathbf{Z})$ -orbit as other.

There are three different equivalences between fans  $F_1$  and  $F_2$  in the same lattice:

- 1. They have the same rays in the same order and the same generating cones in the same order. This is tested by F1 == F2.
- 2. They have the same rays and the same generating cones without taking into account any order. This is tested by F1.is\_equivalent(F2).
- 3. They are in the same orbit of  $GL(n, \mathbf{Z})$  (and, therefore, correspond to isomorphic toric varieties). This is tested by F1.is\_isomorphic(F2).

Note that *virtual\_rays()* are included into consideration for all of the above equivalences.

### INPUT:

• other - a fan.

**OUTPUT:** 

• True if self and other are in the same  $GL(n, \mathbf{Z})$ -orbit, False otherwise.

### See also:

If you want to obtain the actual fan isomorphism, use *isomorphism()*.

### **EXAMPLES:**

Here we pick an  $SL(2, \mathbf{Z})$  matrix m and then verify that the image fan is isomorphic:

```
sage: rays = ((1, 1), (0, 1), (-1, -1), (1, 0))
sage: cones = [(0,1), (1,2), (2,3), (3,0)]
sage: fan1 = Fan(cones, rays)
sage: m = matrix([[-2,3],[1,-1]])
sage: fan2 = Fan(cones, [vector(r)*m for r in rays])
sage: fan1.is_isomorphic(fan2)
True
sage: fan1.is_equivalent(fan2)
False
sage: fan1 == fan2
False
```

These fans are "mirrors" of each other:

```
sage: fan1 = Fan(cones=[(0,1), (1,2)],
                  rays=[(1,0), (0,1), (-1,-1)],
. . . . :
                  check=False)
. . . . .
sage: fan2 = Fan(cones=[(0,1), (1,2)],
                  rays=[(1,0), (0,-1), (-1,1)],
. . . . . .
                  check=False)
sage: fan1 == fan2
False
sage: fan1.is_equivalent(fan2)
False
sage: fan1.is_isomorphic(fan2)
sage: fan1.is_isomorphic(fan1)
True
```

# is\_simplicial()

Check if self is simplicial.

A rational polyhedral fan is **simplicial** if all of its cones are, i.e. primitive vectors along generating rays of every cone form a part of a *rational* basis of the ambient space.

# **OUTPUT**:

• True if self is simplicial and False otherwise.

### **EXAMPLES:**

(continues on next page)

```
sage: fan = Fan([cone1, cone2])
sage: fan.is_simplicial()
True
```

In fact, any fan in a two-dimensional ambient space is simplicial. This is no longer the case in dimension three:

```
sage: fan = NormalFan(lattice_polytope.cross_polytope(3))
sage: fan.is_simplicial()
False
sage: fan.generating_cone(0).nrays()
4
```

# is\_smooth(codim=None)

Check if self is smooth.

A rational polyhedral fan is **smooth** if all of its cones are, i.e. primitive vectors along generating rays of every cone form a part of an *integral* basis of the ambient space. In this case the corresponding toric variety is smooth.

A fan in an n-dimensional lattice is smooth up to codimension c if all cones of codimension greater than or equal to c are smooth, i.e. if all cones of dimension less than or equal to n-c are smooth. In this case the singular set of the corresponding toric variety is of dimension less than c.

### INPUT:

 codim – codimension in which smoothness has to be checked, by default complete smoothness will be checked.

# **OUTPUT**:

True if self is smooth (in codimension codim, if it was given) and False otherwise.

### **EXAMPLES:**

```
sage: fan = toric_varieties.P1xP1().fan()
                                                                      # optional -
→ palp
sage: fan.is_smooth()
                                                                      # optional -
→ palp
True
sage: cone1 = Cone([(1,0), (0,1)])
sage: cone2 = Cone([(-1,0)])
sage: fan = Fan([cone1, cone2])
sage: fan.is_smooth()
True
sage: fan = NormalFan(lattice_polytope.cross_polytope(2))
sage: fan.is_smooth()
False
sage: fan.is_smooth(codim=1)
True
sage: fan.generating_cone(0).rays()
N(-1, -1),
N(-1, 1)
in 2-d lattice N
sage: fan.generating_cone(0).rays().matrix().det()
-2
```

## isomorphism(other)

Return a fan isomorphism from self to other.

#### INPUT:

• other - fan.

#### **OUTPUT:**

A fan isomorphism. If no such isomorphism exists, a FanNotIsomorphicError is raised.

### **EXAMPLES:**

```
sage: rays = ((1, 1), (0, 1), (-1, -1), (3, 1))
sage: cones = [(0,1), (1,2), (2,3), (3,0)]
sage: fan1 = Fan(cones, rays)
sage: m = matrix([[-2,3],[1,-1]])
sage: fan2 = Fan(cones, [vector(r)*m for r in rays])
sage: fan1.isomorphism(fan2)
Fan morphism defined by the matrix
[-2 3]
\begin{bmatrix} 1 & -1 \end{bmatrix}
Domain fan: Rational polyhedral fan in 2-d lattice N
Codomain fan: Rational polyhedral fan in 2-d lattice N
sage: fan2.isomorphism(fan1)
Fan morphism defined by the matrix
[1 3]
[1 2]
Domain fan: Rational polyhedral fan in 2-d lattice N
Codomain fan: Rational polyhedral fan in 2-d lattice N
sage: fan1.isomorphism(toric_varieties.P2().fan())
                                                                        # optional -
→ palp
Traceback (most recent call last):
FanNotIsomorphicError
```

# linear\_equivalence\_ideal(ring)

Return the ideal generated by linear relations.

### INPUT:

• A polynomial ring in self.nrays() variables.

### **OUTPUT**:

Return the ideal, in the given ring, generated by the linear relations of the rays. In toric geometry, this corresponds to rational equivalence of divisors.

#### **EXAMPLES:**

### make\_simplicial(\*\*kwds)

Construct a simplicial fan subdividing self.

It is a synonym for subdivide() with make\_simplicial=True option.

### INPUT:

• this functions accepts only keyword arguments. See *subdivide()* for documentation.

#### **OUTPUT:**

• rational polyhedral fan.

### **EXAMPLES:**

```
sage: fan = NormalFan(lattice_polytope.cross_polytope(3))
sage: fan.is_simplicial()
False
sage: fan.ngenerating_cones()
6
sage: new_fan = fan.make_simplicial()
sage: new_fan.is_simplicial()
True
sage: new_fan.ngenerating_cones()
12
```

# ngenerating\_cones()

Return the number of generating cones of self.

#### **OUTPUT:**

• integer.

# **EXAMPLES:**

```
sage: fan = toric_varieties.P1xP1().fan()  # optional -
    palp
sage: fan.ngenerating_cones()  # optional -
    palp
4
sage: cone1 = Cone([(1,0), (0,1)])
sage: cone2 = Cone([(-1,0)])
sage: fan = Fan([cone1, cone2])
sage: fan.ngenerating_cones()
2
```

## oriented\_boundary(cone)

Return the facets bounding cone with their induced orientation.

# INPUT:

• cone – a cone of the fan or the whole fan.

# **OUTPUT**:

The boundary cones of cone as a formal linear combination of cones with coefficients  $\pm 1$ . Each summand is a facet of cone and the coefficient indicates whether their (chosen) orientation agrees or disagrees with the "outward normal first" boundary orientation. Note that the orientation of any individual cone is arbitrary. This method once and for all picks orientations for all cones and then computes the boundaries relative to that chosen orientation.

If cone is the fan itself, the generating cones with their orientation relative to the ambient space are returned.

See *complex()* for the associated chain complex. If you do not require the orientation, use *cone*. *facets()* instead.

#### **EXAMPLES:**

```
sage: fan = toric_varieties.P(3).fan()
                                                                      # optional -
→ palp
sage: cone = fan(2)[0]
                                                                      # optional -
→ palp
sage: bdry = fan.oriented_boundary(cone); bdry
                                                                      # optional -
-1-d cone of Rational polyhedral fan in 3-d lattice N + 1-d cone of Rational
\rightarrowpolyhedral fan in 3-d lattice N
sage: bdry[0]
                                                                      # optional -
→ palp
(-1, 1-d cone of Rational polyhedral fan in 3-d lattice N)
sage: bdry[1]
                                                                      # optional -
→ palp
(1, 1-d cone of Rational polyhedral fan in 3-d lattice N)
sage: fan.oriented_boundary(bdry[0][1])
                                                                      # optional -
→ palp
-0-d cone of Rational polyhedral fan in 3-d lattice N
sage: fan.oriented_boundary(bdry[1][1])
                                                                      # optional -
→ palp
-O-d cone of Rational polyhedral fan in 3-d lattice N
```

If you pass the fan itself, this method returns the orientation of the generating cones which is determined by the order of the rays in cone.ray\_basis()

```
sage: fan.oriented_boundary(fan)  # optional -
    palp
-3-d cone of Rational polyhedral fan in 3-d lattice N
+ 3-d cone of Rational polyhedral fan in 3-d lattice N
- 3-d cone of Rational polyhedral fan in 3-d lattice N
+ 3-d cone of Rational polyhedral fan in 3-d lattice N
sage: [cone.rays().basis().matrix().det()  # optional -
    palp
....: for cone in fan.generating_cones()]
[-1, 1, -1, 1]
```

A non-full dimensional fan:

```
sage: cone = Cone([(4,5)])
sage: fan = Fan([cone])
sage: fan.oriented_boundary(cone)
0-d cone of Rational polyhedral fan in 2-d lattice N
sage: fan.oriented_boundary(fan)
1-d cone of Rational polyhedral fan in 2-d lattice N
```

```
plot(**options)
```

Plot self.

INPUT:

• any options for toric plots (see toric\_plotter.options), none are mandatory.

### **OUTPUT**:

a plot.

# **EXAMPLES:**

```
sage: fan = toric_varieties.dP6().fan() # optional -

    palp
sage: fan.plot() # optional -

    palp sage.plot
Graphics object consisting of 31 graphics primitives
```

## primitive\_collections()

Return the primitive collections.

### **OUTPUT**:

Return the subsets  $\{i_1, \ldots, i_k\} \subset \{1, \ldots, n\}$  such that

- The points  $\{p_{i_1}, \dots, p_{i_k}\}$  do not span a cone of the fan.
- If you remove any one  $p_{i_j}$  from the set, then they do span a cone of the fan.

**Note:** By replacing the multiindices  $\{i_1, \ldots, i_k\}$  of each primitive collection with the monomials  $x_{i_1} \cdots x_{i_k}$  one generates the Stanley-Reisner ideal in  $\mathbf{Z}[x_1, \ldots]$ .

## **REFERENCES:**

• [Bat1991]

## **EXAMPLES:**

**subdivide**(new\_rays=None, make\_simplicial=False, algorithm='default', verbose=False)

Construct a new fan subdividing self.

## INPUT:

- new\_rays list of new rays to be added during subdivision, each ray must be a list or a vector. May be empty or None (default);
- make\_simplicial if True, the returned fan is guaranteed to be simplicial, default is False;
- algorithm string with the name of the algorithm used for subdivision. Currently there is only one available algorithm called "default";
- verbose if True, some timing information may be printed during the process of subdivision.

### **OUTPUT**:

• rational polyhedral fan.

Currently the "default" algorithm corresponds to iterative stellar subdivision for each ray in new\_rays.

**EXAMPLES:** 

```
sage: fan = NormalFan(lattice_polytope.cross_polytope(3))
sage: fan.is_simplicial()
False
sage: fan.ngenerating_cones()
6
sage: fan.nrays()
8
sage: new_fan = fan.subdivide(new_rays=[(1,0,0)])
sage: new_fan.is_simplicial()
False
sage: new_fan.ngenerating_cones()
9
sage: new_fan.nrays()
9
```

# support\_contains(\*args)

Check if a point is contained in the support of the fan.

The support of a fan is the union of all cones of the fan. If you want to know whether the fan contains a given cone, you should use *contains()* instead.

# INPUT:

• \*args – an element of self.lattice() or something that can be converted to it (for example, a list of coordinates).

#### **OUTPUT:**

• True if point is contained in the support of the fan, False otherwise.

# toric\_variety(\*args, \*\*kwds)

Return the associated toric variety.

#### INPUT

same arguments as ToricVariety()

# **OUTPUT**:

a toric variety

This is equivalent to the command ToricVariety(self) and is provided only as a convenient alternative method to go from the fan to the associated toric variety.

# **EXAMPLES:**

```
sage: Fan([Cone([(1,0)]), Cone([(0,1)])]).toric_variety()
2-d toric variety covered by 2 affine patches
```

# vertex\_graph()

Return the graph of 1- and 2-cones.

# OUTPUT:

An edge-colored graph. The vertices correspond to the 1-cones (i.e. rays) of the fan. Two vertices are joined by an edge iff the rays span a 2-cone of the fan. The edges are colored by pairs of integers that classify the 2-cones up to  $GL(2, \mathbf{Z})$  transformation, see  $classify\_cone\_2d()$ .

# **EXAMPLES:**

```
sage: dP8 = toric_varieties.dP8()
→# optional - palp sage.graphs
sage: g = dP8.fan().vertex_graph(); g
→# optional - palp sage.graphs
Graph on 4 vertices
sage: set(dP8.fan(1)) == set(g.vertices(sort=False))
→# optional - palp sage.graphs
True
sage: g.edge_labels() # all edge labels the same since every cone is smooth
→# optional - palp sage.graphs
[(1, 0), (1, 0), (1, 0), (1, 0)]
sage: g = toric_varieties.Cube_deformation(10).fan().vertex_graph()
→# optional - sage.graphs
sage: g.automorphism_group().order()
→# optional - sage.graphs sage.groups
sage: g.automorphism_group(edge_labels=True).order()
→# optional - sage.graphs sage.groups
```

# virtual\_rays(\*args)

Return (some of the) virtual rays of self.

Let N be the D-dimensional lattice() of a d-dimensional fan  $\Sigma$  in  $N_{\mathbf{R}}$ . Then the corresponding toric variety is of the form  $X \times (\mathbf{C}^*)^{D-d}$ . The actual rays() of  $\Sigma$  give a canonical choice of homogeneous coordinates on X. This function returns an arbitrary but fixed choice of virtual rays corresponding to a (non-canonical) choice of homogeneous coordinates on the torus factor. Combinatorially primitive integral generators of virtual rays span the D-d dimensions of  $N_{\mathbf{Q}}$  "missed" by the actual rays. (In general addition of virtual rays is not sufficient to span N over  $\mathbf{Z}$ .)

**Note:** You may use a particular choice of virtual rays by passing optional argument virtual\_rays to the Fan() constructor.

## INPUT:

• ray\_list – a list of integers, the indices of the requested virtual rays. If not specified, all virtual rays of self will be returned.

### **OUTPUT**:

• a *PointCollection* of primitive integral ray generators. Usually (if the fan is full-dimensional) this will be empty.

## **EXAMPLES:**

```
sage: f = Fan([Cone([(1,0,1,0), (0,1,1,0)])])
sage: f.virtual_rays()
N(1, 0, 0, 0),
N(0, 0, 0, 1)
in 4-d lattice N
sage: f.rays()
N(1, 0, 1, 0),
```

(continues on next page)

```
N(0, 1, 1, 0)
in 4-d lattice N

sage: f.virtual_rays([0])
N(1, 0, 0, 0)
in 4-d lattice N
```

You can also give virtual ray indices directly, without packing them into a list:

```
sage: f.virtual_rays(0)
N(1, 0, 0, 0)
in 4-d lattice N
```

Make sure that trac ticket #16344 is fixed and one can compute the virtual rays of fans in non-saturated lattices:

```
sage: N = ToricLattice(1)
sage: B = N.submodule([(2,)]).basis()
sage: f = Fan([Cone([B[0]])])
sage: len(f.virtual_rays())
0
```

# sage.geometry.fan.discard\_faces(cones)

Return the cones of the given list which are not faces of each other.

## INPUT:

• cones – a list of *cones*.

# **OUTPUT**:

• a list of *cones*, sorted by dimension in decreasing order.

## **EXAMPLES**:

Consider all cones of a fan:

Most of them are not necessary to generate this fan:

```
sage.geometry.fan.is_Fan(x)
```

Check if x is a Fan.

### INPUT:

• x -anything.

### **OUTPUT:**

• True if x is a fan and False otherwise.

#### **EXAMPLES:**

# 2.5.5 Morphisms between toric lattices compatible with fans

This module is a part of the framework for toric varieties (variety, fano\_variety). Its main purpose is to provide support for working with lattice morphisms compatible with fans via FanMorphism class.

### **AUTHORS:**

- Andrey Novoseltsev (2010-10-17): initial version.
- Andrey Novoseltsev (2011-04-11): added tests for injectivity/surjectivity, fibration, bundle, as well as some related methods.

### **EXAMPLES:**

Let's consider the face and normal fans of the "diamond" and the projection to the x-axis:

```
sage: diamond = lattice_polytope.cross_polytope(2)
sage: face = FaceFan(diamond, lattice=ToricLattice(2))
sage: normal = NormalFan(diamond)
sage: N = face.lattice()
sage: H = End(N)
sage: phi = H([N.0, 0])
sage: phi
Free module morphism defined by the matrix
[1 0]
[0 0]
Domain: 2-d lattice N
Codomain: 2-d lattice N
sage: FanMorphism(phi, normal, face)
Traceback (most recent call last):
ValueError: the image of generating cone #1 of the domain fan
is not contained in a single cone of the codomain fan!
```

Some of the cones of the normal fan fail to be mapped to a single cone of the face fan. We can rectify the situation in the following way:

```
sage: fm = FanMorphism(phi, normal, face, subdivide=True)
sage: fm
Fan morphism defined by the matrix
[1 0]
[0 0]
Domain fan: Rational polyhedral fan in 2-d lattice N
Codomain fan: Rational polyhedral fan in 2-d lattice N
sage: fm.domain_fan().rays()
N(1, 1),
N(1, -1),
N(-1, -1),
N(-1, 1),
N(0, -1),
N(0, 1)
in 2-d lattice N
sage: normal.rays()
N(1, 1),
N(1, -1),
N(-1, -1),
N(-1, 1)
in 2-d lattice N
```

As you see, it was necessary to insert two new rays (to prevent "upper" and "lower" cones of the normal fan from being mapped to the whole x-axis).

Bases: sage.modules.free\_module\_morphism.FreeModuleMorphism

Create a fan morphism.

Let  $\Sigma_1$  and  $\Sigma_2$  be two fans in lattices  $N_1$  and  $N_2$  respectively. Let  $\phi$  be a morphism (i.e. a linear map) from  $N_1$  to  $N_2$ . We say that  $\phi$  is *compatible* with  $\Sigma_1$  and  $\Sigma_2$  if every cone  $\sigma_1 \in \Sigma_1$  is mapped by  $\phi$  into a single cone  $\sigma_2 \in \Sigma_2$ , i.e.  $\phi(\sigma_1) \subset \sigma_2$  ( $\sigma_2$  may be different for different  $\sigma_1$ ).

By a **fan morphism** we understand a morphism between two lattices compatible with specified fans in these lattices. Such morphisms behave in exactly the same way as "regular" morphisms between lattices, but:

- fan morphisms have a special constructor allowing some automatic adjustments to the initial fans (see below);
- fan morphisms are aware of the associated fans and they can be accessed via *codomain\_fan()* and *domain\_fan()*:
- fan morphisms can efficiently compute  $image\_cone()$  of a given cone of the domain fan and  $preimage\_cones()$  of a given cone of the codomain fan.

# INPUT:

- morphism either a morphism between domain and codomain, or an integral matrix defining such a morphism;
- domain\_fan a fan in the domain;
- codomain (default: None) either a codomain lattice or a fan in the codomain. If the codomain fan is
  not given, the image fan (fan generated by images of generating cones) of domain\_fan will be used, if
  possible;

- subdivide (default: False) if True and domain\_fan is not compatible with the codomain fan because it is too coarse, it will be automatically refined to become compatible (the minimal refinement is canonical, so there are no choices involved);
- check (default: True) if False, given fans and morphism will be assumed to be compatible. Be careful
  when using this option, since wrong assumptions can lead to wrong and hard-to-detect errors. On the other
  hand, this option may save you some time;
- verbose (default: False) if True, some information may be printed during construction of the fan morphism.

# **OUTPUT**:

• a fan morphism.

#### **EXAMPLES:**

Here we consider the face and normal fans of the "diamond" and the projection to the x-axis:

```
sage: diamond = lattice_polytope.cross_polytope(2)
sage: face = FaceFan(diamond, lattice=ToricLattice(2))
sage: normal = NormalFan(diamond)
sage: N = face.lattice()
sage: H = End(N)
sage: phi = H([N.0, 0])
sage: phi
Free module morphism defined by the matrix
[1 0]
[0 0]
Domain: 2-d lattice N
Codomain: 2-d lattice N
sage: fm = FanMorphism(phi, face, normal)
sage: fm.domain_fan() is face
True
```

Note, that since phi is compatible with these fans, the returned fan is exactly the same object as the initial domain\_fan.

```
sage: FanMorphism(phi, normal, face)
Traceback (most recent call last):
...
ValueError: the image of generating cone #1 of the domain fan
is not contained in a single cone of the codomain fan!
sage: fm = FanMorphism(phi, normal, face, subdivide=True)
sage: fm.domain_fan() is normal
False
sage: fm.domain_fan().ngenerating_cones()
6
```

We had to subdivide two of the four cones of the normal fan, since they were mapped by phi into non-strictly convex cones.

It is possible to omit the codomain fan, in which case the image fan will be used instead of it:

```
sage: fm = FanMorphism(phi, face)
sage: fm.codomain_fan()
Rational polyhedral fan in 2-d lattice N
```

(continues on next page)

```
sage: fm.codomain_fan().rays()
N( 1, 0),
N(-1, 0)
in 2-d lattice N
```

Now we demonstrate a more subtle example. We take the first quadrant as our domain fan. Then we divide the first quadrant into three cones, throw away the middle one and take the other two as our codomain fan. These fans are incompatible with the identity lattice morphism since the image of the domain fan is out of the support of the codomain fan:

```
sage: N = ToricLattice(2)
sage: phi = End(N).identity()
sage: F1 = Fan(cones=[(0,1)], rays=[(1,0), (0,1)])
sage: F2 = Fan(cones=[(0,1), (2,3)],
               rays=[(1,0), (2,1), (1,2), (0,1)])
sage: FanMorphism(phi, F1, F2)
Traceback (most recent call last):
ValueError: the image of generating cone #0 of the domain fan
is not contained in a single cone of the codomain fan!
sage: FanMorphism(phi, F1, F2, subdivide=True)
Traceback (most recent call last):
ValueError: morphism defined by
[1 0]
[0 1]
does not map
Rational polyhedral fan in 2-d lattice N
into the support of
Rational polyhedral fan in 2-d lattice N!
```

The problem was detected and handled correctly (i.e. an exception was raised). However, the used algorithm requires extra checks for this situation after constructing a potential subdivision and this can take significant time. You can save about half the time using check=False option, if you know in advance that it is possible to make fans compatible with the morphism by subdividing the domain fan. Of course, if your assumption was incorrect, the result will be wrong and you will get a fan which *does* map into the support of the codomain fan, but is **not** a subdivision of the domain fan. You can test it on the example above:

# codomain\_fan(dim=None, codim=None)

Return the codomain fan of self.

# INPUT:

• dim – dimension of the requested cones;

• codim – codimension of the requested cones.

### **OUTPUT:**

• rational polyhedral fan if no parameters were given, tuple of cones otherwise.

## **EXAMPLES:**

```
sage: quadrant = Cone([(1,0), (0,1)])
sage: quadrant = Fan([quadrant])
sage: quadrant_bl = quadrant.subdivide([(1,1)])
sage: fm = FanMorphism(identity_matrix(2), quadrant_bl, quadrant)
sage: fm.codomain_fan()
Rational polyhedral fan in 2-d lattice N
sage: fm.codomain_fan() is quadrant
True
```

### domain\_fan(dim=None, codim=None)

Return the codomain fan of self.

### INPUT:

- dim dimension of the requested cones;
- codim codimension of the requested cones.

#### **OUTPUT:**

• rational polyhedral fan if no parameters were given, tuple of cones otherwise.

### **EXAMPLES:**

```
sage: quadrant = Cone([(1,0), (0,1)])
sage: quadrant = Fan([quadrant])
sage: quadrant_bl = quadrant.subdivide([(1,1)])
sage: fm = FanMorphism(identity_matrix(2), quadrant_bl, quadrant)
sage: fm.domain_fan()
Rational polyhedral fan in 2-d lattice N
sage: fm.domain_fan() is quadrant_bl
True
```

### factor()

Factor self into injective \* birational \* surjective morphisms.

# **OUTPUT**:

• a triple of FanMorphism  $(\phi_i, \phi_b, \phi_s)$ , such that  $\phi_s$  is surjective,  $\phi_b$  is birational,  $\phi_i$  is injective, and self is equal to  $\phi_i \circ \phi_b \circ \phi_s$ .

Intermediate fans live in the saturation of the image of self as a map between lattices and are the image of the  $domain\_fan()$  and the restriction of the  $codomain\_fan()$ , i.e. if self maps  $\Sigma \to \Sigma'$ , then we have factorization into

$$\Sigma \twoheadrightarrow \Sigma_s \to \Sigma_i \hookrightarrow \Sigma.$$

# Note:

•  $\Sigma_s$  is the finest fan with the smallest support that is compatible with self: any fan morphism from  $\Sigma$  given by the same map of lattices as self factors through  $\Sigma_s$ .

•  $\Sigma_i$  is the coarsest fan of the largest support that is compatible with self: any fan morphism into  $\Sigma'$  given by the same map of lattices as self factors though  $\Sigma_i$ .

### **EXAMPLES:**

We map an affine plane into a projective 3-space in such a way, that it becomes "a double cover of a chart of the blow up of one of the coordinate planes":

Now we will work with the underlying fan morphism:

```
sage: phi = phi.fan_morphism(); phi
                                                                             #_
→optional - palp
Fan morphism defined by the matrix
[2 0 0]
Γ1 1 0]
Domain fan: Rational polyhedral fan in 2-d lattice N
Codomain fan: Rational polyhedral fan in 3-d lattice N
sage: phi.is_surjective(), phi.is_birational(), phi.is_injective()
→optional - palp
(False, False, False)
sage: phi_i, phi_b, phi_s = phi.factor()
                                                                             #.
→optional - palp
sage: phi_s.is_surjective(), phi_b.is_birational(), phi_i.is_injective()
→optional - palp
(True, True, True)
sage: prod(phi.factor()) == phi
                                                                             #_
→optional - palp
```

Double cover (surjective):

(continues on next page)

```
Domain fan: Rational polyhedral fan in 2-d lattice N

Codomain fan: Rational polyhedral fan in Sublattice <N(1, 0, 0), N(0, 1, 0)>

sage: phi_s.codomain_fan().rays() #__

optional - palp

N(1, 0, 0),

N(1, 1, 0)

in Sublattice <N(1, 0, 0), N(0, 1, 0)>
```

Blowup chart (birational):

Coordinate plane inclusion (injective):

```
sage: phi_i
                                                                            #_
→optional - palp
Fan morphism defined by the matrix
[1 0 0]
[0 1 0]
Domain fan: Rational polyhedral fan in Sublattice <N(1, 0, 0), N(0, 1, 0)>
Codomain fan: Rational polyhedral fan in 3-d lattice N
sage: phi.codomain_fan().rays()
                                                                            #_
→optional - palp
N(1, 0, 0),
N(0, 1, 0),
N(0, 0, 1),
N(-1, -1, -1)
in 3-d lattice N
```

### image\_cone(cone)

Return the cone of the codomain fan containing the image of cone.

# INPUT:

• cone – a *cone* equivalent to a cone of the *domain\_fan()* of self.

## **OUTPUT**:

• a cone of the codomain\_fan() of self.

### **EXAMPLES:**

```
sage: quadrant = Cone([(1,0), (0,1)])
sage: quadrant = Fan([quadrant])
sage: quadrant_bl = quadrant.subdivide([(1,1)])
sage: fm = FanMorphism(identity_matrix(2), quadrant_bl, quadrant)
sage: fm.image_cone(Cone([(1,0)]))
1-d cone of Rational polyhedral fan in 2-d lattice N
sage: fm.image_cone(Cone([(1,1)]))
2-d cone of Rational polyhedral fan in 2-d lattice N
```

### index(cone=None)

Return the index of self as a map between lattices.

#### INPUT:

• cone – (default: None) a cone of the codomain\_fan() of self.

### **OUTPUT**:

· an integer, infinity, or None.

If no cone was specified, this function computes the index of the image of self in the codomain. If a cone  $\sigma$  was given, the index of self over  $\sigma$  is computed in the sense of Definition 2.1.7 of [HLY2002]: if  $\sigma'$  is any cone of the  $domain\_fan()$  of self whose relative interior is mapped to the relative interior of  $\sigma$ , it is the index of the image of  $N'(\sigma')$  in  $N(\sigma)$ , where N' and N are domain and codomain lattices respectively. While that definition was formulated for the case of the finite index only, we extend it to the infinite one as well and return None if there is no  $\sigma'$  at all. See examples below for situations when such things happen. Note also that the index of self is the same as index over the trivial cone.

### **EXAMPLES:**

```
sage: Sigma = toric_varieties.dP8().fan()
                                                                     # optional -
→ palp
sage: Sigma_p = toric_varieties.P1().fan()
sage: phi = FanMorphism(matrix([[1], [-1]]), Sigma, Sigma_p)
                                                                     # optional -
→ palp
sage: phi.index()
                                                                      # optional -
→ palp
1
sage: psi = FanMorphism(matrix([[2], [-2]]), Sigma, Sigma_p)
                                                                      # optional -
→ palp
sage: psi.index()
                                                                      # optional -
→ palp
sage: xi = FanMorphism(matrix([[1, 0]]), Sigma_p, Sigma)
                                                                      # optional -
→ palp
sage: xi.index()
                                                                      # optional -
→ palp
+Infinity
```

Infinite index in the last example indicates that the image has positive codimension in the codomain. Let's look at the rays of our fans:

```
sage: Sigma_p.rays()
N( 1),
N(-1)
in 1-d lattice N
```

(continues on next page)

We see that one of the rays of the fan of P1 is mapped to a ray, while the other one to the interior of some 2-d cone. Both rays correspond to single points on P1, yet one is mapped to the distinguished point of a torus invariant curve of dP8 (with the rest of this curve being uncovered) and the other to a fixed point of dP8 (thus completely covering this torus orbit in dP8).

We should therefore expect the following behaviour: all indices over 1-d cones are None, except for one which is infinite, and all indices over 2-d cones are None, except for one which is 1:

```
sage: [xi.index(cone) for cone in Sigma(1)] # optional -
    palp
[None, None, None, +Infinity]
sage: [xi.index(cone) for cone in Sigma(2)] # optional -
    palp
[None, 1, None, None]
```

# is\_birational()

Check if self is birational.

#### **OUTPUT**:

• True if self is birational, False otherwise.

For fan morphisms this check is equivalent to self.index() == 1 and means that the corresponding map between toric varieties is birational.

# **EXAMPLES:**

```
sage: Sigma = toric_varieties.dP8().fan()
                                                                     # optional -
→ palp
sage: Sigma_p = toric_varieties.P1().fan()
sage: phi = FanMorphism(matrix([[1], [-1]]), Sigma, Sigma_p)
                                                                     # optional -
sage: psi = FanMorphism(matrix([[2], [-2]]), Sigma, Sigma_p)
                                                                     # optional -
→ palp
sage: xi = FanMorphism(matrix([[1, 0]]), Sigma_p, Sigma)
                                                                     # optional -
sage: phi.index(), psi.index(), xi.index()
                                                                     # optional -
→ palp
(1, 2, +Infinity)
sage: phi.is_birational(), psi.is_birational(), xi.is_birational() # optional -
→ palp
(True, False, False)
```

### is\_bundle()

Check if self is a bundle.

#### **OUTPUT:**

• True if self is a bundle, False otherwise.

Let  $\phi: \Sigma \to \Sigma'$  be a fan morphism such that the underlying lattice morphism  $\phi: N \to N'$  is surjective. Let  $\Sigma_0$  be the kernel fan of  $\phi$ . Then  $\phi$  is a **bundle** (or splitting) if there is a subfan  $\widehat{\Sigma}$  of  $\Sigma$  such that the following two conditions are satisfied:

- 1. Cones of  $\Sigma$  are precisely the cones of the form  $\sigma_0 + \widehat{\sigma}$ , where  $\sigma_0 \in \Sigma_0$  and  $\widehat{\sigma} \in \widehat{\Sigma}$ .
- 2. Cones of  $\widehat{\Sigma}$  are in bijection with cones of  $\Sigma'$  induced by  $\phi$  and  $\phi$  maps lattice points in every cone  $\widehat{\sigma} \in \widehat{\Sigma}$  bijectively onto lattice points in  $\phi(\widehat{\sigma})$ .

If a fan morphism  $\phi: \Sigma \to \Sigma'$  is a bundle, then  $X_{\Sigma}$  is a fiber bundle over  $X_{\Sigma'}$  with fibers  $X_{\Sigma_0,N_0}$ , where  $N_0$  is the kernel lattice of  $\phi$ . See [CLS2011] for more details.

### See also:

is\_fibration(), kernel\_fan().

#### **EXAMPLES:**

We consider several maps between fans of a del Pezzo surface and the projective line:

```
sage: Sigma = toric_varieties.dP8().fan()
                                                                      # optional -
sage: Sigma_p = toric_varieties.P1().fan()
sage: phi = FanMorphism(matrix([[1], [-1]]), Sigma, Sigma_p)
                                                                      # optional -
→ palp
sage: psi = FanMorphism(matrix([[2], [-2]]), Sigma, Sigma_p)
                                                                      # optional -
sage: xi = FanMorphism(matrix([[1, 0]]), Sigma_p, Sigma)
                                                                      # optional -
→ palp
sage: phi.is_bundle()
                                                                      # optional -
→ palp
True
                                                                      # optional -
sage: phi.is_fibration()
→ palp
True
sage: phi.index()
                                                                      # optional -
→ palp
1
sage: psi.is_bundle()
                                                                      # optional -
→ palp
False
                                                                      # optional -
sage: psi.is_fibration()
→ palp
True
sage: psi.index()
                                                                      # optional -
→ palp
sage: xi.is_fibration()
                                                                      # optional -
→ palp
False
```

(continues on next page)

The first of these maps induces not only a fibration, but a fiber bundle structure. The second map is very similar, yet it fails to be a bundle, as its index is 2. The last map is not even a fibration.

### is\_dominant()

Return whether the fan morphism is dominant.

A fan morphism  $\phi$  is dominant if it is surjective as a map of vector spaces. That is,  $\phi_{\mathbf{R}}: N_{\mathbf{R}} \to N_{\mathbf{R}}'$  is surjective.

If the domain fan is *complete*, then this implies that the fan morphism is *surjective*.

If the fan morphism is dominant, then the associated morphism of toric varieties is dominant in the algebraic-geometric sense (that is, surjective onto a dense subset).

# **OUTPUT**:

Boolean.

### **EXAMPLES:**

```
sage: P1 = toric_varieties.P1()
sage: A1 = toric_varieties.A1()
sage: phi = FanMorphism(matrix([[1]]), A1.fan(), P1.fan())
sage: phi.is_dominant()
True
sage: phi.is_surjective()
False
```

## is\_fibration()

Check if self is a fibration.

### **OUTPUT**:

• True if self is a fibration, False otherwise.

A fan morphism  $\phi: \Sigma \to \Sigma'$  is a **fibration** if for any cone  $\sigma' \in \Sigma'$  and any primitive preimage cone  $\sigma \in \Sigma$  corresponding to  $\sigma'$  the linear map of vector spaces  $\phi_{\mathbf{R}}$  induces a bijection between  $\sigma$  and  $\sigma'$ , and, in addition,  $\phi$  is *dominant* (that is,  $\phi_{\mathbf{R}}: N_{\mathbf{R}} \to N'_{\mathbf{R}}$  is surjective).

If a fan morphism  $\phi: \Sigma \to \Sigma'$  is a fibration, then the associated morphism between toric varieties  $\tilde{\phi}: X_{\Sigma} \to X_{\Sigma'}$  is a fibration in the sense that it is surjective and all of its fibers have the same dimension, namely  $\dim X_{\Sigma} - \dim X_{\Sigma'}$ . These fibers do *not* have to be isomorphic, i.e. a fibration is not necessarily a fiber bundle. See [HLY2002] for more details.

# See also:

```
is_bundle(), primitive_preimage_cones().
```

### **EXAMPLES:**

We consider several maps between fans of a del Pezzo surface and the projective line:

```
sage: psi = FanMorphism(matrix([[2], [-2]]), Sigma, Sigma_p)
                                                                      # optional -
sage: xi = FanMorphism(matrix([[1, 0]]), Sigma_p, Sigma)
                                                                       # optional -
→ palp
sage: phi.is_bundle()
                                                                       # optional -
→ palp
True
sage: phi.is_fibration()
                                                                      # optional -
→ palp
True
sage: phi.index()
                                                                       # optional -
→ palp
1
sage: psi.is_bundle()
                                                                       # optional -
→ palp
False
sage: psi.is_fibration()
                                                                       # optional -
→ palp
True
                                                                       # optional -
sage: psi.index()
→ palp
sage: xi.is_fibration()
                                                                       # optional -
→ palp
False
                                                                       # optional -
sage: xi.index()
→ palp
+Infinity
```

The first of these maps induces not only a fibration, but a fiber bundle structure. The second map is very similar, yet it fails to be a bundle, as its index is 2. The last map is not even a fibration.

### is\_injective()

Check if self is injective.

## **OUTPUT**:

• True if self is injective, False otherwise.

Let  $\phi: \Sigma \to \Sigma'$  be a fan morphism such that the underlying lattice morphism  $\phi: N \to N'$  bijectively maps N to a *saturated* sublattice of N'. Let  $\psi: \Sigma \to \Sigma'_0$  be the restriction of  $\phi$  to the image. Then  $\phi$  is **injective** if the map between cones corresponding to  $\psi$  (injectively) maps each cone of  $\Sigma$  to a cone of the same dimension.

If a fan morphism  $\phi: \Sigma \to \Sigma'$  is injective, then the associated morphism between toric varieties  $\hat{\phi}: X_{\Sigma} \to X_{\Sigma'}$  is injective.

#### See also:

factor().

# **EXAMPLES:**

Consider the fan of the affine plane:

```
sage: A2 = toric_varieties.A(2).fan()
```

We will map several fans consisting of a single ray into the interior of the 2-cone:

```
sage: Sigma = Fan([Cone([(1,1)])])
sage: m = identity_matrix(2)
sage: FanMorphism(m, Sigma, A2).is_injective()
False
```

This morphism was not injective since (in the toric varieties interpretation) the 1-dimensional orbit corresponding to the ray was mapped to the 0-dimensional orbit corresponding to the 2-cone.

```
sage: Sigma = Fan([Cone([(1,)])])
sage: m = matrix(1, 2, [1,1])
sage: FanMorphism(m, Sigma, A2).is_injective()
True
```

While the fans in this example are close to the previous one, here the ray corresponds to a 0-dimensional orbit

```
sage: Sigma = Fan([Cone([(1,)])])
sage: m = matrix(1, 2, [2,2])
sage: FanMorphism(m, Sigma, A2).is_injective()
False
```

Here the problem is that m maps the domain lattice to a non-saturated sublattice of the codomain. The corresponding map of the toric varieties is a two-sheeted cover of its image.

We also embed the affine plane into the projective one:

# is\_surjective()

Check if self is surjective.

# **OUTPUT**:

• True if self is surjective, False otherwise.

A fan morphism  $\phi: \Sigma \to \Sigma'$  is **surjective** if the corresponding map between cones is surjective, i.e. for each cone  $\sigma' \in \Sigma'$  there is at least one preimage cone  $\sigma \in \Sigma$  such that the relative interior of  $\sigma$  is mapped to the relative interior of  $\sigma'$  and, in addition,  $\phi_{\mathbf{R}}: N_{\mathbf{R}} \to N'_{\mathbf{R}}$  is surjective.

If a fan morphism  $\phi:\Sigma\to\Sigma'$  is surjective, then the associated morphism between toric varieties  $\tilde{\phi}:X_\Sigma\to X_{\Sigma'}$  is surjective.

# See also:

```
is_bundle(), is_fibration(), preimage_cones(), is_complete().
```

#### **EXAMPLES:**

We check that the blow up of the affine plane at the origin is surjective:

```
sage: A2 = toric_varieties.A(2).fan()
sage: B1 = A2.subdivide([(1,1)])
sage: m = identity_matrix(2)
sage: FanMorphism(m, B1, A2).is_surjective()
True
```

It remains surjective if we throw away "south and north poles" of the exceptional divisor:

```
sage: FanMorphism(m, Fan(Bl.cones(1)), A2).is_surjective()
True
```

But a single patch of the blow up does not cover the plane:

```
sage: F = Fan([Bl.generating_cone(0)])
sage: FanMorphism(m, F, A2).is_surjective()
False
```

# kernel\_fan()

Return the subfan of the domain fan mapped into the origin.

### **OUTPUT**:

• a fan.

**Note:** The lattice of the kernel fan is the kernel() sublattice of self.

### See also:

preimage\_fan().

# **EXAMPLES:**

# preimage\_cones(cone)

Return cones of the domain fan whose *image\_cone()* is cone.

# INPUT:

• cone – a *cone* equivalent to a cone of the *codomain\_fan()* of self.

# **OUTPUT**:

• a tuple of cones of the domain\_fan() of self, sorted by dimension.

### See also:

preimage\_fan().

**EXAMPLES:** 

```
sage: quadrant = Cone([(1,0), (0,1)])
sage: quadrant = Fan([quadrant])
sage: quadrant_bl = quadrant.subdivide([(1,1)])
sage: fm = FanMorphism(identity_matrix(2), quadrant_bl, quadrant)
sage: fm.preimage_cones(Cone([(1,0)]))
(1-d cone of Rational polyhedral fan in 2-d lattice N,)
sage: fm.preimage_cones(Cone([(1,0), (0,1)]))
(1-d cone of Rational polyhedral fan in 2-d lattice N,
2-d cone of Rational polyhedral fan in 2-d lattice N,
2-d cone of Rational polyhedral fan in 2-d lattice N)
```

## preimage\_fan(cone)

Return the subfan of the domain fan mapped into cone.

#### INPI IT:

• cone – a cone equivalent to a cone of the codomain\_fan() of self.

#### **OUTPUT:**

a fan.

**Note:** The preimage fan of cone consists of all cones of the *domain\_fan()* which are mapped into cone, including those that are mapped into its boundary. So this fan is not necessarily generated by *preimage\_cones()* of cone.

#### See also:

kernel\_fan(), preimage\_cones().

# **EXAMPLES:**

```
sage: quadrant_cone = Cone([(1,0), (0,1)])
sage: quadrant_fan = Fan([quadrant_cone])
sage: quadrant_bl = quadrant_fan.subdivide([(1,1)])
sage: fm = FanMorphism(identity_matrix(2),
....: quadrant_bl, quadrant_fan)
sage: fm.preimage_fan(Cone([(1,0)])).cones()
((0-d cone of Rational polyhedral fan in 2-d lattice N,))
(1-d cone of Rational polyhedral fan in 2-d lattice N,))
sage: fm.preimage_fan(quadrant_cone).ngenerating_cones()
2
sage: len(fm.preimage_cones(quadrant_cone))
```

# primitive\_preimage\_cones(cone)

Return the primitive cones of the domain fan corresponding to cone.

#### INPLIT

• cone – a cone equivalent to a cone of the codomain\_fan() of self.

#### **OUTPUT:**

· a cone.

Let  $\phi: \Sigma \to \Sigma'$  be a fan morphism, let  $\sigma \in \Sigma$ , and let  $\sigma' = \phi(\sigma)$ . Then  $\sigma$  is a **primitive cone corresponding to**  $\sigma'$  if there is no proper face  $\tau$  of  $\sigma$  such that  $\phi(\tau) = \sigma'$ .

Primitive cones play an important role for fibration morphisms.

#### See also:

```
is_fibration(), preimage_cones(), preimage_fan().
```

## **EXAMPLES:**

Consider a projection of a del Pezzo surface onto the projective line:

```
sage: Sigma = toric_varieties.dP6().fan()
                                                                    # optional -
→ palp
                                                                    # optional -
sage: Sigma.rays()
→ palp
N(0, 1),
N(-1, 0),
N(-1, -1),
N(0, -1),
N(1, 0).
N(1, 1)
in 2-d lattice N
sage: Sigma_p = toric_varieties.P1().fan()
sage: phi = FanMorphism(matrix([[1], [-1]]), Sigma, Sigma_p)
                                                                    # optional -
→ palp
```

Under this map, one pair of rays is mapped to the origin, one in the positive direction, and one in the negative one. Also three 2-dimensional cones are mapped in the positive direction and three in the negative one, so there are 5 preimage cones corresponding to either of the rays of the codomain fan Sigma\_p:

```
sage: len(phi.preimage_cones(Cone([(1,)]))) # optional -
   palp
5
```

Yet only rays are primitive:

```
sage: phi.primitive_preimage_cones(Cone([(1,)])) # optional -
    palp
(1-d cone of Rational polyhedral fan in 2-d lattice N,
    1-d cone of Rational polyhedral fan in 2-d lattice N)
```

Since all primitive cones are mapped onto their images bijectively, we get a fibration:

But since there are several primitive cones corresponding to the same cone of the codomain fan, this map is not a bundle, even though its index is 1:

```
sage: phi.is_bundle() # optional -
    palp
False
sage: phi.index() # optional -
    palp
1
```

#### relative\_star\_generators(domain cone)

Return the relative star generators of domain\_cone.

#### INPUT:

• domain\_cone - a cone of the domain\_fan() of self.

#### **OUTPUT**:

• star\_generators() of domain\_cone viewed as a cone of preimage\_fan() of image\_cone() of domain\_cone.

#### **EXAMPLES:**

```
sage: A2 = toric_varieties.A(2).fan()
sage: Bl = A2.subdivide([(1,1)])
sage: f = FanMorphism(identity_matrix(2), Bl, A2)
sage: for c1 in Bl(1):
....: print(f.relative_star_generators(c1))
(1-d cone of Rational polyhedral fan in 2-d lattice N,)
(1-d cone of Rational polyhedral fan in 2-d lattice N,)
(2-d cone of Rational polyhedral fan in 2-d lattice N,
2-d cone of Rational polyhedral fan in 2-d lattice N)
```

# 2.5.6 Point collections

This module was designed as a part of framework for toric varieties (variety, fano\_variety).

## **AUTHORS:**

- Andrey Novoseltsev (2011-04-25): initial version, based on cone module.
- Andrey Novoseltsev (2012-03-06): additions and doctest changes while switching cones to use point collections.

# **EXAMPLES**:

The idea behind point collections is to have a container for points of the same space that

• behaves like a tuple without significant performance penalty:

```
sage: c = Cone([(0,0,1), (1,0,1), (0,1,1), (1,1,1)]).rays()
sage: c[1]
N(1, 0, 1)
sage: for point in c: point
N(0, 0, 1)
N(1, 0, 1)
N(0, 1, 1)
N(1, 1, 1)
```

• prints in a convenient way and with clear indication of the ambient space:

```
sage: c
N(0, 0, 1),
N(1, 0, 1),
N(0, 1, 1),
N(1, 1, 1)
in 3-d lattice N
```

• allows (cached) access to alternative representations:

```
sage: c.set()
frozenset({N(0, 0, 1), N(0, 1, 1), N(1, 0, 1), N(1, 1, 1)})
```

· allows introduction of additional methods:

```
sage: c.basis()
N(0, 0, 1),
N(1, 0, 1),
N(0, 1, 1)
in 3-d lattice N
```

Examples of natural point collections include ray and line generators of cones, vertices and points of polytopes, normals to facets, their subcollections, etc.

Using this class for all of the above cases allows for unified interface and cache sharing. Suppose that  $\Delta$  is a reflexive polytope. Then the same point collection can be linked as

- 1. vertices of  $\Delta$ ;
- 2. facet normals of its polar  $\Delta^{\circ}$ ;
- 3. ray generators of the face fan of  $\Delta$ ;
- 4. ray generators of the normal fan of  $\Delta$ .

If all these objects are in use and, say, a matrix representation was computed for one of them, it becomes available to all others as well, eliminating the need to spend time and memory four times.

```
class sage.geometry.point_collection.PointCollection
```

```
Bases: sage.structure.sage_object.SageObject
```

Create a point collection.

**Warning:** No correctness check or normalization is performed on the input data. This class is designed for internal operations and you probably should not use it directly.

Point collections are immutable, but cache most of the returned values.

#### INPUT:

- points an iterable structure of immutable elements of module, if points are already accessible to you as a tuple, it is preferable to use it for speed and memory consumption reasons;
- module an ambient module for points. If None (the default), it will be determined as parent() of the first point. Of course, this cannot be done if there are no points, so in this case you must give an appropriate module directly.

# OUTPUT:

• a point collection.

#### basis(

Return a linearly independent subset of points of self.

# **OUTPUT:**

• a *point collection* giving a random (but fixed) choice of an **R**-basis for the vector space spanned by the points of self.

```
sage: c = Cone([(0,0,1), (1,0,1), (0,1,1), (1,1,1)]).rays()
sage: c.basis()
N(0, 0, 1),
N(1, 0, 1),
N(0, 1, 1)
in 3-d lattice N
```

Calling this method twice will always return exactly the same point collection:

```
sage: c.basis().basis() is c.basis()
True
```

# cardinality()

Return the number of points in self.

## **OUTPUT**:

• an integer.

# **EXAMPLES:**

```
sage: c = Cone([(0,0,1), (1,0,1), (0,1,1), (1,1,1)]).rays()
sage: c.cardinality()
4
```

# cartesian\_product(other, module=None)

Return the Cartesian product of self with other.

# INPUT:

- other a point collection;
- module (optional) the ambient module for the result. By default, the direct sum of the ambient modules of self and other is constructed.

# **OUTPUT**:

• a point collection.

## **EXAMPLES:**

```
sage: c = Cone([(0,0,1), (1,1,1)]).rays()
sage: c.cartesian_product(c)
N+N(0, 0, 1, 0, 0, 1),
N+N(1, 1, 1, 0, 0, 1),
N+N(0, 0, 1, 1, 1, 1),
N+N(1, 1, 1, 1, 1, 1)
in 6-d lattice N+N
```

# column\_matrix()

Return a matrix whose columns are points of self.

## OUTPUT:

• a matrix.

```
sage: c = Cone([(0,0,1), (1,0,1), (0,1,1), (1,1,1)]).rays()
sage: c.column_matrix()
[0 1 0 1]
[0 0 1 1]
[1 1 1 1]
```

# dim()

Return the dimension of the space spanned by points of self.

**Note:** You can use either dim() or dimension().

#### **OUTPUT**:

• an integer.

# **EXAMPLES:**

```
sage: c = Cone([(0,0,1), (1,1,1)]).rays()
sage: c.dimension()
2
sage: c.dim()
2
```

# dimension()

Return the dimension of the space spanned by points of self.

**Note:** You can use either dim() or dimension().

# **OUTPUT**:

• an integer.

#### **EXAMPLES:**

```
sage: c = Cone([(0,0,1), (1,1,1)]).rays()
sage: c.dimension()
2
sage: c.dim()
2
```

#### dual\_module()

Return the dual of the ambient module of self.

## **OUTPUT**:

• a module. If possible (that is, if the ambient module() M of self has a dual() method), the dual module is returned. Otherwise,  $R^n$  is returned, where n is the dimension of M and R is its base ring.

# **EXAMPLES:**

```
sage: c = Cone([(0,0,1), (1,0,1), (0,1,1), (1,1,1)]).rays()
sage: c.dual_module()
3-d lattice M
```

# index(\*args)

Return the index of the first occurrence of point in self.

# INPUT:

- point a point of self;
- start (optional) an integer, if given, the search will start at this position;
- stop (optional) an integer, if given, the search will stop at this position.

#### **OUTPUT:**

• an integer if point is in self[start:stop], otherwise a ValueError exception is raised.

## **EXAMPLES:**

```
sage: c = Cone([(0,0,1), (1,0,1), (0,1,1), (1,1,1)]).rays()
sage: c.index((0,1,1))
Traceback (most recent call last):
...
ValueError: tuple.index(x): x not in tuple
```

Note that this was not a mistake: the tuple (0,1,1) is not a point of c! We need to pass actual element of the ambient module of c to get their indices:

```
sage: N = c.module()
sage: c.index(N(0,1,1))
2
sage: c[2]
N(0, 1, 1)
```

#### matrix()

Return a matrix whose rows are points of self.

## **OUTPUT**:

• a matrix.

# **EXAMPLES:**

```
sage: c = Cone([(0,0,1), (1,0,1), (0,1,1), (1,1,1)]).rays()
sage: c.matrix()
[0 0 1]
[1 0 1]
[0 1 1]
[1 1 1]
```

# module()

Return the ambient module of self.

#### **OUTPUT**:

• a module.

# **EXAMPLES:**

```
sage: c = Cone([(0,0,1), (1,0,1), (0,1,1), (1,1,1)]).rays()
sage: c.module()
3-d lattice N
```

# static output\_format=None)

Return or set the output format for ALL point collections.

# INPUT:

- format (optional) if given, must be one of the strings
  - "default" output one point per line with vertical alignment of coordinates in text mode, same as "tuple" for LaTeX;
  - "tuple" output tuple(self) with lattice information;
  - "matrix" output matrix() with lattice information;
  - "column matrix" output column\_matrix() with lattice information;
  - "separated column matrix" same as "column matrix" for text mode, for LaTeX separate columns by lines (not shown by jsMath).

#### **OUTPUT**:

• a string with the current format (only if format was omitted).

This function affects both regular and LaTeX output.

# **EXAMPLES:**

```
sage: c = Cone([(0,0,1), (1,0,1), (0,1,1), (1,1,1)]).rays()
sage: c
N(0, 0, 1),
N(1, 0, 1),
N(0, 1, 1),
N(1, 1, 1)
in 3-d lattice N
sage: c.output_format()
'default'
sage: c.output_format("tuple")
sage: c
(N(0, 0, 1), N(1, 0, 1), N(0, 1, 1), N(1, 1, 1))
in 3-d lattice N
sage: c.output_format("matrix")
sage: c
[0 0 1]
[1 0 1]
[0 1 1]
[1 \ 1 \ 1]
in 3-d lattice N
sage: c.output_format("column matrix")
sage: c
[0 1 0 1]
[0 0 1 1]
[1 1 1 1]
in 3-d lattice N
sage: c.output_format("separated column matrix")
sage: c
[0 1 0 1]
[0 0 1 1]
[1 \ 1 \ 1 \ 1]
in 3-d lattice N
```

Note that the last two outputs are identical, separators are only inserted in the LaTeX mode:

```
sage: latex(c)
\left(\begin{array}{r|r|r|}
0 & 1 & 0 & 1 \\
0 & 0 & 1 & 1 \\
1 & 1 & 1 & 1
\end{array}\right)_{N}
```

Since this is a static method, you can call it for the class directly:

```
sage: from sage.geometry.point_collection import PointCollection
sage: PointCollection.output_format("default")
sage: c
N(0, 0, 1),
N(1, 0, 1),
N(0, 1, 1),
N(0, 1, 1)
in 3-d lattice N
```

#### set()

Return points of self as a frozenset.

## OUTPUT:

• a frozenset.

# **EXAMPLES:**

```
sage: c = Cone([(0,0,1), (1,0,1), (0,1,1), (1,1,1)]).rays()
sage: c.set()
frozenset({N(0, 0, 1), N(0, 1, 1), N(1, 0, 1), N(1, 1, 1)})
```

# write\_for\_palp(f)

Write self into an open file f in PALP format.

# INPUT:

• f - a file opened for writing.

#### **EXAMPLES:**

```
sage: o = lattice_polytope.cross_polytope(3)
sage: from io import StringIO
sage: f = StringIO()
sage: o.vertices().write_for_palp(f)
sage: print(f.getvalue())
6  3
1  0  0
0  1  0
0  0  1
-1  0  0
0  -1  0
0  0  -1
```

# sage.geometry.point\_collection.is\_PointCollection(x)

Check if x is a point collection.

INPUT:

• x -anything.

#### **OUTPUT:**

• True if x is a point collection and False otherwise.

## **EXAMPLES:**

```
sage: from sage.geometry.point_collection import is_PointCollection
sage: is_PointCollection(1)
False
sage: c = Cone([(0,0,1), (1,0,1), (0,1,1), (1,1,1)])
sage: is_PointCollection(c.rays())
True
```

sage.geometry.point\_collection.read\_palp\_point\_collection(f, lattice=None, permutation=False)
Read and return a point collection from an opened file.

Data must be in PALP format:

- the first input line starts with two integers m and n, the number of points and the number of components of each;
- the rest of the first line may contain a permutation;
- the next m lines contain n numbers each.

**Note:** If m < n, it is assumed (for compatibility with PALP) that the matrix is transposed, i.e. that each column is a point.

# INPUT:

- f an opened file with PALP output.
- lattice the lattice for points. If not given, the toric lattice M of dimension n will be used.
- permutation (default: False) if True, try to retrieve the permutation. This parameter makes sense only when PALP computed the normal form of a lattice polytope.

# **OUTPUT**:

• a point collection, optionally followed by a permutation. None if EOF is reached.

## **EXAMPLES:**

```
sage: data = "3 2 regular\n1 2\n3 4\n5 6\n2 3 transposed\n1 2 3\n4 5 6"
sage: print(data)
3 2 regular
1 2
3 4
5 6
2 3 transposed
1 2 3
4 5 6
sage: from io import StringIO
sage: f = StringIO(data)
sage: from sage.geometry.point_collection \
....: import read_palp_point_collection
sage: read_palp_point_collection(f)
```

```
M(1, 2),
M(3, 4),
M(5, 6)
in 2-d lattice M
sage: read_palp_point_collection(f)
M(1, 4),
M(2, 5),
M(3, 6)
in 2-d lattice M
sage: read_palp_point_collection(f) is None
True
```

# 2.5.7 Toric plotter

This module provides a helper class *ToricPlotter* for producing plots of objects related to toric geometry. Default plotting objects can be adjusted using *options()* and reset using *reset\_options()*.

#### **AUTHORS:**

• Andrey Novoseltsev (2010-10-03): initial version, using some code bits by Volker Braun.

#### **EXAMPLES:**

In most cases, this module is used indirectly, e.g.

You may change default plotting options as follows:

```
sage: toric_plotter.options("show_rays")
True
sage: toric_plotter.options(show_rays=False)
sage: toric_plotter.options("show_rays")
False
                                                                            # optional -_
sage: fan.plot() # optional - sage.plot
→palp
Graphics object consisting of 19 graphics primitives
sage: toric_plotter.reset_options()
sage: toric_plotter.options("show_rays")
True
sage: fan.plot() # optional - sage.plot
                                                                             # optional -_
→palp
Graphics object consisting of 31 graphics primitives
```

```
class sage.geometry.toric_plotter.ToricPlotter(all_options, dimension, generators=None)
    Bases: sage.structure.sage_object.SageObject
    Create a toric plotter.
    INPUT:
```

- all\_options a dictionary, containing any of the options related to toric objects (see *options()*) and any other options that will be passed to lower level plotting functions;
- dimension an integer (1, 2, or 3), dimension of toric objects to be plotted;
- generators (optional) a list of ray generators, see examples for a detailed explanation of this argument.

# **OUTPUT**:

a toric plotter.

#### **EXAMPLES:**

In most cases there is no need to create and use *ToricPlotter* directly. Instead, use plotting method of the object which you want to plot, e.g.

If you do want to create your own plotting function for some toric structure, the anticipated usage of toric plotters is the following:

- collect all necessary options in a dictionary;
- pass these options and dimension to *ToricPlotter*;
- call *include\_points()* on ray generators and any other points that you want to be present on the plot (it will try to set appropriate cut-off bounds);
- call adjust\_options() to choose "nice" default values for all options that were not set yet and ensure consistency of rectangular and spherical cut-off bounds;
- call set\_rays() on ray generators to scale them to the cut-off bounds of the plot;
- call appropriate plot\_\* functions to actually construct the plot.

For example, the plot from the previous example can be obtained as follows:

```
sage: from sage.geometry.toric_plotter import ToricPlotter
sage: options = dict() # use default for everything
sage: tp = ToricPlotter(options, fan.lattice().degree())
                                                                          # optional -
→ palp
sage: tp.include_points(fan.rays())
                                                                          # optional -
→ palp
sage: tp.adjust_options()
                                                                          # optional -
→ palp
sage: tp.set_rays(fan.rays())
                                                                          # optional -
→ palp
sage: result = tp.plot_lattice()
                                                                          # optional -
→ palp
sage: result += tp.plot_rays()
                                                                          # optional -
→ palp
sage: result += tp.plot_generators()
                                                                          # optional -
→ palp
```

In most situations it is only necessary to include generators of rays, in this case they can be passed to the constructor as an optional argument. In the example above, the toric plotter can be completely set up using

All options are exposed as attributes of toric plotters and can be modified after constructions, however you will have to manually call <code>adjust\_options()</code> and <code>set\_rays()</code> again if you decide to change the plotting mode and/or cut-off bounds. Otherwise plots maybe invalid.

#### adjust\_options()

Adjust plotting options.

This function determines appropriate default values for those options, that were not specified by the user, based on the other options. See *ToricPlotter* for a detailed example.

#### **OUTPUT**:

none.

# include\_points(points, force=False)

Try to include points into the bounding box of self.

# INPUT:

- points a list of points;
- force boolean (default: False). by default, only bounds that were not set before will be chosen to include points. Use force=True if you don't mind increasing existing bounding box.

#### **OUTPUT:**

· none.

# **EXAMPLES:**

```
sage: from sage.geometry.toric_plotter import ToricPlotter
sage: tp = ToricPlotter(dict(), 2)
sage: print(tp.radius)
None
sage: tp.include_points([(3, 4)])
sage: print(tp.radius)
5.5...
sage: tp.include_points([(5, 12)])
sage: print(tp.radius)
5.5...
sage: tp.include_points([(5, 12)], force=True)
sage: print(tp.radius)
13.5...
```

#### plot\_generators()

Plot ray generators.

Ray generators must be specified during construction or using set\_rays() before calling this method.

# **OUTPUT**:

• a plot.

# **EXAMPLES:**

```
sage: from sage.geometry.toric_plotter import ToricPlotter
sage: tp = ToricPlotter(dict(), 2, [(3,4)])
sage: tp.plot_generators()
Graphics object consisting of 1 graphics primitive
```

# plot\_labels(labels, positions)

Plot labels at specified positions.

# INPUT:

- labels a string or a list of strings;
- positions a list of points.

# OUTPUT:

• a plot.

#### **EXAMPLES:**

```
sage: from sage.geometry.toric_plotter import ToricPlotter
sage: tp = ToricPlotter(dict(), 2)
sage: tp.plot_labels("u", [(1.5,0)])
Graphics object consisting of 1 graphics primitive
```

# plot\_lattice()

Plot the lattice (i.e. its points in the cut-off bounds of self).

# OUTPUT:

• a plot.

#### **EXAMPLES:**

```
sage: from sage.geometry.toric_plotter import ToricPlotter
sage: tp = ToricPlotter(dict(), 2)
sage: tp.adjust_options()
sage: tp.plot_lattice()
Graphics object consisting of 1 graphics primitive
```

# plot\_points(points)

Plot given points.

# INPUT:

• points – a list of points.

# OUTPUT:

• a plot.

```
sage: from sage.geometry.toric_plotter import ToricPlotter
sage: tp = ToricPlotter(dict(), 2)
sage: tp.adjust_options()
sage: tp.plot_points([(1,0), (0,1)])
Graphics object consisting of 1 graphics primitive
```

# plot\_ray\_labels()

Plot ray labels.

Usually ray labels are plotted together with rays, but in some cases it is desirable to output them separately.

Ray generators must be specified during construction or using set\_rays() before calling this method.

#### **OUTPUT**:

• a plot.

## **EXAMPLES:**

```
sage: from sage.geometry.toric_plotter import ToricPlotter
sage: tp = ToricPlotter(dict(), 2, [(3,4)])
sage: tp.plot_ray_labels()
Graphics object consisting of 1 graphics primitive
```

## plot\_rays()

Plot rays and their labels.

Ray generators must be specified during construction or using set\_rays() before calling this method.

#### **OUTPUT**:

• a plot.

# **EXAMPLES:**

```
sage: from sage.geometry.toric_plotter import ToricPlotter
sage: tp = ToricPlotter(dict(), 2, [(3,4)])
sage: tp.plot_rays()
Graphics object consisting of 2 graphics primitives
```

# plot\_walls(walls)

Plot walls, i.e. 2-d cones, and their labels.

Ray generators must be specified during construction or using  $set\_rays()$  before calling this method and these specified ray generators will be used in conjunction with  $ambient\_ray\_indices()$  of walls.

# INPUT:

• walls – a list of 2-d cones.

#### **OUTPUT**:

• a plot.

```
sage: quadrant = Cone([(1,0), (0,1)])
sage: from sage.geometry.toric_plotter import ToricPlotter
sage: tp = ToricPlotter(dict(), 2, quadrant.rays())
sage: tp.plot_walls([quadrant])
Graphics object consisting of 2 graphics primitives
```

Let's also check that the truncating polyhedron is functioning correctly:

```
sage: tp = ToricPlotter({"mode": "box"}, 2, quadrant.rays())
sage: tp.plot_walls([quadrant])
Graphics object consisting of 2 graphics primitives
```

# set\_rays(generators)

Set up rays and their generators to be used by plotting functions.

As an alternative to using this method, you can pass generators to ToricPlotter constructor.

#### INPUT:

• generators - a list of primitive non-zero ray generators.

#### **OUTPUT**:

· none.

#### **EXAMPLES:**

```
sage: from sage.geometry.toric_plotter import ToricPlotter
sage: tp = ToricPlotter(dict(), 2)
sage: tp.adjust_options()
sage: tp.plot_rays()
Traceback (most recent call last):
...
AttributeError: 'ToricPlotter' object has no attribute 'rays'
sage: tp.set_rays([(0,1)])
sage: tp.plot_rays()
Graphics object consisting of 2 graphics primitives
```

# sage.geometry.toric\_plotter.color\_list(color, n)

Normalize a list of n colors.

# INPUT:

- color anything specifying a Color, a list of such specifications, or the string "rainbow";
- n an integer.

#### **OUTPUT**:

• a list of n colors.

If color specified a single color, it is repeated n times. If it was a list of n colors, it is returned without changes. If it was "rainbow", the rainbow of n colors is returned.

#### **EXAMPLES:**

```
sage: from sage.geometry.toric_plotter import color_list
sage: color_list("grey", 1)
[RGB color (0.5019607843137255, 0.5019607843137255, 0.5019607843137255)]
sage: len(color_list("grey", 3))
3
sage: L = color_list("rainbow", 3)
sage: L
[RGB color (1.0, 0.0, 0.0),
RGB color (0.0, 1.0, 0.0),
RGB color (0.0, 0.0, 1.0)]
```

```
sage: color_list(L, 3)
[RGB color (1.0, 0.0, 0.0),
RGB color (0.0, 1.0, 0.0),
RGB color (0.0, 0.0, 1.0)]
sage: color_list(L, 4)
Traceback (most recent call last):
...
ValueError: expected 4 colors, got 3!
```

sage.geometry.toric\_plotter.label\_list(label, n, math\_mode, index\_set=None)
Normalize a list of n labels.

## INPUT:

- label None, a string, or a list of string;
- n an integer;
- math\_mode boolean, if True, will produce LaTeX expressions for labels;
- index\_set a list of integers (default: range(n)) that will be used as subscripts for labels.

#### **OUTPUT:**

• a list of n labels.

If label was a list of n entries, it is returned without changes. If label is None, a list of n None's is returned. If label is a string, a list of strings of the form \$label\_{i}\$ is returned, where i ranges over index\_set. (If math\_mode=False, the form "label\_i" is used instead.) If n=1, there is no subscript added, unless index\_set was specified explicitly.

# **EXAMPLES:**

```
sage: from sage.geometry.toric_plotter import label_list
sage: label_list("u", 3, False)
['u_0', 'u_1', 'u_2']
sage: label_list("u", 3, True)
['$u_{0}$', '$u_{1}$', '$u_{2}$']
sage: label_list("u", 1, True)
['$u$']
```

sage.geometry.toric\_plotter.**options**(option=None, \*\*kwds)
Get or set options for plots of toric geometry objects.

**Note:** This function provides access to global default options. Any of these options can be overridden by passing them directly to plotting functions. See also *reset\_options()*.

# INPUT:

• None:

#### OR:

• option – a string, name of the option whose value you wish to get;

# OR:

• keyword arguments specifying new values for one or more options.

#### **OUTPUT:**

- if there was no input, the dictionary of current options for toric plots;
- if option argument was given, the current value of option;
- if other keyword arguments were given, none.

#### **Name Conventions**

To clearly distinguish parts of toric plots, in options and methods we use the following name conventions:

**Generator** A primitive integral vector generating a 1-dimensional cone, plotted as an arrow from the origin (or a line, if the head of the arrow is beyond cut-off bounds for the plot).

**Ray** A 1-dimensional cone, plotted as a line from the origin to the cut-off bounds for the plot.

**Wall** A 2-dimensional cone, plotted as a region between rays (in the above sense). Its exact shape depends on the plotting mode (see below).

**Chamber** A 3-dimensional cone, plotting is not implemented yet.

# **Plotting Modes**

A plotting mode mostly determines the shape of the cut-off region (which is always relevant for toric plots except for trivial objects consisting of the origin only). The following options are available:

**Box** The cut-off region is a box with edges parallel to coordinate axes.

Generators The cut-off region is determined by primitive integral generators of rays. Note that this notion is well-defined only for rays and walls, in particular you should plot the lattice on your own (plot\_lattice() will use box mode which is likely to be unsuitable). While this method may not be suitable for general fans, it is quite natural for fans of CPR-Fano toric varieties. <sage.schemes.toric.fano\_variety. CPRFanoToricVariety\_field

**Round** The cut-off regions is a sphere centered at the origin.

# **Available Options**

Default values for the following options can be set using this function:

- mode "box", "generators", or "round", see above for descriptions;
- show\_lattice boolean, whether to show lattice points in the cut-off region or not;
- show\_rays boolean, whether to show rays or not;
- show\_generators boolean, whether to show rays or not;
- show\_walls boolean, whether to show rays or not;
- generator\_color a color for generators;
- label\_color a color for labels;
- point\_color a color for lattice points;
- ray\_color a color for rays, a list of colors (one for each ray), or the string "rainbow";
- wall\_color a color for walls, a list of colors (one for each wall), or the string "rainbow";
- wall\_alpha a number between 0 and 1, the alpha-value for walls (determining their transparency);
- point\_size an integer, the size of lattice points;
- ray\_thickness an integer, the thickness of rays;
- generator\_thickness an integer, the thickness of generators;

- font\_size an integer, the size of font used for labels;
- ray\_label a string or a list of strings used for ray labels; use None to hide labels;
- wall\_label a string or a list of strings used for wall labels; use None to hide labels;
- radius a positive number, the radius of the cut-off region for "round" mode;
- xmin, xmax, ymin, ymax, zmin, zmax numbers determining the cut-off region for "box" mode. Note that you cannot exclude the origin if you try to do so, bounds will be automatically expanded to include it;
- lattice\_filter a callable, taking as an argument a lattice point and returning True if this point should be included on the plot (useful, e.g. for plotting sublattices);
- wall\_zorder, ray\_zorder, generator\_zorder, point\_zorder, label\_zorder integers, z-orders
  for different classes of objects. By default all values are negative, so that you can add other graphic objects
  on top of a toric plot. You may need to adjust these parameters if you want to put a toric plot on top of
  something else or if you want to overlap several toric plots.

You can see the current default value of any options by typing, e.g.

```
sage: toric_plotter.options("show_rays")
True
```

If the default value is None, it means that the actual default is determined later based on the known options. Note, that not all options can be determined in such a way, so you should not set options to None unless it was its original state. (You can always revert to this "original state" using reset\_options().)

# **EXAMPLES:**

The following line will make all subsequent toric plotting commands to draw "rainbows" from walls:

```
sage: toric_plotter.options(wall_color="rainbow")
```

If you prefer a less colorful output (e.g. if you need black-and-white illustrations for a paper), you can use something like this:

```
sage: toric_plotter.options(wall_color="grey")
```

sage.geometry.toric\_plotter.reset\_options()

Reset options for plots of toric geometry objects.

#### **OUTPUT**:

· none.

# **EXAMPLES:**

```
sage: toric_plotter.options("show_rays")
True
sage: toric_plotter.options(show_rays=False)
sage: toric_plotter.options("show_rays")
False
```

Now all toric plots will not show rays, unless explicitly requested. If you want to go back to "default defaults", use this method:

```
sage: toric_plotter.reset_options()
sage: toric_plotter.options("show_rays")
True
```

```
sage.geometry.toric_plotter.sector(ray1, ray2, **extra_options)
Plot a sector between ray1 and ray2 centered at the origin.
```

**Note:** This function was intended for plotting strictly convex cones, so it plots the smaller sector between ray1 and ray2 and, therefore, they cannot be opposite. If you do want to use this function for bigger regions, split them into several parts.

**Note:** As of version 4.6 Sage does not have a graphic primitive for sectors in 3-dimensional space, so this function will actually approximate them using polygons (the number of vertices used depends on the angle between rays).

#### INPUT:

- ray1, ray2 rays in 2- or 3-dimensional space of the same length;
- extra\_options a dictionary of options that should be passed to lower level plotting functions.

#### **OUTPUT:**

· a plot.

#### **EXAMPLES:**

```
sage: from sage.geometry.toric_plotter import sector
sage: sector((1,0), (0,1))
Graphics object consisting of 1 graphics primitive
sage: sector((3,2,1), (1,2,3))
Graphics3d Object
```

# 2.5.8 Groebner Fans

Sage provides much of the functionality of gfan, which is a software package whose main function is to enumerate all reduced Groebner bases of a polynomial ideal. The reduced Groebner bases yield the maximal cones in the Groebner fan of the ideal. Several subcomputations can be issued and additional tools are included. Among these the highlights are:

- Commands for computing tropical varieties.
- Interactive walks in the Groebner fan of an ideal.
- Commands for graphical renderings of Groebner fans and monomial ideals.

## **AUTHORS:**

- Anders Nedergaard Jensen: Wrote the gfan C++ program, which implements algorithms many of which were invented by Jensen, Komei Fukuda, and Rekha Thomas. All the underlying hard work of the Groebner fans functionality of Sage depends on this C++ program.
- William Stein (2006-04-20): Wrote first version of the Sage code for working with Groebner fans.
- Tristram Bogart: the design of the Sage interface to gfan is joint work with Tristram Bogart, who also supplied numerous examples.
- Marshall Hampton (2008-03-25): Rewrote various functions to use gfan-0.3. This is still a work in progress, comments are appreciated on sage-devel@googlegroups.com (or personally at hamptonio@gmail.com).

```
sage: x,y = QQ['x,y'].gens()
sage: i = ideal(x^2 - y^2 + 1)
sage: g = i.groebner_fan()
sage: g.reduced_groebner_bases()
[[x^2 - y^2 + 1], [-x^2 + y^2 - 1]]
```

#### REFERENCES:

• Anders N. Jensen; *Gfan, a software system for Groebner fans*; http://home.math.au.dk/jensen/software/gfan/gfan.html

```
Bases: sage.structure.sage_object.SageObject
```

This class is used to access capabilities of the program Gfan.

In addition to computing Groebner fans, Gfan can compute other things in tropical geometry such as tropical prevarieties.

#### INPUT:

- I ideal in a multivariate polynomial ring
- is\_groebner\_basis bool (default False). if True, then I.gens() must be a Groebner basis with respect to the standard degree lexicographic term order.
- symmetry default: None; if not None, describes symmetries of the ideal
- verbose default: False; if True, printout useful info during computations

## **EXAMPLES:**

```
sage: R.<x,y,z> = QQ[]
sage: I = R.ideal([x^2y - z, y^2z - x, z^2x - y])
sage: G = I.groebner_fan(); G
Groebner fan of the ideal:
Ideal (x^2y - z, y^2z - x, x^2z - y) of Multivariate Polynomial Ring in x, y, z_\(\text{\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\text{$\tex
```

Here is an example of the use of the tropical\_intersection command, and then using the RationalPolyhedralFan class to compute the Stanley-Reisner ideal of the tropical prevariety:

```
sage: R.<x,y,z> = QQ[]
sage: I = R.ideal([(x+y+z)^3-1,(x+y+z)^3-x,(x+y+z)-3])
sage: GF = I.groebner_fan()
sage: PF = GF.tropical_intersection()
sage: PF.rays()
[[-1, 0, 0], [0, -1, 0], [0, 0, -1], [1, 1, 1]]
sage: RPF = PF.to_RationalPolyhedralFan()
sage: RPF.Stanley_Reisner_ideal(PolynomialRing(QQ,4,'A, B, C, D'))
Ideal (A*B, A*C, B*C*D) of Multivariate Polynomial Ring in A, B, C, D over Rational_
→Field
```

## buchberger()

Return a lexicographic reduced Groebner basis for the ideal.

```
sage: R.<x,y,z> = PolynomialRing(QQ,3)
sage: G = R.ideal([x - z^3, y^2 - x + x^2 - z^3*x]).groebner_fan()
sage: G.buchberger()
[-z^3 + y^2, -z^3 + x]
```

#### characteristic()

Return the characteristic of the base ring.

#### **EXAMPLES:**

```
sage: R.<x,y,z> = PolynomialRing(QQ,3)
sage: i1 = ideal(x*z + 6*y*z - z^2, x*y + 6*x*z + y*z - z^2, y^2 + x*z + y*z)
sage: gf = i1.groebner_fan()
sage: gf.characteristic()
0
```

# dimension\_of\_homogeneity\_space()

Return the dimension of the homogeneity space.

#### **EXAMPLES:**

```
sage: R.<x,y> = PolynomialRing(QQ,2)
sage: G = R.ideal([y^3 - x^2, y^2 - 13*x]).groebner_fan()
sage: G.dimension_of_homogeneity_space()
0
```

# gfan(cmd='bases', I=None, format=None)

Return the gfan output as a string given an input cmd.

The default is to produce the list of reduced Groebner bases in gfan format.

#### INPUT:

- cmd string (default: 'bases'), GFan command
- I ideal (default:None)
- format bool (default:None), deprecated

#### **EXAMPLES:**

# homogeneity\_space()

Return the homogeneity space of a the list of polynomials that define this Groebner fan.

## **EXAMPLES:**

```
sage: R.<x,y> = PolynomialRing(QQ,2)
sage: G = R.ideal([y^3 - x^2, y^2 - 13*x]).groebner_fan()
sage: H = G.homogeneity_space()
```

# ideal()

Return the ideal the was used to define this Groebner fan.

# **EXAMPLES:**

```
sage: R.<x1,x2> = PolynomialRing(QQ,2)
sage: gf = R.ideal([x1^3-x2,x2^3-2*x1-2]).groebner_fan()
sage: gf.ideal()
Ideal (x1^3 - x2, x2^3 - 2*x1 - 2) of Multivariate Polynomial Ring in x1, x2

→over Rational Field
```

#### interactive(\*args, \*\*kwds)

See the documentation for self[0].interactive(). This does not work with the notebook.

#### **EXAMPLES:**

```
sage: print("This is not easily doc-testable; please write a good one!")
This is not easily doc-testable; please write a good one!
```

# maximal\_total\_degree\_of\_a\_groebner\_basis()

Return the maximal total degree of any Groebner basis.

#### **EXAMPLES:**

```
sage: R.<x,y> = PolynomialRing(QQ,2)
sage: G = R.ideal([y^3 - x^2, y^2 - 13*x]).groebner_fan()
sage: G.maximal_total_degree_of_a_groebner_basis()
4
```

# minimal\_total\_degree\_of\_a\_groebner\_basis()

Return the minimal total degree of any Groebner basis.

#### **EXAMPLES:**

```
sage: R.<x,y> = PolynomialRing(QQ,2)
sage: G = R.ideal([y^3 - x^2, y^2 - 13*x]).groebner_fan()
sage: G.minimal_total_degree_of_a_groebner_basis()
2
```

#### mixed volume()

Return the mixed volume of the generators of this ideal.

This is not really an ideal property, it can depend on the generators used.

The generators must give a square system (as many polynomials as variables).

```
sage: R.<x,y,z> = QQ[]
sage: example_ideal = R.ideal([x^2-y-1,y^2-z-1,z^2-x-1])
sage: gf = example_ideal.groebner_fan()
sage: mv = gf.mixed_volume()
sage: mv
8

sage: R2.<x,y> = QQ[]
sage: g1 = 1 - x + x^7*y^3 + 2*x^8*y^4
sage: g2 = 2 + y + 3*x^7*y^3 + x^8*y^4
sage: example2 = R2.ideal([g1,g2])
sage: example2.groebner_fan().mixed_volume()
15
```

#### number\_of\_reduced\_groebner\_bases()

Return the number of reduced Groebner bases.

**EXAMPLES:** 

```
sage: R.<x,y> = PolynomialRing(QQ,2)
sage: G = R.ideal([y^3 - x^2, y^2 - 13*x]).groebner_fan()
sage: G.number_of_reduced_groebner_bases()
3
```

#### number of variables()

Return the number of variables.

**EXAMPLES:** 

```
sage: R.<x,y> = PolynomialRing(QQ,2)
sage: G = R.ideal([y^3 - x^2, y^2 - 13*x]).groebner_fan()
sage: G.number_of_variables()
2
```

```
sage: R = PolynomialRing(QQ,'x',10)
sage: R.inject_variables(globals())
Defining x0, x1, x2, x3, x4, x5, x6, x7, x8, x9
sage: G = ideal([x0 - x9, sum(R.gens())]).groebner_fan()
sage: G.number_of_variables()
10
```

# polyhedralfan()

Return a polyhedral fan object corresponding to the reduced Groebner bases.

**EXAMPLES:** 

```
sage: R3.<x,y,z> = PolynomialRing(QQ,3)
sage: gf = R3.ideal([x^8-y^4,y^4-z^2,z^2-1]).groebner_fan()
sage: pf = gf.polyhedralfan()
sage: pf.rays()
[[0, 0, 1], [0, 1, 0], [1, 0, 0]]
```

# reduced\_groebner\_bases()

**EXAMPLES:** 

```
[y^4 - z^2, x - y^2*z, y^2*z^3 - y, y*z^4 - z, -y^3 + z^5],

[y^9 - z, y^6*z - y, x - y^2*z, -y^4 + z^2]]

sage: R3.<x,y,z> = PolynomialRing(GF(2477),3)

sage: gf = R3.ideal([300*x^3-y,y^2-z,z^2-12]).groebner_fan()

sage: gf.reduced_groebner_bases()

[[z^2 - 12, y^2 - z, x^3 + 933*y],

[y^4 - 12, x^3 + 933*y, -y^2 + z],

[x^6 - 1062*z, z^2 - 12, -300*x^3 + y],

[x^12 + 200, -300*x^3 + y, -828*x^6 + z]]
```

**render**(file=None, larger=False, shift=0, rgbcolor=(0, 0, 0), polyfill=<function max\_degree at 0x7fcb57611d30>, scale\_colors=True)

Render a Groebner fan as sage graphics or save as an xfig file.

More precisely, the output is a drawing of the Groebner fan intersected with a triangle. The corners of the triangle are (1,0,0) to the right, (0,1,0) to the left and (0,0,1) at the top. If there are more than three variables in the ring we extend these coordinates with zeros.

#### INPUT:

- file a filename if you prefer the output saved to a file. This will be in xfig format.
- shift shift the positions of the variables in the drawing. For example, with shift=1, the corners will be b (right), c (left), and d (top). The shifting is done modulo the number of variables in the polynomial ring. The default is 0.
- larger bool (default: False); if True, make the triangle larger so that the shape of the Groebner region appears. Affects the xfig file but probably not the sage graphics (?)
- rgbcolor This will not affect the saved xfig file, only the sage graphics produced.
- polyfill Whether or not to fill the cones with a color determined by the highest degree in each reduced Groebner basis for that cone.
- scale\_colors if True, this will normalize color values to try to maximize the range

## **EXAMPLES:**

```
sage: R.<x,y,z> = PolynomialRing(QQ,3)
sage: G = R.ideal([y^3 - x^2, y^2 - 13*x,z]).groebner_fan()
sage: test_render = G.render()
```

```
sage: R.<x,y,z> = PolynomialRing(QQ,3)
sage: G = R.ideal([x^2*y - z, y^2*z - x, z^2*x - y]).groebner_fan()
sage: test_render = G.render(larger=True)
```

#### render3d(verbose=False)

For a Groebner fan of an ideal in a ring with four variables, this function intersects the fan with the standard simplex perpendicular to (1,1,1,1), creating a 3d polytope, which is then projected into 3 dimensions. The edges of this projected polytope are returned as lines.

```
sage: R4.<w,x,y,z> = PolynomialRing(QQ,4)
sage: gf = R4.ideal([w^2-x,x^2-y,y^2-z,z^2-x]).groebner_fan()
sage: three_d = gf.render3d()
```

#### ring()

Return the multivariate polynomial ring.

#### **EXAMPLES:**

```
sage: R.<x1,x2> = PolynomialRing(QQ,2)
sage: gf = R.ideal([x1^3-x2,x2^3-x1-2]).groebner_fan()
sage: gf.ring()
Multivariate Polynomial Ring in x1, x2 over Rational Field
```

#### tropical\_basis(check=True, verbose=False)

Return a tropical basis for the tropical curve associated to this ideal.

# INPUT:

• check - bool (default: True); if True raises a ValueError exception if this ideal does not define a tropical curve (i.e., the condition that R/I has dimension equal to 1 + the dimension of the homogeneity space is not satisfied).

#### **EXAMPLES:**

```
sage: R.<x,y,z> = PolynomialRing(QQ,3, order='lex')
sage: G = R.ideal([y^3-3*x^2, z^3-x-y-2*y^3+2*x^2]).groebner_fan()
sage: G
Groebner fan of the ideal:
Ideal (-3*x^2 + y^3, 2*x^2 - x - 2*y^3 - y + z^3) of Multivariate Polynomial_
→Ring in x, y, z over Rational Field
sage: G.tropical_basis()
[-3*x^2 + y^3, 2*x^2 - x - 2*y^3 - y + z^3, 3/4*x + y^3 + 3/4*y - 3/4*z^3]
```

# tropical\_intersection(parameters=[], symmetry\_generators=[], \*args, \*\*kwds)

Return information about the tropical intersection of the polynomials defining the ideal.

This is the common refinement of the outward-pointing normal fans of the Newton polytopes of the generators of the ideal. Note that some people use the inward-pointing normal fans.

## INPUT:

- parameters (optional) a list of variables to be considered as parameters
- symmetry\_generators (optional) generators of the symmetry group

OUTPUT: a TropicalPrevariety object

## **EXAMPLES:**

```
sage: R.<x,y,z> = PolynomialRing(QQ,3)
sage: I = R.ideal(x*z + 6*y*z - z^2, x*y + 6*x*z + y*z - z^2, y^2 + x*z + y*z)
sage: gf = I.groebner_fan()
sage: pf = gf.tropical_intersection()
sage: pf.rays()
[[-2, 1, 1]]

sage: R.<x,y,z> = PolynomialRing(QQ,3)
sage: f1 = x*y*z - 1
sage: f2 = f1*(x^2 + y^2 + z^2)
sage: f3 = f2*(x + y + z - 1)
sage: I = R.ideal([f1,f2,f3])
sage: gf = I.groebner_fan()
```

```
sage: pf = gf.tropical_intersection(symmetry_generators = '(1,2,0),(1,0,2)')
sage: pf.rays()
[[-2, 1, 1], [1, -2, 1], [1, 1, -2]]

sage: R.<x,y,z> = QQ[]
sage: I = R.ideal([(x+y+z)^2-1,(x+y+z)-x,(x+y+z)-3])
sage: GF = I.groebner_fan()
sage: TI = GF.tropical_intersection()
sage: TI.rays()
[[-1, 0, 0], [0, -1, -1], [1, 1, 1]]
sage: GF = I.groebner_fan()
sage: TI = GF.tropical_intersection(parameters=[y])
sage: TI.rays()
[[-1, 0, 0]]
```

## weight\_vectors()

Return the weight vectors corresponding to the reduced Groebner bases.

#### **EXAMPLES:**

```
sage: r3.<x,y,z> = PolynomialRing(QQ,3)
sage: g = r3.ideal([x^3+y,y^3-z,z^2-x]).groebner_fan()
sage: g.weight_vectors()
[(3, 7, 1), (5, 1, 2), (7, 1, 4), (5, 1, 4), (1, 1, 1), (1, 4, 8), (1, 4, 10)]
sage: r4.<x,y,z,w> = PolynomialRing(QQ,4)
sage: g4 = r4.ideal([x^3+y,y^3-z,z^2-x,z^3 - w]).groebner_fan()
sage: len(g4.weight_vectors())
23
```

# class sage.rings.polynomial.groebner\_fan.InitialForm(cone, rays, initial\_forms)

Bases: sage.structure.sage\_object.SageObject

A system of initial forms from a polynomial system.

To each form is associated a cone and a list of polynomials (the initial form system itself).

This class is intended for internal use inside of the *TropicalPrevariety* class.

# **EXAMPLES:**

```
sage: from sage.rings.polynomial.groebner_fan import InitialForm
sage: R.<x,y> = QQ[]
sage: inform = InitialForm([0], [[-1, 0]], [y^2 - 1, y^2 - 2, y^2 - 3])
sage: inform._cone
[0]
```

## cone()

The cone associated with the initial form system.

# EXAMPLES:

```
sage: R.<x,y> = QQ[]
sage: I = R.ideal([(x+y)^2-1,(x+y)^2-2,(x+y)^2-3])
sage: GF = I.groebner_fan()
sage: PF = GF.tropical_intersection()
```

```
sage: pfi0 = PF.initial_form_systems()[0]
sage: pfi0.cone()
[0]
```

# initial\_forms()

The initial forms (polynomials).

#### **EXAMPLES:**

```
sage: R.<x,y> = QQ[]
sage: I = R.ideal([(x+y)^2-1,(x+y)^2-2,(x+y)^2-3])
sage: GF = I.groebner_fan()
sage: PF = GF.tropical_intersection()
sage: pfi0 = PF.initial_form_systems()[0]
sage: pfi0.initial_forms()
[y^2 - 1, y^2 - 2, y^2 - 3]
```

## internal\_ray()

A ray internal to the cone associated with the initial form system.

#### **EXAMPLES:**

```
sage: R.<x,y> = QQ[]
sage: I = R.ideal([(x+y)^2-1,(x+y)^2-2,(x+y)^2-3])
sage: GF = I.groebner_fan()
sage: PF = GF.tropical_intersection()
sage: pfi0 = PF.initial_form_systems()[0]
sage: pfi0.internal_ray()
(-1, 0)
```

# rays()

The rays of the cone associated with the initial form system.

## **EXAMPLES:**

```
sage: R.<x,y> = QQ[]
sage: I = R.ideal([(x+y)^2-1,(x+y)^2-2,(x+y)^2-3])
sage: GF = I.groebner_fan()
sage: PF = GF.tropical_intersection()
sage: pfi0 = PF.initial_form_systems()[0]
sage: pfi0.rays()
[[-1, 0]]
```

 $\begin{tabular}{ll} \textbf{class} & sage.rings.polynomial.groebner\_fan. \textbf{PolyhedralCone} ( \textit{gfan\_polyhedral\_cone}, \textit{ring=Rational} \\ & Field ) \end{tabular}$ 

```
Bases: sage.structure.sage_object.SageObject
```

Convert polymake/gfan data on a polyhedral cone into a sage class.

Currently (18-03-2008) needs a lot of work.

# **EXAMPLES:**

```
sage: R3.<x,y,z> = PolynomialRing(QQ,3)
sage: gf = R3.ideal([x^8-y^4,y^4-z^2,z^2-2]).groebner_fan()
sage: a = gf[0].groebner_cone()
```

```
sage: a.facets()
[[0, 0, 1], [0, 1, 0], [1, 0, 0]]
```

#### ambient\_dim()

Return the ambient dimension of the Groebner cone.

**EXAMPLES:** 

```
sage: R3.<x,y,z> = PolynomialRing(QQ,3)
sage: gf = R3.ideal([x^8-y^4,y^4-z^2,z^2-2]).groebner_fan()
sage: a = gf[0].groebner_cone()
sage: a.ambient_dim()
3
```

#### dim()

Return the dimension of the Groebner cone.

**EXAMPLES:** 

```
sage: R3.\langle x,y,z\rangle = PolynomialRing(QQ,3)
sage: gf = R3.ideal([x^8-y^4,y^4-z^2,z^2-2]).groebner_fan()
sage: a = gf[0].groebner_cone()
sage: a.dim()
3
```

#### facets()

Return the inward facet normals of the Groebner cone.

**EXAMPLES:** 

```
sage: R3.\langle x,y,z\rangle = PolynomialRing(QQ,3)
sage: gf = R3.ideal([x^8-y^4,y^4-z^2,z^2-2]).groebner_fan()
sage: a = gf[0].groebner_cone()
sage: a.facets()
[[0, 0, 1], [0, 1, 0], [1, 0, 0]]
```

# lineality\_dim()

Return the lineality dimension of the Groebner cone. This is just the difference between the ambient dimension and the dimension of the cone.

**EXAMPLES:** 

```
sage: R3.\langle x,y,z\rangle = PolynomialRing(QQ,3)
sage: gf = R3.ideal([x^8-y^4,y^4-z^2,z^2-2]).groebner_fan()
sage: a = gf[0].groebner_cone()
sage: a.lineality_dim()
```

# relative\_interior\_point()

Return a point in the relative interior of the Groebner cone.

**EXAMPLES:** 

```
sage: R3.\langle x, y, z \rangle = PolynomialRing(QQ,3)
sage: gf = R3.ideal([x^8-y^4,y^4-z^2,z^2-2]).groebner_fan()
```

```
sage: a = gf[0].groebner_cone()
sage: a.relative_interior_point()
[1, 1, 1]
```

 $\textbf{class} \ \, \textbf{sage.rings.polynomial.groebner\_fan.PolyhedralFan} (\textit{gfan\_polyhedral\_fan}, \\$ 

```
parameter_indices=None)
```

Bases: sage.structure.sage\_object.SageObject

Convert polymake/gfan data on a polyhedral fan into a sage class.

## INPUT:

• gfan\_polyhedral\_fan - output from gfan of a polyhedral fan.

# **EXAMPLES:**

```
sage: R.<x,y,z> = PolynomialRing(QQ,3)
sage: i2 = ideal(x*z + 6*y*z - z^2, x*y + 6*x*z + y*z - z^2, y^2 + x*z + y*z)
sage: gf2 = i2.groebner_fan(verbose=False)
sage: pf = gf2.polyhedralfan()
sage: pf.rays()
[[-1, 0, 1], [-1, 1, 0], [1, -2, 1], [1, 1, -2], [2, -1, -1]]
```

#### ambient\_dim()

Return the ambient dimension of the Groebner fan.

#### **EXAMPLES:**

```
sage: R3.<x,y,z> = PolynomialRing(QQ,3)
sage: gf = R3.ideal([x^8-y^4,y^4-z^2,z^2-2]).groebner_fan()
sage: a = gf.polyhedralfan()
sage: a.ambient_dim()
3
```

# cones()

A dictionary of cones in which the keys are the cone dimensions. For each dimension, the value is a list of the cones, where each element consists of a list of ray indices.

# **EXAMPLES:**

```
sage: R.<x,y,z> = QQ[]
sage: f = 1+x+y+x*y
sage: I = R.ideal([f+z*f, 2*f+z*f, 3*f+z^2*f])
sage: GF = I.groebner_fan()
sage: PF = GF.tropical_intersection()
sage: PF.cones()
{1: [[0], [1], [2], [3], [4], [5]], 2: [[0, 1], [0, 2], [0, 3], [0, 4], [1, 2],
\rightarrow [1, 3], [2, 4], [3, 4], [1, 5], [2, 5], [3, 5], [4, 5]]}
```

# dim()

Return the dimension of the Groebner fan.

# **EXAMPLES:**

```
sage: R3.<x,y,z> = PolynomialRing(QQ,3)
sage: gf = R3.ideal([x^8-y^4,y^4-z^2,z^2-2]).groebner_fan()
(centinues on payt page)
```

```
sage: a = gf.polyhedralfan()
sage: a.dim()
3
```

# f\_vector()

The f-vector of the fan.

#### **EXAMPLES:**

```
sage: R.<x,y,z> = QQ[]
sage: f = 1+x+y+x*y
sage: I = R.ideal([f+z*f, 2*f+z*f, 3*f+z^2*f])
sage: GF = I.groebner_fan()
sage: PF = GF.tropical_intersection()
sage: PF.f_vector()
[1, 6, 12]
```

## is\_simplicial()

Whether the fan is simplicial or not.

#### **EXAMPLES:**

```
sage: R.<x,y,z> = QQ[]
sage: f = 1+x+y+x*y
sage: I = R.ideal([f+z*f, 2*f+z*f, 3*f+z^2*f])
sage: GF = I.groebner_fan()
sage: PF = GF.tropical_intersection()
sage: PF.is_simplicial()
True
```

# lineality\_dim()

Return the lineality dimension of the fan. This is the dimension of the largest subspace contained in the fan.

# **EXAMPLES:**

```
sage: R3.<x,y,z> = PolynomialRing(QQ,3)
sage: gf = R3.ideal([x^8-y^4,y^4-z^2,z^2-2]).groebner_fan()
sage: a = gf.polyhedralfan()
sage: a.lineality_dim()
0
```

## maximal\_cones()

A dictionary of the maximal cones in which the keys are the cone dimensions. For each dimension, the value is a list of the maximal cones, where each element consists of a list of ray indices.

#### **EXAMPLES:**

2.5. Toric geometry

# rays()

A list of rays of the polyhedral fan.

#### **EXAMPLES:**

```
sage: R.<x,y,z> = PolynomialRing(QQ,3)
sage: i2 = ideal(x*z + 6*y*z - z^2, x*y + 6*x*z + y*z - z^2, y^2 + x*z + y*z)
sage: gf2 = i2.groebner_fan(verbose=False)
sage: pf = gf2.polyhedralfan()
sage: pf.rays()
[[-1, 0, 1], [-1, 1, 0], [1, -2, 1], [1, 1, -2], [2, -1, -1]]
```

## to\_RationalPolyhedralFan()

Converts to the RationalPolyhedralFan class, which is more actively maintained. While the information in each class is essentially the same, the methods and implementation are different.

#### **EXAMPLES:**

Here we use the RationalPolyhedralFan's Gale\_transform method on a tropical prevariety.

```
sage: fan.Gale_transform()
[ 1  0  0  0  0  1  -2]
[ 0  1  0  0  1  0  -2]
[ 0  0  1  1  0  0  -2]
```

class sage.rings.polynomial.groebner\_fan.ReducedGroebnerBasis(groebner\_fan, gens, gfan\_gens)

```
Bases: sage.structure.sage_object.SageObject, list
```

A class for representing reduced Groebner bases as produced by gfan.

#### INPUT:

- groebner\_fan a GroebnerFan object from an ideal
- · gens the generators of the ideal
- gfan\_gens the generators as a gfan string

# EXAMPLES:

```
sage: R.<a,b> = PolynomialRing(QQ,2)
sage: gf = R.ideal([a^2-b^2,b-a-1]).groebner_fan()
```

```
sage: from sage.rings.polynomial.groebner_fan import ReducedGroebnerBasis
sage: ReducedGroebnerBasis(gf,gf[0],gf[0]._gfan_gens())
[b - 1/2, a + 1/2]
```

#### groebner\_cone(restrict=False)

Return defining inequalities for the full-dimensional Groebner cone associated to this marked minimal reduced Groebner basis.

#### INPUT:

• restrict - bool (default: False); if True, add an inequality for each coordinate, so that the cone is restricted to the positive orthant.

OUTPUT: tuple of integer vectors

#### **EXAMPLES:**

```
sage: R.<x,y> = PolynomialRing(QQ,2)
sage: G = R.ideal([y^3 - x^2, y^2 - 13*x]).groebner_fan()
sage: poly_cone = G[1].groebner_cone()
sage: poly_cone.facets()
[[-1, 2], [1, -1]]
sage: [g.groebner_cone().facets() for g in G]
[[[0, 1], [1, -2]], [[-1, 2], [1, -1]], [[-1, 1], [1, 0]]]
sage: G[1].groebner_cone(restrict=True).facets()
[[-1, 2], [1, -1]]
```

#### ideal()

Return the ideal generated by this basis.

## **EXAMPLES:**

**interactive**(*latex=False*, *flippable=False*, *wall=False*, *inequalities=False*, *weight=False*)

Do an interactive walk of the Groebner fan starting at this reduced Groebner basis.

## **EXAMPLES:**

Bases: sage.rings.polynomial.groebner\_fan.PolyhedralFan

This class is a subclass of the PolyhedralFan class, with some additional methods for tropical prevarieties.

#### INPUT:

- gfan\_polyhedral\_fan output from gfan of a polyhedral fan.
- polynomial\_system a list of polynomials
- poly\_ring the polynomial ring of the list of polynomials
- parameters (optional) a list of variables to be considered as parameters

#### **EXAMPLES:**

```
sage: R.<x,y,z> = QQ[]
sage: I = R.ideal([(x+y+z)^2-1,(x+y+z)-x,(x+y+z)-3])
sage: GF = I.groebner_fan()
sage: TI = GF.tropical_intersection()
sage: TI._polynomial_system
[x^2 + 2*x*y + y^2 + 2*x*z + 2*y*z + z^2 - 1, y + z, x + y + z - 3]
```

## initial\_form\_systems()

Return a list of systems of initial forms for each cone in the tropical prevariety.

#### **EXAMPLES:**

```
sage: R.<x,y> = QQ[]
sage: I = R.ideal([(x+y)^2-1,(x+y)^2-2,(x+y)^2-3])
sage: GF = I.groebner_fan()
sage: PF = GF.tropical_intersection()
sage: pfi = PF.initial_form_systems()
sage: for q in pfi:
...:     print(q.initial_forms())
[y^2 - 1, y^2 - 2, y^2 - 3]
[x^2 - 1, x^2 - 2, x^2 - 3]
[x^2 + 2*x*y + y^2, x^2 + 2*x*y + y^2, x^2 + 2*x*y + y^2]
```

sage.rings.polynomial.groebner\_fan.ideal\_to\_gfan\_format(input\_ring, polys)
Return the ideal in gfan's notation.

#### **EXAMPLES:**

```
sage: R.<x,y,z> = PolynomialRing(QQ,3)
sage: polys = [x^2*y - z, y^2*z - x, z^2*x - y]
sage: from sage.rings.polynomial.groebner_fan import ideal_to_gfan_format
sage: ideal_to_gfan_format(R, polys)
'Q[x, y, z]{x^2*y-z,y^2*z-x,x*z^2-y}'
```

sage.rings.polynomial.groebner\_fan.max\_degree(list\_of\_polys)

Compute the maximum degree of a list of polynomials

```
sage: from sage.rings.polynomial.groebner_fan import max_degree
sage: R.<x,y> = PolynomialRing(QQ,2)
sage: p_list = [x^2-y,x*y^10-x]
sage: max_degree(p_list)
11.0
```

```
sage.rings.polynomial.groebner_fan.prefix_check(str_list)
```

Check if any strings in a list are prefixes of another string in the list.

#### **EXAMPLES:**

```
sage: from sage.rings.polynomial.groebner_fan import prefix_check
sage: prefix_check(['z1','z1z1'])
False
sage: prefix_check(['z1','zz1'])
True
```

sage.rings.polynomial.groebner\_fan.ring\_to\_gfan\_format(input\_ring)

Converts a ring to gfan's format.

#### **EXAMPLES:**

```
sage: R.<w,x,y,z> = QQ[]
sage: from sage.rings.polynomial.groebner_fan import ring_to_gfan_format
sage: ring_to_gfan_format(R)
'Q[w, x, y, z]'
sage: R2.<x,y> = GF(2)[]
sage: ring_to_gfan_format(R2)
'Z/2Z[x, y]'
```

sage.rings.polynomial.groebner\_fan.verts\_for\_normal(normal, poly)

Return the exponents of the vertices of a Newton polytope that make up the supporting hyperplane for the given outward normal.

#### **EXAMPLES:**

```
sage: from sage.rings.polynomial.groebner_fan import verts_for_normal
sage: R.<x,y,z> = PolynomialRing(QQ,3)
sage: f1 = x*y*z - 1
sage: f2 = f1*(x^2 + y^2 + 1)
sage: verts_for_normal([1,1,1],f2)
[(3, 1, 1), (1, 3, 1)]
```

# 2.6 Base classes for polyhedra

# 2.6.1 Base class for polyhedra: Initialization and access to Vrepresentation and Hrepresentation

Bases: sage.structure.element.Element, sage.geometry.abc.Polyhedron

Initialization and basic access for polyhedra.

See sage.geometry.polyhedron.base.Polyhedron\_base.

# Hrep\_generator()

Return an iterator over the objects of the H-representation (inequalities or equations).

```
sage: p = polytopes.hypercube(3)
sage: next(p.Hrep_generator())
An inequality (-1, 0, 0) x + 1 >= 0
```

#### Hrepresentation(index=None)

Return the objects of the H-representation. Each entry is either an inequality or a equation.

#### INPUT:

• index - either an integer or None

#### **OUTPUT**:

The optional argument is an index running from 0 to self.n\_Hrepresentation()-1. If present, the H-representation object at the given index will be returned. Without an argument, returns the list of all H-representation objects.

## **EXAMPLES:**

```
sage: p = polytopes.hypercube(3, backend='field')
sage: p.Hrepresentation(0)
An inequality (-1, 0, 0) x + 1 >= 0
sage: p.Hrepresentation(0) == p.Hrepresentation()[0]
True
```

# **Hrepresentation\_str**( $separator = \n'$ , latex = False, style = '>=', align = None, \*\*kwds)

Return a human-readable string representation of the Hrepresentation of this polyhedron.

#### INPUT:

- separator a string. Default is "\n".
- latex a boolean. Default is False.
- style either "positive" (making all coefficients positive) or "<=", or ">=". Default is ">=".
- align a boolean or None'. Default is ``None in which case align is True if separator is the newline character. If set, then the lines of the output string are aligned by the comparison symbol by padding blanks.

Keyword parameters of *repr\_pretty()* are passed on:

- prefix a string
- indices a tuple or other iterable

## **OUTPUT**:

A string.

#### **EXAMPLES:**

```
sage: P = polytopes.permutahedron(3)
sage: print(P.Hrepresentation_str())
x0 + x1 + x2 == 6
    x0 + x1 >= 3
    -x0 - x1 >= -5
        x1 >= 1
        -x0 >= -3
        x0 >= 1
        -x1 >= -3
```

```
sage: print(P.Hrepresentation_str(style='<='))</pre>
-x0 - x1 - x2 == -6
    -x0 - x1 <= -3
     x0 + x1 <= 5
         -x1 <= -1
          x0 <= 3
         -x0 <= -1
          x1 <= 3
sage: print(P.Hrepresentation_str(style='positive'))
x0 + x1 + x2 == 6
    x0 + x1 >= 3
          5 >= x0 + x1
         x1 >= 1
          3 >= x0
         x0 >= 1
           3 >= x1
sage: print(P.Hrepresentation_str(latex=True))
\begin{array}{rcl}
                            & 6 \\
x_{0} + x_{1} + x_{2} = 
       x_{0} + x_{1} & geq & 3 \
       -x_{0} - x_{1} & geq & -5 \
               x_{1} & geq & 1 \
              -x_{0} & \gcd & -3 \
               x_{0} & geq & 1 \
               -x_{1} & \gcd & -3
\end{array}
sage: print(P.Hrepresentation_str(align=False))
x0 + x1 + x2 == 6
x0 + x1 >= 3
-x0 - x1 > = -5
x1 >= 1
-x0 >= -3
x0 >= 1
-x1 > = -3
sage: c = polytopes.cube()
sage: c.Hrepresentation_str(separator=', ', style='positive')
'1 >= x0, 1 >= x1, 1 >= x2, 1 + x0 >= 0, 1 + x2 >= 0, 1 + x1 >= 0'
```

# Vrep\_generator()

Return an iterator over the objects of the V-representation (vertices, rays, and lines).

# **EXAMPLES:**

```
sage: p = polytopes.cyclic_polytope(3,4)
sage: vg = p.Vrep_generator()
sage: next(vg)
A vertex at (0, 0, 0)
sage: next(vg)
```

```
A vertex at (1, 1, 1)
```

# Vrepresentation(index=None)

Return the objects of the V-representation. Each entry is either a vertex, a ray, or a line.

See sage.geometry.polyhedron.constructor for a definition of vertex/ray/line.

# INPUT:

• index – either an integer or None

#### **OUTPUT:**

The optional argument is an index running from 0 to self.n\_Vrepresentation()-1. If present, the V-representation object at the given index will be returned. Without an argument, returns the list of all V-representation objects.

#### **EXAMPLES:**

```
sage: p = polytopes.simplex(4, project=True)
sage: p.Vrepresentation(0)
A vertex at (0.7071067812, 0.4082482905, 0.2886751346, 0.2236067977)
sage: p.Vrepresentation(0) == p.Vrepresentation() [0]
True
```

#### backend()

Return the backend used.

#### **OUTPUT**:

The name of the backend used for computations. It will be one of the following backends:

- ppl the Parma Polyhedra Library
- cdd CDD
- normaliz normaliz
- polymake polymake
- field a generic Sage implementation

# **EXAMPLES:**

```
sage: triangle = Polyhedron(vertices = [[1, 0], [0, 1], [1, 1]])
sage: triangle.backend()
'ppl'
sage: D = polytopes.dodecahedron()  # optional - sage.rings.number_field
sage: D.backend()  # optional - sage.rings.number_field
'field'
sage: P = Polyhedron([[1.23]])
sage: P.backend()
'cdd'
```

# base\_extend(base\_ring, backend=None)

Return a new polyhedron over a larger base ring.

This method can also be used to change the backend.

# INPUT:

• base\_ring - the new base ring

• backend – the new backend, see *Polyhedron()*. If None (the default), attempt to keep the same backend. Otherwise, use the same defaulting behavior as described there.

#### **OUTPUT:**

The same polyhedron, but over a larger base ring and possibly with a changed backend.

#### **EXAMPLES:**

## base\_ring()

Return the base ring.

#### **OUTPUT**:

The ring over which the polyhedron is defined. Must be a sub-ring of the reals to define a polyhedron, in particular comparison must be defined. Popular choices are

- ZZ (the ring of integers, lattice polytope),
- QQ (exact arithmetic using gmp),
- RDF (double precision floating-point arithmetic), or
- AA (real algebraic field).

## **EXAMPLES:**

```
sage: triangle = Polyhedron(vertices = [[1,0],[0,1],[1,1]])
sage: triangle.base_ring() == ZZ
True
```

## cdd\_Hrepresentation()

Write the inequalities/equations data of the polyhedron in cdd's H-representation format.

## See also:

write\_cdd\_Hrepresentation() - export the polyhedron as a H-representation to a file.

**OUTPUT**: a string

## **EXAMPLES:**

```
sage: p = polytopes.hypercube(2)
sage: print(p.cdd_Hrepresentation())
H-representation
begin
4 3 rational
1 -1 0
1 0 -1
1 1 0
1 0 1
end
```

## cdd\_Vrepresentation()

Write the vertices/rays/lines data of the polyhedron in cdd's V-representation format.

#### See also:

write\_cdd\_Vrepresentation() - export the polyhedron as a V-representation to a file.

**OUTPUT**: a string

#### **EXAMPLES:**

```
sage: q = Polyhedron(vertices = [[1,1],[0,0],[1,0],[0,1]])
sage: print(q.cdd_Vrepresentation())
V-representation
begin
4 3 rational
1 0 0
1 0 1
1 1 0
1 1 1 end
```

#### **change\_ring**(base\_ring, backend=None)

Return the polyhedron obtained by coercing the entries of the vertices/lines/rays of this polyhedron into the given ring.

This method can also be used to change the backend.

## INPUT:

- base\_ring the new base ring
- backend the new backend or None (default), see *Polyhedron()*. If None (the default), attempt to keep the same backend. Otherwise, use the same defaulting behavior as described there.

#### **EXAMPLES:**

```
True
sage: P = Polyhedron(vertices=[(-1.3,0), (0,2.3)], base_ring=RDF); P.vertices()
(A vertex at (-1.3, 0.0), A vertex at (0.0, 2.3))
sage: P.change_ring(QQ).vertices()
(A vertex at (-13/10, 0), A vertex at (0, 23/10))
sage: P == P.change_ring(QQ)
True
sage: P.change_ring(ZZ)
Traceback (most recent call last):
TypeError: cannot change the base ring to the Integer Ring
sage: P = polytopes.regular_polygon(3); P
                                                                     # optional -
→ sage.rings.number_field
A 2-dimensional polyhedron in AA^2 defined as the convex hull of 3 vertices
sage: P.vertices()
                                                                     # optional -
→ sage.rings.number_field
(A vertex at (0.?e-16, 1.000000000000000),
A vertex at (0.866025403784439?, -0.5000000000000000),
A vertex at (-0.866025403784439?, -0.5000000000000000))
sage: P.change_ring(QQ)
                                                                     # optional -
→ sage.rings.number_field
Traceback (most recent call last):
TypeError: cannot change the base ring to the Rational Field
```

**Warning:** The base ring RDF should be used with care. As it is not an exact ring, certain computations may break or silently produce wrong results, for example changing the base ring from an exact ring into RDF may cause a loss of data:

```
sage: P = Polyhedron([[2/3,0],[6666666666666667/10^16,0]], base_ring=AA); P

→ # optional - sage.rings.number_field
A 1-dimensional polyhedron in AA^2 defined as the convex hull of 2 vertices
sage: Q = P.change_ring(RDF); Q  # optional -

→ sage.rings.number_field
A 0-dimensional polyhedron in RDF^2 defined as the convex hull of 1 vertex
sage: P.n_vertices() == Q.n_vertices()  # optional -

→ sage.rings.number_field
False
```

## equation\_generator()

Return a generator for the linear equations satisfied by the polyhedron.

#### **EXAMPLES:**

```
sage: p = polytopes.regular_polygon(8,base_ring=RDF)
sage: p3 = Polyhedron(vertices = [x+[0] for x in p.vertices()], base_ring=RDF)
sage: next(p3.equation_generator())
An equation (0.0, 0.0, 1.0) x + 0.0 == 0
```

#### equations()

Return all linear constraints of the polyhedron.

**OUTPUT**:

A tuple of equations.

**EXAMPLES**:

```
sage: test_p = Polyhedron(vertices = [[1,2,3,4],[2,1,3,4],[4,3,2,1],[3,4,1,2]])
sage: test_p.equations()
(An equation (1, 1, 1, 1) x - 10 == 0,)
```

## equations\_list()

Return the linear constraints of the polyhedron. As with inequalities, each constraint is given as [b-a1-a2...an] where for variables x1, x2,..., xn, the polyhedron satisfies the equation b = a1\*x1 + a2\*x2 + ... + an\*xn.

**Note:** It is recommended to use *equations()* or *equation\_generator()* instead to iterate over the list of *Equation* objects.

#### **EXAMPLES:**

```
sage: test_p = Polyhedron(vertices = [[1,2,3,4],[2,1,3,4],[4,3,2,1],[3,4,1,2]])
sage: test_p.equations_list()
[[-10, 1, 1, 1, 1]]
```

## inequalities()

Return all inequalities.

OUTPUT:

A tuple of inequalities.

**EXAMPLES:** 

```
sage: p = Polyhedron(vertices = [[0,0,0],[0,0,1],[0,1,0],[1,0,0],[2,2,2]])
sage: p.inequalities()[0:3]
(An inequality (1, 0, 0) x + 0 \ge 0,
An inequality (0, 1, 0) \times + 0 >= 0,
An inequality (0, 0, 1) \times + 0 >= 0
sage: p3 = Polyhedron(vertices=Permutations([1, 2, 3, 4]))
                                                                       # optional -
→ sage.combinat
sage: ieqs = p3.inequalities()
                                                                       # optional -
→ sage.combinat
sage: ieqs[0]
                                                                       # optional -
→ sage.combinat
An inequality (0, 1, 1, 1) \times -6 >= 0
sage: list(_)
                                                                       # optional -
→ sage.combinat
[-6, 0, 1, 1, 1]
```

# inequalities\_list()

Return a list of inequalities as coefficient lists.

**Note:** It is recommended to use *inequalities()* or *inequality\_generator()* instead to iterate over the list of *Inequality* objects.

#### **EXAMPLES:**

```
sage: p = Polyhedron(vertices = [[0,0,0],[0,0,1],[0,1,0],[1,0,0],[2,2,2]])
sage: p.inequalities_list()[0:3]
[[0, 1, 0, 0], [0, 0, 1, 0], [0, 0, 0, 1]]
sage: p3 = Polyhedron(vertices=Permutations([1, 2, 3, 4]))
                                                                     # optional -
→ sage.combinat
sage: ieqs = p3.inequalities_list()
                                                                     # optional -
→ sage.combinat
sage: ieqs[0]
                                                                     # optional -
→ sage.combinat
[-6, 0, 1, 1, 1]
sage: ieqs[-1]
                                                                     # optional -
→ sage.combinat
[-3, 0, 1, 0, 1]
sage: ieqs == [list(x) for x in p3.inequality_generator()]
                                                                     # optional -
→ sage.combinat
True
```

#### inequality\_generator()

Return a generator for the defining inequalities of the polyhedron.

#### **OUTPUT**:

A generator of the inequality Hrepresentation objects.

## **EXAMPLES:**

```
sage: triangle = Polyhedron(vertices=[[1,0],[0,1],[1,1]])
sage: for v in triangle.inequality_generator(): print(v)
An inequality (1, 1) x - 1 >= 0
An inequality (0, -1) x + 1 >= 0
An inequality (-1, 0) x + 1 >= 0
sage: [ v for v in triangle.inequality_generator() ]
[An inequality (1, 1) x - 1 >= 0,
   An inequality (0, -1) x + 1 >= 0,
   An inequality (-1, 0) x + 1 >= 0]
sage: [ [v.A(), v.b()] for v in triangle.inequality_generator() ]
[[(1, 1), -1], [(0, -1), 1], [(-1, 0), 1]]
```

#### is\_compact()

Test for boundedness of the polytope.

## **EXAMPLES:**

```
sage: p = Polyhedron(ieqs = [[0,1,0,0],[0,0,1,0],[0,0,0,1],[1,-1,0,0]])
sage: p.is_compact()
False
```

## is\_immutable()

Return True if the polyhedron is immutable, i.e. it cannot be modified in place.

**EXAMPLES**:

```
sage: p = polytopes.cube(backend='field')
sage: p.is_immutable()
True
```

#### is\_mutable()

Return True if the polyhedron is mutable, i.e. it can be modified in place.

**EXAMPLES**:

```
sage: p = polytopes.cube(backend='field')
sage: p.is_mutable()
False
```

## line\_generator()

Return a generator for the lines of the polyhedron.

**EXAMPLES:** 

```
sage: pr = Polyhedron(rays = [[1,0],[-1,0],[0,1]], vertices = [[-1,-1]])
sage: next(pr.line_generator()).vector()
(1, 0)
```

#### lines()

Return all lines of the polyhedron.

**OUTPUT**:

A tuple of lines.

**EXAMPLES:** 

## lines\_list()

Return a list of lines of the polyhedron. The line data is given as a list of coordinates rather than as a Hrepresentation object.

**Note:** It is recommended to use *line\_generator()* instead to iterate over the list of *Line* objects.

**EXAMPLES:** 

#### n\_Hrepresentation()

Return the number of objects that make up the H-representation of the polyhedron.

**OUTPUT**:

Integer.

**EXAMPLES:** 

```
sage: p = polytopes.cross_polytope(4)
sage: p.n_Hrepresentation()
16
sage: p.n_Hrepresentation() == p.n_inequalities() + p.n_equations()
True
```

#### n\_Vrepresentation()

Return the number of objects that make up the V-representation of the polyhedron.

**OUTPUT**:

Integer.

**EXAMPLES:** 

```
sage: p = polytopes.simplex(4)
sage: p.n_Vrepresentation()
5
sage: p.n_Vrepresentation() == p.n_vertices() + p.n_rays() + p.n_lines()
True
```

## n\_equations()

Return the number of equations. The representation will always be minimal, so the number of equations is the codimension of the polyhedron in the ambient space.

**EXAMPLES:** 

```
sage: p = Polyhedron(vertices = [[1,0,0],[0,1,0],[0,0,1]])
sage: p.n_equations()
1
```

# n\_facets()

Return the number of inequalities. The representation will always be minimal, so the number of inequalities is the number of facets of the polyhedron in the ambient space.

**EXAMPLES:** 

```
sage: p = Polyhedron(vertices = [[1,0,0],[0,1,0],[0,0,1]])
sage: p.n_inequalities()
3
```

```
sage: p = Polyhedron(vertices = [[t,t^2,t^3] for t in range(6)])
sage: p.n_facets()
8
```

#### n\_inequalities()

Return the number of inequalities. The representation will always be minimal, so the number of inequalities is the number of facets of the polyhedron in the ambient space.

**EXAMPLES**:

```
sage: p = Polyhedron(vertices = [[1,0,0],[0,1,0],[0,0,1]])
sage: p.n_inequalities()
3

sage: p = Polyhedron(vertices = [[t,t^2,t^3] for t in range(6)])
sage: p.n_facets()
8
```

#### n\_lines()

Return the number of lines. The representation will always be minimal.

**EXAMPLES:** 

```
sage: p = Polyhedron(vertices = [[0,0]], rays=[[0,1],[0,-1]])
sage: p.n_lines()
1
```

# n\_rays()

Return the number of rays. The representation will always be minimal.

EXAMPLES:

```
sage: p = Polyhedron(vertices = [[1,0],[0,1]], rays=[[1,1]])
sage: p.n_rays()
1
```

#### n\_vertices()

Return the number of vertices. The representation will always be minimal.

**Warning:** If the polyhedron has lines, return the number of vertices in the Vrepresentation. As the represented polyhedron has no 0-dimensional faces (i.e. vertices),  $n_{vertices}$  corresponds to the number of k-faces, where k is the number of lines:

```
sage: P = Polyhedron(rays=[[1,0,0]],lines=[[0,1,0]])
sage: P.n_vertices()
1
sage: P.faces(0)
()
sage: P.f_vector()
(1, 0, 1, 1)

sage: P = Polyhedron(rays=[[1,0,0]],lines=[[0,1,0],[0,1,1]])
sage: P.n_vertices()
1
```

```
sage: P.f_vector()
(1, 0, 0, 1, 1)
```

## **EXAMPLES:**

```
sage: p = Polyhedron(vertices = [[1,0],[0,1],[1,1]], rays=[[1,1]])
sage: p.n_vertices()
2
```

## ray\_generator()

Return a generator for the rays of the polyhedron.

**EXAMPLES:** 

```
sage: pi = Polyhedron(ieqs = [[1,1,0],[1,0,1]])
sage: pir = pi.ray_generator()
sage: [x.vector() for x in pir]
[(1, 0), (0, 1)]
```

#### rays()

Return a list of rays of the polyhedron.

**OUTPUT**:

A tuple of rays.

**EXAMPLES:** 

```
sage: p = Polyhedron(ieqs = [[0,0,0,1],[0,0,1,0],[1,1,0,0]])
sage: p.rays()
(A ray in the direction (1, 0, 0),
   A ray in the direction (0, 1, 0),
   A ray in the direction (0, 0, 1))
```

# rays\_list()

Return a list of rays as coefficient lists.

**Note:** It is recommended to use rays() or  $ray\_generator()$  instead to iterate over the list of Ray objects.

#### **OUTPUT**:

A list of rays as lists of coordinates.

EXAMPLES:

```
sage: p = Polyhedron(ieqs = [[0,0,0,1],[0,0,1,0],[1,1,0,0]])
sage: p.rays_list()
[[1, 0, 0], [0, 1, 0], [0, 0, 1]]
sage: p.rays_list() == [list(r) for r in p.ray_generator()]
True
```

## vertex\_generator()

Return a generator for the vertices of the polyhedron.

**Warning:** If the polyhedron has lines, return a generator for the vertices of the Vrepresentation. However, the represented polyhedron has no 0-dimensional faces (i.e. vertices):

```
sage: P = Polyhedron(rays=[[1,0,0]],lines=[[0,1,0]])
sage: list(P.vertex_generator())
[A vertex at (0, 0, 0)]
sage: P.faces(0)
()
```

#### **EXAMPLES:**

```
sage: triangle = Polyhedron(vertices=[[1,0],[0,1],[1,1]])
sage: for v in triangle.vertex_generator(): print(v)
A vertex at (0, 1)
A vertex at (1, 0)
A vertex at (1, 1)
sage: v_gen = triangle.vertex_generator()
sage: next(v_gen)
                  # the first vertex
A vertex at (0, 1)
sage: next(v_gen)
                  # the second vertex
A vertex at (1, 0)
                  # the third vertex
sage: next(v_gen)
A vertex at (1, 1)
sage: try: next(v_gen)
                        # there are only three vertices
except StopIteration: print("STOP")
STOP
sage: type(v_gen)
<... 'generator'>
sage: [ v for v in triangle.vertex_generator() ]
[A vertex at (0, 1), A vertex at (1, 0), A vertex at (1, 1)]
```

#### vertices()

Return all vertices of the polyhedron.

#### **OUTPUT**:

A tuple of vertices.

**Warning:** If the polyhedron has lines, return the vertices of the **Vrepresentation**. However, the represented polyhedron has no 0-dimensional faces (i.e. vertices):

```
sage: P = Polyhedron(rays=[[1,0,0]],lines=[[0,1,0]])
sage: P.vertices()
(A vertex at (0, 0, 0),)
sage: P.faces(0)
()
```

#### **EXAMPLES:**

```
sage: triangle = Polyhedron(vertices=[[1,0],[0,1],[1,1]])
sage: triangle.vertices()
(A vertex at (0, 1), A vertex at (1, 0), A vertex at (1, 1))
```

## vertices\_list()

Return a list of vertices of the polyhedron.

**Note:** It is recommended to use *vertex\_generator()* instead to iterate over the list of *Vertex* objects.

**Warning:** If the polyhedron has lines, return the vertices of the **Vrepresentation**. However, the represented polyhedron has no 0-dimensional faces (i.e. vertices):

```
sage: P = Polyhedron(rays=[[1,0,0]],lines=[[0,1,0]])
sage: P.vertices_list()
[[0, 0, 0]]
sage: P.faces(0)
()
```

#### **EXAMPLES**:

# vertices\_matrix(base\_ring=None)

Return the coordinates of the vertices as the columns of a matrix.

#### INPUT:

• base\_ring – A ring or None (default). The base ring of the returned matrix. If not specified, the base ring of the polyhedron is used.

## **OUTPUT**:

A matrix over base\_ring whose columns are the coordinates of the vertices. A TypeError is raised if the coordinates cannot be converted to base\_ring.

**Warning:** If the polyhedron has lines, return the coordinates of the vertices of the Vrepresentation. However, the represented polyhedron has no 0-dimensional faces (i.e. vertices):

```
sage: P = Polyhedron(rays=[[1,0,0]],lines=[[0,1,0]])
sage: P.vertices_matrix()
[0]
[0]
[0]
sage: P.faces(0)
()
```

## **EXAMPLES:**

```
sage: triangle = Polyhedron(vertices=[[1,0],[0,1],[1,1]])
sage: triangle.vertices_matrix()
[0 1 1]
[1 0 1]
sage: (triangle/2).vertices_matrix()
[ 0 1/2 1/2]
[1/2  0 1/2]
sage: (triangle/2).vertices_matrix(ZZ)
Traceback (most recent call last):
...
TypeError: no conversion of this rational to integer
```

## write\_cdd\_Hrepresentation(filename)

Export the polyhedron as a H-representation to a file.

INPUT:

• filename – the output file.

#### See also:

cdd\_Hrepresentation() - return the H-representation of the polyhedron as a string.

## **EXAMPLES:**

```
sage: from sage.misc.temporary_file import tmp_filename
sage: filename = tmp_filename(ext='.ext')
sage: polytopes.cube().write_cdd_Hrepresentation(filename)
```

#### write\_cdd\_Vrepresentation(filename)

Export the polyhedron as a V-representation to a file.

## INPUT:

• filename – the output file.

## See also:

cdd\_Vrepresentation() - return the V-representation of the polyhedron as a string.

#### **EXAMPLES:**

```
sage: from sage.misc.temporary_file import tmp_filename
sage: filename = tmp_filename(ext='.ext')
sage: polytopes.cube().write_cdd_Vrepresentation(filename)
```

# 2.6.2 Base class for polyhedra: Implementation of the ConvexSet\_base API

Define methods that exist for convex sets, but not constructions such as dilation or product.

 $Bases: sage.geometry.polyhedron.base 0.Polyhedron\_base 0, sage.geometry.convex\_set. \\ ConvexSet\_closed$ 

Convex set methods for polyhedra, but not constructions such as dilation or product.

See sage.geometry.polyhedron.base.Polyhedron\_base.

## Hrepresentation\_space()

Return the linear space containing the H-representation vectors.

**OUTPUT:** 

A free module over the base ring of dimension  $ambient\_dim() + 1$ .

**EXAMPLES:** 

```
sage: poly_test = Polyhedron(vertices = [[1,0,0,0],[0,1,0,0]])
sage: poly_test.Hrepresentation_space()
Ambient free module of rank 5 over the principal ideal domain Integer Ring
```

#### Vrepresentation\_space()

Return the ambient free module.

**OUTPUT:** 

A free module over the base ring of dimension ambient\_dim().

**EXAMPLES:** 

```
sage: poly_test = Polyhedron(vertices = [[1,0,0,0],[0,1,0,0]])
sage: poly_test.Vrepresentation_space()
Ambient free module of rank 4 over the principal ideal domain Integer Ring
sage: poly_test.ambient_space() is poly_test.Vrepresentation_space()
True
```

#### a\_maximal\_chain()

Return a maximal chain of the face lattice in increasing order.

Subclasses must provide an implementation of this method.

**EXAMPLES:** 

```
sage: from sage.geometry.polyhedron.base1 import Polyhedron_base1
sage: P = polytopes.cube()
sage: Polyhedron_base1.a_maximal_chain
<abstract method a_maximal_chain at ...>
```

#### ambient(base field=None)

Return the ambient vector space.

It is the ambient free module (*Vrepresentation\_space()*) tensored with a field.

INPUT:

• base\_field – (default: the fraction field of the base ring) a field.

#### **EXAMPLES:**

#### ambient\_dim()

Return the dimension of the ambient space.

#### **EXAMPLES:**

```
sage: poly_test = Polyhedron(vertices = [[1,0,0,0],[0,1,0,0]])
sage: poly_test.ambient_dim()
4
```

#### ambient\_space()

Return the ambient free module.

#### **OUTPUT:**

A free module over the base ring of dimension ambient\_dim().

# **EXAMPLES:**

```
sage: poly_test = Polyhedron(vertices = [[1,0,0,0],[0,1,0,0]])
sage: poly_test.Vrepresentation_space()
Ambient free module of rank 4 over the principal ideal domain Integer Ring
sage: poly_test.ambient_space() is poly_test.Vrepresentation_space()
True
```

## ambient\_vector\_space(base\_field=None)

Return the ambient vector space.

It is the ambient free module (*Vrepresentation\_space()*) tensored with a field.

#### INPUT:

• base\_field – (default: the fraction field of the base ring) a field.

#### **EXAMPLES**:

```
sage: poly_test = Polyhedron(vertices = [[1,0,0,0],[0,1,0,0]])
sage: poly_test.ambient_vector_space()
Vector space of dimension 4 over Rational Field
sage: poly_test.ambient_vector_space() is poly_test.ambient()
True
```

## an\_affine\_basis()

Return points in self that form a basis for the affine span of self.

This implementation of the method an\_affine\_basis() for polytopes guarantees the following:

- All points are vertices.
- The basis is obtained by considering a maximal chain of faces in the face lattice and picking for each cover relation one vertex that is in the difference. Thus this method is independent of the concrete realization of the polytope.

For unbounded polyhedra, the result may contain arbitrary points of self, not just vertices.

#### **EXAMPLES:**

```
sage: P = polytopes.cube()
sage: P.an_affine_basis()
[A vertex at (-1, -1, -1),
    A vertex at (1, -1, -1),
    A vertex at (1, -1, 1),
    A vertex at (1, 1, -1)]

sage: P = polytopes.permutahedron(5)
sage: P.an_affine_basis()
[A vertex at (1, 2, 3, 5, 4),
    A vertex at (2, 1, 3, 5, 4),
    A vertex at (1, 3, 2, 5, 4),
    A vertex at (4, 1, 3, 5, 2),
    A vertex at (4, 2, 5, 3, 1)]
```

# Unbounded polyhedra:

```
sage: p = Polyhedron(vertices=[(0, 0)], rays=[(1,0), (0,1)])
sage: p.an_affine_basis()
[A vertex at (0, 0), (1, 0), (0, 1)]
sage: p = Polyhedron(vertices=[(2, 1)], rays=[(1,0), (0,1)])
sage: p.an_affine_basis()
[A vertex at (2, 1), (3, 1), (2, 2)]
sage: p = Polyhedron(vertices=[(2, 1)], rays=[(1,0)], lines=[(0,1)])
sage: p.an_affine_basis()
[(2, 1), A vertex at (2, 0), (3, 0)]
```

#### contains(point)

Test whether the polyhedron contains the given point.

#### See also:

interior\_contains(), relative\_interior\_contains().

#### INPUT:

• point – coordinates of a point (an iterable)

#### OUTPUT:

Boolean.

#### **EXAMPLES:**

```
sage: P = Polyhedron(vertices=[[1,1],[1,-1],[0,0]])
sage: P.contains( [1,0] )
True
sage: P.contains( P.center() ) # true for any convex set
True
```

As a shorthand, one may use the usual in operator:

```
sage: P.center() in P
True
sage: [-1,-1] in P
False
```

The point need not have coordinates in the same field as the polyhedron:

```
sage: ray = Polyhedron(vertices=[(0,0)], rays=[(1,0)], base_ring=QQ)
                                         # irrational coordinates are ok
sage: ray.contains([sqrt(2)/3,0])
\rightarrow optional - sage.symbolic
True
sage: a = var('a')
                                                                               #__
→optional - sage.symbolic
                                          # a might be negative!
sage: ray.contains([a,0])
                                                                               #_
→optional - sage.symbolic
False
sage: assume(a>0)
                                                                               #__
→optional - sage.symbolic
sage: ray.contains([a,0])
                                                                               #_
→optional - sage.symbolic
sage: ray.contains(['hello', 'kitty']) # no common ring for coordinates
False
```

The empty polyhedron needs extra care, see trac ticket #10238:

```
sage: empty = Polyhedron(); empty
The empty polyhedron in ZZ^0
sage: empty.contains([])
False
sage: empty.contains([0])  # not a point in QQ^0
False
sage: full = Polyhedron(vertices=[()]); full
A 0-dimensional polyhedron in ZZ^0 defined as the convex hull of 1 vertex
sage: full.contains([])
True
sage: full.contains([0])
False
```

#### dim()

Return the dimension of the polyhedron.

#### **OUTPUT:**

-1 if the polyhedron is empty, otherwise a non-negative integer.

# **EXAMPLES:**

```
sage: simplex = Polyhedron(vertices = [[1,0,0,0],[0,0,0,1],[0,1,0,0],[0,0,1,0]])
sage: simplex.dim()
3
sage: simplex.ambient_dim()
4
```

The empty set is a special case (trac ticket #12193):

```
sage: P1=Polyhedron(vertices=[[1,0,0],[0,1,0],[0,0,1]])
sage: P2=Polyhedron(vertices=[[2,0,0],[0,2,0],[0,0,2]])
sage: P12 = P1.intersection(P2)
sage: P12
The empty polyhedron in ZZ^3
sage: P12.dim()
-1
```

#### dimension()

Return the dimension of the polyhedron.

#### **OUTPUT**:

-1 if the polyhedron is empty, otherwise a non-negative integer.

# EXAMPLES:

```
sage: simplex = Polyhedron(vertices = [[1,0,0,0],[0,0,0,1],[0,1,0,0],[0,0,1,0]])
sage: simplex.dim()
3
sage: simplex.ambient_dim()
4
```

The empty set is a special case (trac ticket #12193):

```
sage: P1=Polyhedron(vertices=[[1,0,0],[0,1,0],[0,0,1]])
sage: P2=Polyhedron(vertices=[[2,0,0],[0,2,0],[0,0,2]])
sage: P12 = P1.intersection(P2)
sage: P12
The empty polyhedron in ZZ^3
sage: P12.dim()
-1
```

## interior()

The interior of self.

# **OUTPUT**:

• either an empty polyhedron or an instance of RelativeInterior

#### **EXAMPLES:**

If the polyhedron is full-dimensional, the result is the same as that of relative\_interior():

```
sage: P_full = Polyhedron(vertices=[[0,0],[1,1],[1,-1]])
sage: P_full.interior()
Relative interior of
    a 2-dimensional polyhedron in ZZ^2 defined as the convex hull of 3 vertices
```

If the polyhedron is of strictly smaller dimension than the ambient space, its interior is empty:

```
sage: P_lower = Polyhedron(vertices=[[0,1], [0,-1]])
sage: P_lower.interior()
The empty polyhedron in ZZ^2
```

# interior\_contains(point)

Test whether the interior of the polyhedron contains the given point.

#### See also:

```
contains(), relative\_interior\_contains().
```

INPUT:

• point – coordinates of a point

**OUTPUT:** 

True or False.

**EXAMPLES:** 

```
sage: P = Polyhedron(vertices=[[0,0],[1,1],[1,-1]])
sage: P.contains( [1,0] )
True
sage: P.interior_contains( [1,0] )
False
```

If the polyhedron is of strictly smaller dimension than the ambient space, its interior is empty:

```
sage: P = Polyhedron(vertices=[[0,1],[0,-1]])
sage: P.contains( [0,0] )
True
sage: P.interior_contains( [0,0] )
False
```

The empty polyhedron needs extra care, see trac ticket #10238:

```
sage: empty = Polyhedron(); empty
The empty polyhedron in ZZ^0
sage: empty.interior_contains([])
False
```

# is\_empty()

Test whether the polyhedron is the empty polyhedron

**OUTPUT:** 

Boolean.

**EXAMPLES:** 

```
sage: P = Polyhedron(vertices=[[1,0,0],[0,1,0],[0,0,1]]); P
A 2-dimensional polyhedron in ZZ^3 defined as the convex hull of 3 vertices
sage: P.is_empty(), P.is_universe()
(False, False)

sage: Q = Polyhedron(vertices=()); Q
The empty polyhedron in ZZ^0
sage: Q.is_empty(), Q.is_universe()
(True, False)

sage: R = Polyhedron(lines=[(1,0),(0,1)]); R
A 2-dimensional polyhedron in ZZ^2 defined as the convex hull of 1 vertex and 2______
ilines
sage: R.is_empty(), R.is_universe()
(False, True)
```

#### is\_relatively\_open()

Return whether self is relatively open.

**OUTPUT:** 

Boolean.

**EXAMPLES:** 

```
sage: P = Polyhedron(vertices=[(1,0), (-1,0)]); P
A 1-dimensional polyhedron in ZZ^2 defined as the convex hull of 2 vertices
sage: P.is_relatively_open()
False
sage: P0 = Polyhedron(vertices=[[1, 2]]); P0
A 0-dimensional polyhedron in ZZ^2 defined as the convex hull of 1 vertex
sage: P0.is_relatively_open()
True
sage: Empty = Polyhedron(ambient_dim=2); Empty
The empty polyhedron in ZZ^2
sage: Empty.is_relatively_open()
True
sage: Line = Polyhedron(vertices=[(1, 1)], lines=[(1, 0)]); Line
A 1-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex and 1.
→line
sage: Line.is_relatively_open()
True
```

## is\_universe()

Test whether the polyhedron is the whole ambient space

**OUTPUT**:

Boolean.

**EXAMPLES:** 

#### relative\_interior()

Return the relative interior of self.

#### **EXAMPLES:**

```
sage: P = Polyhedron(vertices=[(1,0), (-1,0)])
sage: ri_P = P.relative_interior(); ri_P
Relative interior of
a 1-dimensional polyhedron in ZZ^2 defined as the convex hull of 2 vertices
sage: (0, 0) in ri_P
True
sage: (1, 0) in ri_P
False
sage: P0 = Polyhedron(vertices=[[1, 2]])
sage: P0.relative_interior() is P0
True
sage: Empty = Polyhedron(ambient_dim=2)
sage: Empty.relative_interior() is Empty
True
sage: Line = Polyhedron(vertices=[(1, 1)], lines=[(1, 0)])
sage: Line.relative_interior() is Line
True
```

# relative\_interior\_contains(point)

Test whether the relative interior of the polyhedron contains the given point.

#### See also:

```
sage: P = Polyhedron(vertices=[(1,0), (-1,0)])
sage: P.contains( (0,0) )
True
sage: P.interior_contains( (0,0) )
False
sage: P.relative_interior_contains( (0,0) )
True
sage: P.relative_interior_contains( (1,0) )
False
```

The empty polyhedron needs extra care, see trac ticket #10238:

```
sage: empty = Polyhedron(); empty
The empty polyhedron in ZZ^0
sage: empty.relative_interior_contains([])
False
```

## representative\_point()

Return a "generic" point.

#### See also:

sage.geometry.polyhedron.base.Polyhedron\_base.center().

#### **OUTPUT:**

A point as a coordinate vector. The point is chosen to be interior if possible. If the polyhedron is not full-dimensional, the point is in the relative interior. If the polyhedron is zero-dimensional, its single point is returned.

#### **EXAMPLES:**

```
sage: p = Polyhedron(vertices=[(3,2)], rays=[(1,-1)])
sage: p.representative_point()
(4, 1)
sage: p.center()
(3, 2)
sage: Polyhedron(vertices=[(3,2)]).representative_point()
(3, 2)
```

# 2.6.3 Base class for polyhedra: Methods related to lattice points

Bases: sage.geometry.polyhedron.base1.Polyhedron\_base1

Methods related to lattice points.

See sage.geometry.polyhedron.base.Polyhedron\_base.

# get\_integral\_point(index, \*\*kwds)

Return the index-th integral point in this polyhedron.

This is equivalent to sorted(self.integral\_points())[index]. However, so long as integral\_points\_count() does not need to enumerate all integral points, neither does this method. Hence it can be significantly faster. If the polyhedron is not compact, a ValueError is raised.

#### INPUT:

- index integer. The index of the integral point to be found. If this is not in [0, self. integral\_point\_count()), an IndexError is raised.
- \*\*kwds optional keyword parameters that are passed to integral\_points\_count().

#### ALGORITHM:

The function computes each of the components of the requested point in turn. To compute  $x_i$ , the ith component, it bisects the upper and lower bounds on  $x_i$  given by the bounding box. At each bisection, it uses  $integral\_points\_count()$  to determine on which side of the bisecting hyperplane the requested point lies.

#### See also:

integral\_points\_count().

#### **EXAMPLES:**

```
sage: P = Polyhedron(vertices=[(-1,-1),(1,0),(1,1),(0,1)])
sage: P.get_integral_point(1)
(0, 0)
sage: P.get_integral_point(4)
(1, 1)
sage: sorted(P.integral_points())
[(-1, -1), (0, 0), (0, 1), (1, 0), (1, 1)]
sage: P.get_integral_point(5)
Traceback (most recent call last):
IndexError: ...
sage: Q = Polyhedron([(1,3), (2, 7), (9, 77)])
sage: [Q.get_integral_point(i) for i in range(Q.integral_points_count())] ==_
→sorted(Q.integral_points())
True
sage: Q.get_integral_point(0, explicit_enumeration_threshold=0, triangulation=
→'cddlib') # optional - latte_int
(1, 3)
sage: Q.get_integral_point(0, explicit_enumeration_threshold=0, triangulation=
→'cddlib', foo=True) # optional - latte_int
Traceback (most recent call last):
RuntimeError: ...
sage: R = Polyhedron(vertices=[[1/2, 1/3]], rays=[[1, 1]])
sage: R.get_integral_point(0)
Traceback (most recent call last):
. . .
ValueError: ...
```

## h\_star\_vector()

Return the  $h^*$ -vector of the lattice polytope.

The  $h^*$ -vector records the coefficients of the polynomial in the numerator of the Ehrhart series of a lattice polytope.

#### INPUT:

• self – A lattice polytope.

#### **OUTPUT**:

A list whose entries give the  $h^*$ -vector.

#### **EXAMPLES:**

The  $h^*$ -vector of a unimodular simplex S (a simplex with volume =  $\frac{1}{dim(S)!}$ ) is always 1. Here we test this on simplices up to dimension 3:

For a less trivial example, we compute the  $h^*$ -vector of the 0/1-cube, which has the Eulerian numbers (3, i) for  $i \in [0, 2]$  as an  $h^*$ -vector:

#### integral\_points(threshold=100000)

Return the integral points in the polyhedron.

Uses either the naive algorithm (iterate over a rectangular bounding box) or triangulation + Smith form.

## INPUT:

• threshold – integer (default: 100000). Use the naive algorithm as long as the bounding box is smaller than this.

#### **OUTPUT:**

The list of integral points in the polyhedron. If the polyhedron is not compact, a ValueError is raised.

## **EXAMPLES:**

```
sage: Polyhedron(vertices=[(-1,-1),(1,0),(1,1),(0,1)]).integral_points()
((-1, -1), (0, 0), (0, 1), (1, 0), (1, 1))

sage: simplex = Polyhedron([(1,2,3), (2,3,7), (-2,-3,-11)])
sage: simplex.integral_points()
((-2, -3, -11), (0, 0, -2), (1, 2, 3), (2, 3, 7))
```

The polyhedron need not be full-dimensional:

```
sage: simplex = Polyhedron([(1,2,3,5), (2,3,7,5), (-2,-3,-11,5)])
sage: simplex.integral_points()
((-2, -3, -11, 5), (0, 0, -2, 5), (1, 2, 3, 5), (2, 3, 7, 5))

sage: point = Polyhedron([(2,3,7)])
sage: point.integral_points()
((2, 3, 7),)

sage: empty = Polyhedron()
sage: empty.integral_points()
()
```

Here is a simplex where the naive algorithm of running over all points in a rectangular bounding box no longer works fast enough:

```
sage: v = [(1,0,7,-1), (-2,-2,4,-3), (-1,-1,-1,4), (2,9,0,-5), (-2,-1,5,1)]
sage: simplex = Polyhedron(v); simplex
A 4-dimensional polyhedron in ZZ^4 defined as the convex hull of 5 vertices
sage: len(simplex.integral_points())
49
```

A case where rounding in the right direction goes a long way:

```
sage: P = 1/10*polytopes.hypercube(14, backend='field')
sage: P.integral_points()
((0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0),)
```

Finally, the 3-d reflexive polytope number 4078:

```
sage: v = [(1,0,0), (0,1,0), (0,0,1), (0,0,-1), (0,-2,1),
           (-1,2,-1), (-1,2,-2), (-1,1,-2), (-1,-1,2), (-1,-3,2)
sage: P = Polyhedron(v)
sage: pts1 = P.integral_points()
                                                     # Sage's own code
sage: all(P.contains(p) for p in pts1)
True
sage: pts2 = LatticePolytope(v).points()
                                                                     # optional -
→ palp
sage: for p in pts1: p.set_immutable()
sage: set(pts1) == set(pts2)
                                                                     # optional -
→ palp
True
sage: timeit('Polyhedron(v).integral_points()') # not tested - random
625 loops, best of 3: 1.41 ms per loop
sage: timeit('LatticePolytope(v).points()')
                                                  # not tested - random
25 loops, best of 3: 17.2 ms per loop
```

#### integral\_points\_count(\*\*kwds)

Return the number of integral points in the polyhedron.

This generic version of this method simply calls <code>integral\_points()</code>.

**EXAMPLES:** 

```
sage: P = polytopes.cube()
sage: P.integral_points_count()
27
```

We shrink the polyhedron a little bit:

```
sage: Q = P*(8/9)
sage: Q.integral_points_count()
1
```

Same for a polyhedron whose coordinates are not rationals. Note that the answer is an integer even though there are no guarantees for exactness:

```
sage: Q = P*RDF(8/9)
sage: Q.integral_points_count()
1
```

Unbounded polyhedra (with or without lattice points) are not supported:

```
sage: P = Polyhedron(vertices=[[1/2, 1/3]], rays=[[1, 1]])
sage: P.integral_points_count()
Traceback (most recent call last):
...
NotImplementedError: ...
sage: P = Polyhedron(vertices=[[1, 1]], rays=[[1, 1]])
sage: P.integral_points_count()
Traceback (most recent call last):
...
NotImplementedError: ...
```

## is\_lattice\_polytope()

Return whether the polyhedron is a lattice polytope.

#### **OUTPUT**:

True if the polyhedron is compact and has only integral vertices, False otherwise.

## **EXAMPLES:**

## lattice\_polytope(envelope=False)

Return an encompassing lattice polytope.

#### INPUT:

• envelope – boolean (default: False). If the polyhedron has non-integral vertices, this option decides whether to return a strictly larger lattice polytope or raise a ValueError. This option has no effect if the polyhedron has already integral vertices.

## **OUTPUT:**

A *LatticePolytope*. If the polyhedron is compact and has integral vertices, the lattice polytope equals the polyhedron. If the polyhedron is compact but has at least one non-integral vertex, a strictly larger lattice

polytope is returned.

If the polyhedron is not compact, a NotImplementedError is raised.

If the polyhedron is not integral and envelope=False, a ValueError is raised.

#### ALGORITHM:

For each non-integral vertex, a bounding box of integral points is added and the convex hull of these integral points is returned.

#### **EXAMPLES:**

First, a polyhedron with integral vertices:

Here is a polyhedron with non-integral vertices:

```
sage: P = Polyhedron( vertices = [(1/2, 1/2), (0, 1), (-1, 0), (0, -1)])
sage: lp = P.lattice_polytope()
Traceback (most recent call last):
ValueError: Some vertices are not integral. You probably want
to add the argument "envelope=True" to compute an enveloping
lattice polytope.
sage: lp = P.lattice_polytope(True)
sage: 1p
                                                                    # optional -
→ palp
2-d reflexive polytope #5 in 2-d lattice M
sage: lp.vertices()
M(-1, 0),
M(0, -1),
M(1, 1),
M(0, 1),
M(1, 0)
in 2-d lattice M
```

#### random\_integral\_point(\*\*kwds)

Return an integral point in this polyhedron chosen uniformly at random.

#### INPUT:

• \*\*kwds – optional keyword parameters that are passed to get\_integral\_point().

#### **OUTPUT**:

The integral point in the polyhedron chosen uniformly at random. If the polyhedron is not compact, a ValueError is raised. If the polyhedron does not contain any integral points, an EmptySetError is raised.

#### See also:

```
get_integral_point().
```

#### **EXAMPLES:**

```
sage: P = Polyhedron(vertices=[(-1,-1),(1,0),(1,1),(0,1)])
sage: P.random_integral_point() # random
(0, 0)
sage: P.random_integral_point() in P.integral_points()
sage: P.random_integral_point(explicit_enumeration_threshold=0, triangulation=
→'cddlib') # random, optional - latte_int
(1, 1)
sage: P.random_integral_point(explicit_enumeration_threshold=0, triangulation=
→'cddlib', foo=7) # optional - latte_int
Traceback (most recent call last):
RuntimeError: ...
sage: Q = Polyhedron(vertices=[(2, 1/3)], rays=[(1, 2)])
sage: Q.random_integral_point()
Traceback (most recent call last):
ValueError: ...
sage: R = Polyhedron(vertices=[(1/2, 0), (1, 1/2), (0, 1/2)])
sage: R.random_integral_point()
Traceback (most recent call last):
EmptySetError: ...
```

# 2.6.4 Base class for polyhedra: Methods regarding the combinatorics of a polyhedron

Excluding methods relying on sage.graphs.

Bases: sage.geometry.polyhedron.base2.Polyhedron\_base2

Methods related to the combinatorics of a polyhedron.

See sage.geometry.polyhedron.base.Polyhedron\_base.

## a\_maximal\_chain()

Return a maximal chain of the face lattice in increasing order.

## **EXAMPLES:**

```
sage: P = polytopes.cube()
sage: P.a_maximal_chain()
[A -1-dimensional face of a Polyhedron in ZZ^3,
   A 0-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 1_
    vertex,
```

```
A 1-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 2

  vertices,

A 2-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 4.
→vertices.
A 3-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 8.
→vertices]
sage: P = polytopes.cube()
sage: chain = P.a_maximal_chain(); chain
[A -1-dimensional face of a Polyhedron in ZZ^3,
A 0-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 1.
⊸vertex.
A 1-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 2
→vertices,
A 2-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 4.
→vertices,
A 3-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 8.
→vertices]
sage: [face.ambient_V_indices() for face in chain]
[(), (5,), (0, 5), (0, 3, 4, 5), (0, 1, 2, 3, 4, 5, 6, 7)]
```

#### adjacency\_matrix(algorithm=None)

Return the binary matrix of vertex adjacencies.

#### INPUT:

- algorithm string (optional); specify whether the face generator starts with facets or vertices:
  - 'primal' start with the facets
  - 'dual' start with the vertices
  - None choose automatically

#### **EXAMPLES:**

```
sage: polytopes.simplex(4).vertex_adjacency_matrix()
[0 1 1 1 1]
[1 0 1 1 1]
[1 1 0 1 1]
[1 1 1 0 1]
[1 1 1 0 0]
```

The rows and columns of the vertex adjacency matrix correspond to the Vrepresentation() objects: vertices, rays, and lines. The (i,j) matrix entry equals 1 if the i-th and j-th V-representation object are adjacent.

Two vertices are adjacent if they are the endpoints of an edge, that is, a one-dimensional face. For unbounded polyhedra this clearly needs to be generalized and we define two V-representation objects (see <code>sage.geometry.polyhedron.constructor</code>) to be adjacent if they together generate a one-face. There are three possible combinations:

- Two vertices can bound a finite-length edge.
- A vertex and a ray can generate a half-infinite edge starting at the vertex and with the direction given by the ray.
- A vertex and a line can generate an infinite edge. The position of the vertex on the line is arbitrary in this case, only its transverse position matters. The direction of the edge is given by the line generator.

For example, take the half-plane:

```
sage: half_plane = Polyhedron(ieqs=[(0,1,0)])
sage: half_plane.Hrepresentation()
(An inequality (1, 0) x + 0 >= 0,)
```

Its (non-unique) V-representation consists of a vertex, a ray, and a line. The only edge is spanned by the vertex and the line generator, so they are adjacent:

```
sage: half_plane.Vrepresentation()
(A line in the direction (0, 1), A ray in the direction (1, 0), A vertex at (0, □ → 0))
sage: half_plane.vertex_adjacency_matrix()
[0 0 1]
[0 0 0]
[1 0 0]
```

In one dimension higher, that is for a half-space in 3 dimensions, there is no one-dimensional face. Hence nothing is adjacent:

```
sage: Polyhedron(ieqs=[(0,1,0,0)]).vertex_adjacency_matrix()
[0 0 0 0]
[0 0 0 0]
[0 0 0 0]
[0 0 0 0]
```

#### **EXAMPLES:**

In a bounded polygon, every vertex has precisely two adjacent ones:

If the V-representation of the polygon contains vertices and one ray, then each V-representation object is adjacent to two V-representation objects:

If the V-representation of the polygon contains vertices and two distinct rays, then each vertex is adjacent to two V-representation objects (which can now be vertices or rays). The two rays are not adjacent to each other:

The vertex adjacency matrix has base ring integers. This way one can express various counting questions:

```
sage: P = polytopes.cube()
sage: Q = P.stack(P.faces(2)[0])
sage: M = Q.vertex_adjacency_matrix()
sage: sum(M)
(4, 4, 3, 3, 4, 4, 4, 3, 3)
sage: G = Q.vertex_graph() # optional - sage.graphs
sage: G.degree() # optional - sage.graphs
[4, 4, 3, 3, 4, 4, 4, 3, 3]
```

## bounded\_edges()

Return the bounded edges (excluding rays and lines).

**OUTPUT:** 

A generator for pairs of vertices, one pair per edge.

**EXAMPLES:** 

```
sage: p = Polyhedron(vertices=[[1,0],[0,1]], rays=[[1,0],[0,1]])
sage: [ e for e in p.bounded_edges() ]
[(A vertex at (0, 1), A vertex at (1, 0))]
sage: for e in p.bounded_edges(): print(e)
(A vertex at (0, 1), A vertex at (1, 0))
```

# combinatorial\_polyhedron()

Return the combinatorial type of self.

 $See \qquad sage. geometry. polyhedron. combinatorial\_polyhedron. base. \\ CombinatorialPolyhedron.$ 

**EXAMPLES:** 

```
sage: polytopes.cube().combinatorial_polyhedron()
A 3-dimensional combinatorial polyhedron with 6 facets

sage: polytopes.cyclic_polytope(4,10).combinatorial_polyhedron()
A 4-dimensional combinatorial polyhedron with 35 facets

sage: Polyhedron(rays=[[0,1], [1,0]]).combinatorial_polyhedron()
A 2-dimensional combinatorial polyhedron with 2 facets
```

**f\_vector**(num\_threads=None, parallelization\_depth=None, algorithm=None)

Return the f-vector.

INPUT:

- num\_threads integer (optional); specify the number of threads; otherwise determined by ncpus()
- parallelization\_depth integer (optional); specify how deep in the lattice the parallelization is done
- algorithm string (optional); specify whether the face generator starts with facets or vertices:
  - 'primal' start with the facets
  - 'dual' start with the vertices
  - None choose automatically

#### **OUTPUT**:

Return a vector whose i-th entry is the number of i-2-dimensional faces of the polytope.

**Note:** The vertices as given by vertices() do not need to correspond to 0-dimensional faces. If a polyhedron contains k lines they correspond to k-dimensional faces. See example below.

#### **EXAMPLES:**

```
sage: p = Polyhedron(vertices=[[1, 2, 3], [1, 3, 2],
....: [2, 1, 3], [2, 3, 1], [3, 1, 2], [3, 2, 1], [0, 0, 0]])
sage: p.f_vector()
(1, 7, 12, 7, 1)

sage: polytopes.cyclic_polytope(4,10).f_vector()
(1, 10, 45, 70, 35, 1)

sage: polytopes.hypercube(5).f_vector()
(1, 32, 80, 80, 40, 10, 1)
```

Polyhedra with lines do not have 0-faces:

```
sage: Polyhedron(ieqs=[[1,-1,0,0],[1,1,0,0]]).f_vector()
(1, 0, 0, 2, 1)
```

However, the method Polyhedron\_base.vertices() returns two points that belong to the Vrepresentation:

```
sage: P = Polyhedron(ieqs=[[1,-1,0],[1,1,0]])
sage: P.vertices()
(A vertex at (1, 0), A vertex at (-1, 0))
sage: P.f_vector()
(1, 0, 2, 1)
```

face\_generator(face\_dimension=None, algorithm=None, \*\*kwds)

Return an iterator over the faces of given dimension.

If dimension is not specified return an iterator over all faces.

#### INPUT:

- face\_dimension integer (default None), yield only faces of this dimension if specified
- algorithm string (optional); specify whether to start with facets or vertices:
  - 'primal' start with the facets

- 'dual' start with the vertices
- None choose automatically

#### **OUTPUT**:

A FaceIterator\_geom. This class iterates over faces as PolyhedronFace. See face for details. The order is random but fixed.

#### **EXAMPLES:**

```
sage: P = polytopes.cube()
sage: it = P.face_generator()
sage: it
Iterator over the faces of a 3-dimensional polyhedron in ZZ^3
sage: list(it)
[A 3-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 8.
→vertices,
A -1-dimensional face of a Polyhedron in ZZ^3.
A 2-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 4.
→vertices,
A 2-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 4.
→vertices,
A 2-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 4.
→vertices.
A 2-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 4.
→vertices.
A 2-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 4.
→vertices.
A 2-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 4.
→vertices.
A 1-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 2.
→vertices,
A 1-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 2.
→vertices,
A 1-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 2
→vertices,
A 1-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 2.
vertices,
A 0-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 1
A 0-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 1.
A 0-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 1.
A 0-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 1.
→vertex.
A 1-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 2.
→vertices.
A 1-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 2.
→vertices,
A 1-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 2
→vertices.
A 0-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 1.
⊶vertex,
```

```
A 0-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 1_{\square}
A 1-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 2.
→vertices.
A 1-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 2.
→vertices.
A 0-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 1.
A 1-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 2.
→vertices.
A 1-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 2.
A 0-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 1.
A 1-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 2
→vertices]
sage: P = polytopes.hypercube(4)
sage: list(P.face_generator(2))[:4]
[A 2-dimensional face of a Polyhedron in ZZ^4 defined as the convex hull of 4_{L}
→vertices.
 A 2-dimensional face of a Polyhedron in ZZ^4 defined as the convex hull of 4_{\square}
 A 2-dimensional face of a Polyhedron in ZZ^4 defined as the convex hull of 4_{\mbox{\tiny L}}
→vertices,
 A 2-dimensional face of a Polyhedron in ZZ^4 defined as the convex hull of 4.
→vertices]
```

If a polytope has more facets than vertices, the dual mode is chosen:

```
sage: P = polytopes.cross_polytope(3)
sage: list(P.face_generator())
[A 3-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 6.
→vertices,
A -1-dimensional face of a Polyhedron in ZZ^3,
A 0-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 1.
A 0-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 1.
A 0-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 1.
A 0-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 1.
⊸vertex.
A 0-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 1.
A 0-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 1.
A 1-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 2
→vertices,
A 1-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 2.
→vertices,
A 1-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 2.
 →vertices.
                                                                  (continues on next page)
```

```
A 1-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 2.
vertices,
A 2-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 3.
→vertices.
A 2-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 3.
→vertices.
A 2-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 3.
A 2-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 3.
→vertices.
A 1-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 2.
A 1-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 2.
→vertices,
A 1-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 2
→vertices.
A 2-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 3.
→vertices.
A 2-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 3.
→vertices.
A 1-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 2.
→vertices.
A 1-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 2.

  vertices,
A 2-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 3.
→vertices,
A 1-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 2.
→vertices,
A 1-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 2.
→vertices,
A 2-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 3.
∽vertices,
A 1-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 2
→vertices]
```

The face iterator can also be slightly modified. In non-dual mode we can skip subfaces of the current (proper) face:

```
(1,),

(0,),

(2, 3),

(1, 3),

(1, 2, 3),

(1, 2),

(0, 2),

(0, 1, 2),

(0, 1)]
```

In dual mode we can skip supfaces of the current (proper) face:

```
sage: P = polytopes.cube()
sage: it = P.face_generator(algorithm='dual')
sage: _ = next(it), next(it)
sage: face = next(it)
sage: face.ambient_V_indices()
(7,)
sage: it.ignore_supfaces()
sage: next(it)
A 0-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 1.
→vertex
sage: face = next(it)
sage: face.ambient_V_indices()
(5,)
sage: it.ignore_supfaces()
sage: [face.ambient_V_indices() for face in it]
[(4,),
(3,),
(2,),
 (1,),
 (0,),
 (1, 6),
 (3, 4),
 (2, 3),
 (0, 3),
 (0, 1, 2, 3),
 (1, 2),
(0, 1)
```

In non-dual mode, we cannot skip supfaces:

In dual mode, we cannot skip subfaces:

We can only skip sub-/supfaces of proper faces:

#### See also:

FaceIterator\_geom.

#### ALGORITHM:

See FaceIterator.

#### faces(face dimension)

Return the faces of given dimension

# INPUT:

• face\_dimension – integer. The dimension of the faces whose representation will be returned.

## **OUTPUT**:

A tuple of *PolyhedronFace*. See module *sage.geometry.polyhedron.face* for details. The order is random but fixed.

#### See also:

```
face_generator(), facet().
```

## **EXAMPLES:**

Here we find the vertex and face indices of the eight three-dimensional facets of the four-dimensional hypercube:

```
sage: p = polytopes.hypercube(4)
sage: list(f.ambient_V_indices() for f in p.faces(3))
[(0, 5, 6, 7, 8, 9, 14, 15),
   (1, 4, 5, 6, 10, 13, 14, 15),
   (1, 2, 6, 7, 8, 10, 11, 15),
   (8, 9, 10, 11, 12, 13, 14, 15),
   (0, 3, 4, 5, 9, 12, 13, 14),
   (0, 2, 3, 7, 8, 9, 11, 12),
   (1, 2, 3, 4, 10, 11, 12, 13),
```

```
(0, 1, 2, 3, 4, 5, 6, 7)]
sage: face = p.faces(3)[3]
sage: face.ambient_Hrepresentation()
(An inequality (1, 0, 0, 0) x + 1 >= 0,)
sage: face.vertices()
(A vertex at (-1, -1, 1, -1),
A vertex at (-1, 1, 1, 1),
A vertex at (-1, 1, 1, -1),
A vertex at (-1, 1, 1, 1),
A vertex at (-1, 1, 1, 1),
A vertex at (-1, 1, -1, 1),
A vertex at (-1, 1, -1, 1),
A vertex at (-1, -1, -1, 1),
A vertex at (-1, -1, -1, -1))
```

You can use the *index()* method to enumerate vertices and inequalities:

```
sage: def get_idx(rep): return rep.index()
sage: [get_idx(_) for _ in face.ambient_Hrepresentation()]
sage: [get_idx(_) for _ in face.ambient_Vrepresentation()]
[8, 9, 10, 11, 12, 13, 14, 15]
sage: [ ([get_idx(_) for _ in face.ambient_Vrepresentation()],
         [get_idx(_) for _ in face.ambient_Hrepresentation()])
. . . . :
        for face in p.faces(3) ]
[([0, 5, 6, 7, 8, 9, 14, 15], [7]),
([1, 4, 5, 6, 10, 13, 14, 15], [6]),
([1, 2, 6, 7, 8, 10, 11, 15], [5]),
 ([8, 9, 10, 11, 12, 13, 14, 15], [4]),
 ([0, 3, 4, 5, 9, 12, 13, 14], [3]),
 ([0, 2, 3, 7, 8, 9, 11, 12], [2]),
 ([1, 2, 3, 4, 10, 11, 12, 13], [1]),
 ([0, 1, 2, 3, 4, 5, 6, 7], [0])]
```

## facet\_adjacency\_matrix(algorithm=None)

Return the adjacency matrix for the facets.

#### INPUT:

- algorithm string (optional); specify whether the face generator starts with facets or vertices:
  - 'primal' start with the facets
  - 'dual' start with the vertices
  - None choose automatically

#### **EXAMPLES:**

```
sage: s4 = polytopes.simplex(4, project=True)
sage: s4.facet_adjacency_matrix()
[0 1 1 1 1]
[1 0 1 1 1]
[1 1 0 1 1]
```

```
[1 1 1 0 1]
[1 1 1 0]

sage: p = Polyhedron(vertices=[(0,0),(1,0),(0,1)])
sage: p.facet_adjacency_matrix()
[0 1 1]
[1 0 1]
[1 0 0]
```

The facet adjacency matrix has base ring integers. This way one can express various counting questions:

```
sage: P = polytopes.cube()
sage: Q = P.stack(P.faces(2)[0])
sage: M = Q.facet_adjacency_matrix()
sage: sum(M)
(4, 4, 4, 4, 3, 3, 3, 4)
```

#### facets()

Return the facets of the polyhedron.

Facets are the maximal nontrivial faces of polyhedra. The empty face and the polyhedron itself are trivial.

A facet of a d-dimensional polyhedron is a face of dimension d-1. For  $d\neq 0$  the converse is true as well.

#### **OUTPUT:**

A tuple of PolyhedronFace. See face for details. The order is random but fixed.

## See also:

facets()

## **EXAMPLES:**

Here we find the eight three-dimensional facets of the four-dimensional hypercube:

```
sage: p = polytopes.hypercube(4)
sage: p.facets()
(A 3-dimensional face of a Polyhedron in ZZ^4 defined as the convex hull of 8.
→vertices,
A 3-dimensional face of a Polyhedron in ZZ^4 defined as the convex hull of 8.
→vertices.
A 3-dimensional face of a Polyhedron in ZZ^4 defined as the convex hull of 8.
→vertices.
A 3-dimensional face of a Polyhedron in ZZ^4 defined as the convex hull of 8.
→vertices,
A 3-dimensional face of a Polyhedron in ZZ^4 defined as the convex hull of 8.
→vertices.
A 3-dimensional face of a Polyhedron in ZZ^4 defined as the convex hull of 8.
→vertices.
A 3-dimensional face of a Polyhedron in ZZ^4 defined as the convex hull of 8.
→vertices,
A 3-dimensional face of a Polyhedron in ZZ^4 defined as the convex hull of 8.
-vertices)
```

This is the same result as explicitly finding the three-dimensional faces:

```
sage: dim = p.dimension()
sage: p.faces(dim-1)
(A 3-dimensional face of a Polyhedron in ZZ^4 defined as the convex hull of 8.
→vertices,
A 3-dimensional face of a Polyhedron in ZZ^4 defined as the convex hull of 8.
→vertices,
A 3-dimensional face of a Polyhedron in ZZ^4 defined as the convex hull of 8.
→vertices.
A 3-dimensional face of a Polyhedron in ZZ^4 defined as the convex hull of 8.
→vertices.
A 3-dimensional face of a Polyhedron in ZZ^4 defined as the convex hull of 8.
→vertices.
A 3-dimensional face of a Polyhedron in ZZ^4 defined as the convex hull of 8.
A 3-dimensional face of a Polyhedron in ZZ^4 defined as the convex hull of 8.
→vertices,
A 3-dimensional face of a Polyhedron in ZZ^4 defined as the convex hull of 8.
→vertices)
```

The 0-dimensional polyhedron does not have facets:

```
sage: P = Polyhedron([[0]])
sage: P.facets()
()
```

#### greatest\_common\_subface\_of\_Hrep(\*Hrepresentatives)

Return the largest face that is contained in Hrepresentatives.

## INPUT:

• Hrepresentatives – facets or indices of Hrepresentatives; the indices are assumed to be the indices of the *Hrepresentation()* 

OUTPUT: a PolyhedronFace

# EXAMPLES:

The indices are the indices of the *Hrepresentation()*. O corresponds to an equation and is ignored:

The input is flexible:

The Hrepresentatives must belong to self:

```
sage: P = polytopes.cube(backend='ppl')
sage: Q = polytopes.cube(backend='field')
sage: f = P.facets()[0]
sage: P.meet_of_Hrep(f)
A 2-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 4.
→vertices
sage: Q.meet_of_Hrep(f)
Traceback (most recent call last):
ValueError: not a facet of ``self``
sage: f = P.inequalities()[0]
sage: P.meet_of_Hrep(f)
A 2-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 4.
→vertices
sage: Q.meet_of_Hrep(f)
Traceback (most recent call last):
ValueError: not a facet of ``self``
```

## incidence\_matrix()

Return the incidence matrix.

**Note:** The columns correspond to inequalities/equations in the order *Hrepresentation()*, the rows correspond to vertices/rays/lines in the order *Vrepresentation()*.

## See also:

slack\_matrix().

**EXAMPLES:** 

```
sage: p = polytopes.cuboctahedron()
sage: p.incidence_matrix()

[0 0 1 1 0 1 0 0 0 0 1 0 1 0 1 0 0 0]

[0 0 0 1 0 0 1 0 1 0 1 0 1 0 0 0 0 0]

[0 0 1 1 1 0 0 1 0 0 0 0 0 0 0]

[1 0 0 1 1 0 1 0 0 0 0 0 0 0]

[0 0 0 0 0 1 0 0 1 1 1 0 0 0]

[0 0 1 0 0 1 0 1 0 1 0 0 0 1 0 0]

[1 0 0 0 0 0 1 0 1 0 1 0 0 0 1 0]

[1 0 0 0 0 0 1 0 1 0 1 0 0 0 1 0]

[1 0 0 0 0 1 0 0 1 0 1 0 0 0 1 0]
```

```
[0 1 0 0 0 1 0 0 0 1 0 1 0 0]
[0 1 0 0 0 0 0 0 1 1 0 0 1 0]
[0 1 0 0 0 0 0 1 0 0 0 1 0 1]
[1 1 0 0 0 0 0 0 0 0 0 0 1 1]
sage: v = p.Vrepresentation(0)
sage: v
A vertex at (-1, -1, 0)
sage: h = p.Hrepresentation(2)
sage: h
An inequality (1, 1, -1) x + 2 >= 0
                       # evaluation (1, 1, -1) * (-1/2, -1/2, 0) + 1
sage: h.eval(v)
sage: h*v
                       # same as h.eval(v)
sage: p.incidence_matrix() [0,2] # this entry is (v,h)
sage: h.contains(v)
True
sage: p.incidence_matrix() [2,0]
                                  # note: not symmetric
```

The incidence matrix depends on the ambient dimension:

```
sage: simplex = polytopes.simplex(); simplex
A 3-dimensional polyhedron in ZZ^4 defined as the convex hull of 4 vertices
sage: simplex.incidence_matrix()
[1 1 1 1 0]
[1 1 1 0 1]
[1 0 1 1 1]
sage: simplex = simplex.affine_hull_projection(); simplex
A 3-dimensional polyhedron in ZZ^3 defined as the convex hull of 4 vertices
sage: simplex.incidence_matrix()
[1 1 1 0]
[1 1 0 1]
[1 0 1 1]
[0 1 1 1]
```

An incidence matrix does not determine a unique polyhedron:

```
sage: P = Polyhedron(vertices=[[0,1],[1,1],[1,0]])
sage: P.incidence_matrix()
[1 1 0]
[1 0 1]
[0 1 1]

sage: Q = Polyhedron(vertices=[[0,1], [1,0]], rays=[[1,1]])
sage: Q.incidence_matrix()
[1 1 0]
[1 0 1]
[0 1 1]
```

An example of two polyhedra with isomorphic face lattices but different incidence matrices:

```
sage: Q.incidence_matrix()
[1 1 0]
[1 0 1]
[0 1 1]

sage: R = Polyhedron(vertices=[[0,1], [1,0]], rays=[[1,3/2], [3/2,1]])
sage: R.incidence_matrix()
[1 1 0]
[1 0 1]
[0 1 0]
[0 0 1]
```

The incidence matrix has base ring integers. This way one can express various counting questions:

## is\_bipyramid(certificate=False)

Test whether the polytope is combinatorially equivalent to a bipyramid over some polytope.

#### INPUT:

• certificate – boolean (default: False); specifies whether to return two vertices of the polytope which are the apices of a bipyramid, if found

#### **OUTPUT**:

If certificate is True, returns a tuple containing:

- 1. Boolean.
- 2. None or a tuple containing:
  - a. The first apex.
  - b. The second apex.

If certificate is False returns a boolean.

## **EXAMPLES:**

```
sage: P = polytopes.octahedron()
sage: P.is_bipyramid()
True
sage: P.is_bipyramid(certificate=True)
(True, [A vertex at (1, 0, 0), A vertex at (-1, 0, 0)])
sage: Q = polytopes.cyclic_polytope(3,7)
sage: Q.is_bipyramid()
False
sage: R = Q.bipyramid()
sage: R.is_bipyramid(certificate=True)
(True, [A vertex at (1, 3, 13, 63), A vertex at (-1, 3, 13, 63)])
```

# is\_lawrence\_polytope()

Return True if self is a Lawrence polytope.

A polytope is called a Lawrence polytope if it has a centrally symmetric (normalized) Gale diagram.

## **EXAMPLES:**

```
sage: P = polytopes.hypersimplex(5,2)
                                                                     # optional -
→ sage.combinat
sage: L = P.lawrence_polytope()
                                                                     # optional -
→ sage.combinat
sage: L.is_lattice_polytope()
                                                                     # optional -
→ sage.combinat
True
sage: egyptian_pyramid = polytopes.regular_polygon(4).pyramid()
                                                                     # optional -
→ sage.number_field
sage: egyptian_pyramid.is_lawrence_polytope()
                                                                     # optional -
→ sage.number_field
True
sage: polytopes.octahedron().is_lawrence_polytope()
False
```

#### REFERENCES:

For more information, see [BaSt1990].

## is\_neighborly(k=None)

Return whether the polyhedron is neighborly.

If the input k is provided, then return whether the polyhedron is k-neighborly

A polyhedron is neighborly if every set of n vertices forms a face for n up to floor of half the dimension of the polyhedron. It is k-neighborly if this is true for n up to k.

## INPUT:

• k – the dimension up to which to check if every set of k vertices forms a face. If no k is provided, check up to floor of half the dimension of the polyhedron.

#### **OUTPUT**:

- True if every set of up to k vertices forms a face,
- False otherwise

#### See also:

neighborliness()

## **EXAMPLES:**

```
sage: cube = polytopes.hypercube(3)
sage: cube.is_neighborly()
True
sage: cube = polytopes.hypercube(4)
sage: cube.is_neighborly()
False
```

Cyclic polytopes are neighborly:

The neighborliness of a polyhedron equals floor of dimension half (or larger in case of a simplex) if and only if the polyhedron is neighborly:

## is\_prism(certificate=False)

Test whether the polytope is combinatorially equivalent to a prism of some polytope.

#### INPUT:

• certificate – boolean (default: False); specifies whether to return two facets of the polytope which are the bases of a prism, if found

#### **OUTPUT:**

If certificate is True, returns a tuple containing:

- 1. Boolean.
- 2. None or a tuple containing:
  - a. List of the vertices of the first base facet.
  - b. List of the vertices of the second base facet.

If certificate is False returns a boolean.

## **EXAMPLES:**

```
sage: P = polytopes.cube()
sage: P.is_prism()
True
sage: P.is_prism(certificate=True)
(True,
[(A vertex at (1, -1, -1),
  A vertex at (1, -1, 1),
  A vertex at (-1, -1, 1),
  A vertex at (-1, -1, -1),
 (A vertex at (1, 1, -1),
  A vertex at (1, 1, 1),
  A vertex at (-1, 1, -1),
  A vertex at (-1, 1, 1))])
sage: Q = polytopes.cyclic_polytope(3,8)
sage: Q.is_prism()
False
sage: R = Q.prism()
sage: R.is_prism(certificate=True)
(True,
[(A vertex at (0, 3, 9, 27),
  A vertex at (0, 6, 36, 216),
```

```
A vertex at (0, 0, 0, 0),
A vertex at (0, 7, 49, 343),
A vertex at (0, 5, 25, 125),
A vertex at (0, 1, 1, 1),
A vertex at (0, 2, 4, 8),
A vertex at (0, 4, 16, 64)),
(A vertex at (1, 6, 36, 216),
A vertex at (1, 0, 0, 0),
A vertex at (1, 7, 49, 343),
A vertex at (1, 5, 25, 125),
A vertex at (1, 1, 1, 1),
A vertex at (1, 2, 4, 8),
A vertex at (1, 4, 16, 64),
A vertex at (1, 3, 9, 27))])
```

## is\_pyramid(certificate=False)

Test whether the polytope is a pyramid over one of its facets.

#### INPUT:

• certificate – boolean (default: False); specifies whether to return a vertex of the polytope which is the apex of a pyramid, if found

#### OUTPUT:

If certificate is True, returns a tuple containing:

- 1. Boolean.
- 2. The apex of the pyramid or None.

If certificate is False returns a boolean.

#### **EXAMPLES**:

For the 0-dimensional polyhedron, the output is True, but it cannot be constructed as a pyramid over the empty polyhedron:

```
sage: P = Polyhedron([[0]])
sage: P.is_pyramid()
True
sage: Polyhedron().pyramid()
```

```
Traceback (most recent call last):
...
ZeroDivisionError: rational division by zero
```

#### is\_simple()

Test for simplicity of a polytope.

See Wikipedia article Simple polytope

#### **EXAMPLES**:

```
sage: p = Polyhedron([[0,0,0],[1,0,0],[0,1,0],[0,0,1]])
sage: p.is_simple()
True
sage: p = Polyhedron([[0,0,0],[4,4,0],[4,0,0],[0,4,0],[2,2,2]])
sage: p.is_simple()
False
```

#### is\_simplex()

Return whether the polyhedron is a simplex.

A simplex is a bounded polyhedron with d+1 vertices, where d is the dimension.

## **EXAMPLES:**

```
sage: Polyhedron([(0,0,0), (1,0,0), (0,1,0)]).is_simplex()
True
sage: polytopes.simplex(3).is_simplex()
True
sage: polytopes.hypercube(3).is_simplex()
False
```

## is\_simplicial()

Tests if the polytope is simplicial

A polytope is simplicial if every facet is a simplex.

See Wikipedia article Simplicial\_polytope

## **EXAMPLES:**

```
sage: p = polytopes.hypercube(3)
sage: p.is_simplicial()
False
sage: q = polytopes.simplex(5, project=True)
sage: q.is_simplicial()
True
sage: p = Polyhedron([[0,0,0],[1,0,0],[0,1,0],[0,0,1]])
sage: p.is_simplicial()
True
sage: q = Polyhedron([[1,1,1],[-1,1,1],[1,-1,1],[-1,-1,1],[1,1,-1]])
sage: q.is_simplicial()
False
sage: P = polytopes.simplex(); P
A 3-dimensional polyhedron in ZZ^4 defined as the convex hull of 4 vertices
```

```
sage: P.is_simplicial()
True
```

The method is not implemented for unbounded polyhedra:

```
sage: p = Polyhedron(vertices=[(0,0)],rays=[(1,0),(0,1)])
sage: p.is_simplicial()
Traceback (most recent call last):
...
NotImplementedError: this function is implemented for polytopes only
```

# join\_of\_Vrep(\*Vrepresentatives)

Return the smallest face that contains Vrepresentatives.

## INPUT:

• Vrepresentatives – vertices/rays/lines of self or indices of such

OUTPUT: a PolyhedronFace

**Note:** In the case of unbounded polyhedra, the join of rays etc. may not be well-defined.

## **EXAMPLES:**

```
sage: P = polytopes.permutahedron(5)
sage: P.join_of_Vrep(1)
A 0-dimensional face of a Polyhedron in ZZ^5 defined as the convex hull of 1_
    vertex
sage: P.join_of_Vrep()
A -1-dimensional face of a Polyhedron in ZZ^5
sage: P.join_of_Vrep(0,12,13).ambient_V_indices()
(0, 12, 13, 68)
```

The input is flexible:

```
sage: P.join_of_Vrep(2, P.vertices()[3], P.Vrepresentation(4))
A 2-dimensional face of a Polyhedron in ZZ^5 defined as the convex hull of 6

→vertices
```

In the case of an unbounded polyhedron, the join may not be well-defined:

The Vrepresentatives must be of self:

```
sage: P = polytopes.cube(backend='ppl')
sage: Q = polytopes.cube(backend='field')
sage: v = P.vertices()[0]
sage: P.join_of_Vrep(v)
A 0-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 1...
...
vertex
sage: Q.join_of_Vrep(v)
Traceback (most recent call last):
...
ValueError: not a Vrepresentative of ``self``
sage: f = P.faces(0)[0]
sage: P.join_of_Vrep(v)
A 0-dimensional face of a Polyhedron in ZZ^3 defined as the convex hull of 1...
...
vertex
sage: Q.join_of_Vrep(v)
Traceback (most recent call last):
...
ValueError: not a Vrepresentative of ``self``
```

## least\_common\_superface\_of\_Vrep(\*Vrepresentatives)

Return the smallest face that contains Vrepresentatives.

## INPUT:

• Vrepresentatives – vertices/rays/lines of self or indices of such

OUTPUT: a PolyhedronFace

**Note:** In the case of unbounded polyhedra, the join of rays etc. may not be well-defined.

# EXAMPLES:

The input is flexible:

```
sage: P.join_of_Vrep(2, P.vertices()[3], P.Vrepresentation(4))
A 2-dimensional face of a Polyhedron in ZZ^5 defined as the convex hull of 6.

→vertices
```

In the case of an unbounded polyhedron, the join may not be well-defined:

```
sage: P = Polyhedron(vertices=[[1,0], [0,1]], rays=[[1,1]])
sage: P.join_of_Vrep(0)
A 0-dimensional face of a Polyhedron in QQ^2 defined as the convex hull of 1.
⊸vertex
sage: P.join_of_Vrep(0,1)
A 1-dimensional face of a Polyhedron in QQ^2 defined as the convex hull of 2.
→vertices
sage: P.join_of_Vrep(0,2)
A 1-dimensional face of a Polyhedron in QQ^2 defined as the convex hull of 1.
→vertex and 1 ray
sage: P.join_of_Vrep(1,2)
A 1-dimensional face of a Polyhedron in QQ^2 defined as the convex hull of 1.
→vertex and 1 ray
sage: P.join_of_Vrep(2)
Traceback (most recent call last):
ValueError: the join is not well-defined
```

The Vrepresentatives must be of self:

#### meet\_of\_Hrep(\*Hrepresentatives)

Return the largest face that is contained in Hrepresentatives.

#### INPUT:

• Hrepresentatives – facets or indices of Hrepresentatives; the indices are assumed to be the indices of the *Hrepresentation()* 

OUTPUT: a PolyhedronFace

#### **EXAMPLES:**

The indices are the indices of the *Hrepresentation()*. **0** corresponds to an equation and is ignored:

```
sage: P.meet_of_Hrep(0)
A 4-dimensional face of a Polyhedron in ZZ^5 defined as the convex hull of 120_
    vertices
```

The input is flexible:

```
sage: P.meet_of_Hrep(P.facets()[-1], P.inequalities()[2], 7)
A 1-dimensional face of a Polyhedron in ZZ^5 defined as the convex hull of 2...
→vertices
```

The Hrepresentatives must belong to self:

```
sage: Q.meet_of_Hrep(f)
Traceback (most recent call last):
...
ValueError: not a facet of ``self``
```

# neighborliness()

Return the largest k, such that the polyhedron is k-neighborly.

A polyhedron is k-neighborly if every set of n vertices forms a face for n up to k.

In case of the d-dimensional simplex, it returns d + 1.

#### See also:

is\_neighborly()

#### **EXAMPLES:**

```
sage: cube = polytopes.cube()
sage: cube.neighborliness()
sage: P = Polyhedron(); P
The empty polyhedron in ZZ^0
sage: P.neighborliness()
sage: P = Polyhedron([[0]]); P
A 0-dimensional polyhedron in ZZ^1 defined as the convex hull of 1 vertex
sage: P.neighborliness()
sage: S = polytopes.simplex(5); S
A 5-dimensional polyhedron in ZZ^6 defined as the convex hull of 6 vertices
sage: S.neighborliness()
sage: C = polytopes.cyclic_polytope(7,10); C
A 7-dimensional polyhedron in QQ^7 defined as the convex hull of 10 vertices
sage: C.neighborliness()
sage: C = polytopes.cyclic_polytope(6,11); C
A 6-dimensional polyhedron in QQ^6 defined as the convex hull of 11 vertices
sage: C.neighborliness()
sage: [polytopes.cyclic_polytope(5,n).neighborliness() for n in range(6,10)]
[6, 2, 2, 2]
```

# simpliciality()

Return the largest integer k such that the polytope is k-simplicial.

A polytope is k-simplicial, if every k-face is a simplex. If self is a simplex, returns its dimension.

## **EXAMPLES**:

```
sage: polytopes.cross_polytope(4).simpliciality()
3
sage: polytopes.simplex(3).simpliciality()
3
sage: polytopes.simplex(1).simpliciality()
1
```

The method is not implemented for unbounded polyhedra:

```
sage: p = Polyhedron(vertices=[(0,0)],rays=[(1,0),(0,1)])
sage: p.simpliciality()
Traceback (most recent call last):
...
NotImplementedError: this function is implemented for polytopes only
```

## simplicity()

Return the largest integer k such that the polytope is k-simple.

A polytope P is k-simple, if every (d-1-k)-face is contained in exactly k+1 facets of P for  $1 \le k \le d-1$ . Equivalently it is k-simple if the polar/dual polytope is k-simplicial. If self is a simplex, it returns its dimension.

## **EXAMPLES:**

The method is not implemented for unbounded polyhedra:

```
sage: p = Polyhedron(vertices=[(0,0)],rays=[(1,0),(0,1)])
sage: p.simplicity()
Traceback (most recent call last):
...
NotImplementedError: this function is implemented for polytopes only
```

#### slack\_matrix()

Return the slack matrix.

The entries correspond to the evaluation of the Hrepresentation elements on the Vrepresentation elements.

**Note:** The columns correspond to inequalities/equations in the order *Hrepresentation()*, the rows correspond to vertices/rays/lines in the order *Vrepresentation()*.

#### See also:

incidence\_matrix().

#### **EXAMPLES:**

```
sage: P = polytopes.cube()
sage: P.slack_matrix()
[0 2 2 2 0 0]
[0 0 2 2 0 2]
[0 0 0 2 2 2]
[0 2 0 2 2 0]
[2 2 0 0 2 0]
[2 2 2 0 0 0]
[2 0 2 0 0 2]
[2 0 0 0 2 2]
sage: P = polytopes.cube(intervals='zero_one')
sage: P.slack_matrix()
[0 1 1 1 0 0]
[0 0 1 1 0 1]
[0 0 0 1 1 1]
[0 1 0 1 1 0]
[1 \ 1 \ 0 \ 0 \ 1 \ 0]
[1 \ 1 \ 1 \ 0 \ 0 \ 0]
[1 0 1 0 0 1]
[1 0 0 0 1 1]
sage: P = polytopes.dodecahedron().faces(2)[0].as_polyhedron()
sage: P.slack_matrix()
[1/2*sqrt5 - 1/2]
                                                                   1 1/2*sqrt5 - 1/
<u>⇔</u>2
                   0]
0 1/2*sqrt5 - 1/2 1/2*sqrt5 - 1/2
→1
                   0]
               0 1/2*sqrt5 - 1/2
                                                  1
                                                                   0 1/2*sqrt5 - 1/
-→2
                  0]
               1 1/2*sqrt5 - 1/2
                                                  0 1/2*sqrt5 - 1/2
∽0
                  0]
                                1 1/2*sqrt5 - 1/2
[1/2*sqrt5 - 1/2]
→0
                   0]
sage: P = Polyhedron(rays=[[1, 0], [0, 1]])
sage: P.slack_matrix()
[0 0]
[0 1]
[1 0]
```

# vertex\_adjacency\_matrix(algorithm=None)

Return the binary matrix of vertex adjacencies.

# INPUT:

- algorithm string (optional); specify whether the face generator starts with facets or vertices:
  - 'primal' start with the facets
  - 'dual' start with the vertices

- None - choose automatically

#### **EXAMPLES:**

```
sage: polytopes.simplex(4).vertex_adjacency_matrix()
[0 1 1 1 1]
[1 0 1 1 1]
[1 1 0 1 1]
[1 1 1 0 1]
[1 1 1 0 0]
```

The rows and columns of the vertex adjacency matrix correspond to the Vrepresentation() objects: vertices, rays, and lines. The (i,j) matrix entry equals 1 if the i-th and j-th V-representation object are adjacent.

Two vertices are adjacent if they are the endpoints of an edge, that is, a one-dimensional face. For unbounded polyhedra this clearly needs to be generalized and we define two V-representation objects (see <code>sage.geometry.polyhedron.constructor</code>) to be adjacent if they together generate a one-face. There are three possible combinations:

- Two vertices can bound a finite-length edge.
- A vertex and a ray can generate a half-infinite edge starting at the vertex and with the direction given by the ray.
- A vertex and a line can generate an infinite edge. The position of the vertex on the line is arbitrary in this case, only its transverse position matters. The direction of the edge is given by the line generator.

For example, take the half-plane:

```
sage: half_plane = Polyhedron(ieqs=[(0,1,0)])
sage: half_plane.Hrepresentation()
(An inequality (1, 0) x + 0 >= 0,)
```

Its (non-unique) V-representation consists of a vertex, a ray, and a line. The only edge is spanned by the vertex and the line generator, so they are adjacent:

```
sage: half_plane.Vrepresentation()
(A line in the direction (0, 1), A ray in the direction (1, 0), A vertex at (0, 0))
sage: half_plane.vertex_adjacency_matrix()
[0 0 1]
[0 0 0]
[1 0 0]
```

In one dimension higher, that is for a half-space in 3 dimensions, there is no one-dimensional face. Hence nothing is adjacent:

```
sage: Polyhedron(ieqs=[(0,1,0,0)]).vertex_adjacency_matrix()
[0 0 0 0]
[0 0 0 0]
[0 0 0 0]
[0 0 0 0]
```

## **EXAMPLES:**

In a bounded polygon, every vertex has precisely two adjacent ones:

If the V-representation of the polygon contains vertices and one ray, then each V-representation object is adjacent to two V-representation objects:

If the V-representation of the polygon contains vertices and two distinct rays, then each vertex is adjacent to two V-representation objects (which can now be vertices or rays). The two rays are not adjacent to each other:

The vertex adjacency matrix has base ring integers. This way one can express various counting questions:

```
sage: P = polytopes.cube()
sage: Q = P.stack(P.faces(2)[0])
sage: M = Q.vertex_adjacency_matrix()
sage: sum(M)
(4, 4, 3, 3, 4, 4, 4, 3, 3)
sage: G = Q.vertex_graph() # optional - sage.graphs
sage: G.degree() # optional - sage.graphs
[4, 4, 3, 3, 4, 4, 4, 3, 3]
```

# 2.6.5 Base class for polyhedra: Graph-theoretic methods

Define methods relying on sage.graphs.

Bases: sage.geometry.polyhedron.base3.Polyhedron\_base3

Methods relying on sage.graphs.

See sage.geometry.polyhedron.base.Polyhedron\_base.

```
combinatorial_automorphism_group(vertex_graph_only=False)
```

Computes the combinatorial automorphism group.

If vertex\_graph\_only is True, the automorphism group of the vertex-edge graph of the polyhedron is returned. Otherwise the automorphism group of the vertex-facet graph, which is isomorphic to the automorphism group of the face lattice is returned.

#### INPUT:

• vertex\_graph\_only - boolean (default: False); whether to return the automorphism group of the vertex edges graph or of the lattice

#### **OUTPUT**:

A PermutationGroup that is isomorphic to the combinatorial automorphism group is returned.

- if vertex\_graph\_only is True: The automorphism group of the vertex-edge graph of the polyhedron
- if vertex\_graph\_only is False (default): The automorphism group of the vertex-facet graph of the polyhedron, see vertex\_facet\_graph(). This group is isomorphic to the automorphism group of the face lattice of the polyhedron.

#### NOTE:

Depending on vertex\_graph\_only, this method returns groups that are not necessarily isomorphic, see the examples below.

## See also:

```
is_combinatorially_isomorphic(), graph(), vertex_facet_graph().
```

## **EXAMPLES:**

Permutations of the vertex graph only exchange vertices with vertices:

```
sage: P = Polyhedron(vertices=[(1,0), (1,1)], rays=[(1,0)])
sage: P.combinatorial_automorphism_group(vertex_graph_only=True)
Permutation Group with generators [(A vertex at (1,0),A vertex at (1,1))]
```

This shows an example of two polytopes whose vertex-edge graphs are isomorphic, but their face\_lattices are not isomorphic:

```
sage: Q=Polyhedron([[-123984206864/2768850730773, -101701330976/922950243591, -
\leftarrow 64154618668/2768850730773, -2748446474675/2768850730773],
....: [-11083969050/98314591817, -4717557075/98314591817, -32618537490/
\rightarrow 98314591817, -91960210208/98314591817],
....: [-9690950/554883199, -73651220/554883199, 1823050/554883199, -549885101/
\rightarrow 554883199], [-5174928/72012097, 5436288/72012097, -37977984/72012097, \cup
\leftarrow 60721345/72012097,
....: [-19184/902877, 26136/300959, -21472/902877, 899005/902877], [53511524/
-1167061933, 88410344/1167061933, 621795064/1167061933, 982203941/1167061933],
....: [4674489456/83665171433, -4026061312/83665171433, 28596876672/83665171433,
-78383796375/83665171433], [857794884940/98972360190089, -10910202223200/
\rightarrow 98972360190089, 2974263671400/98972360190089, -98320463346111/
\rightarrow 98972360190089]])
sage: C = polytopes.cyclic_polytope(4,8)
sage: C.is_combinatorially_isomorphic(Q)
False
sage: C.combinatorial_automorphism_group(vertex_graph_only=True).is_
-isomorphic(Q.combinatorial_automorphism_group(vertex_graph_only=True))
True
sage: C.combinatorial_automorphism_group(vertex_graph_only=False).is_
isomorphic(Q.combinatorial_automorphism_group(vertex_graph_only=False))
False
```

The automorphism group of the face lattice is isomorphic to the combinatorial automorphism group:

```
sage: CG = C.hasse_diagram().automorphism_group()
sage: C.combinatorial_automorphism_group().is_isomorphic(CG)
True
sage: QG = Q.hasse_diagram().automorphism_group()
sage: Q.combinatorial_automorphism_group().is_isomorphic(QG)
True
```

## face\_lattice()

Return the face-lattice poset.

#### **OUTPUT**:

A FinitePoset. Elements are given as *PolyhedronFace*.

In the case of a full-dimensional polytope, the faces are pairs (vertices, inequalities) of the spanning vertices and corresponding saturated inequalities. In general, a face is defined by a pair (V-rep. objects, H-rep. objects). The V-representation objects span the face, and the corresponding H-representation objects are those inequalities and equations that are saturated on the face.

The bottom-most element of the face lattice is the "empty face". It contains no V-representation object. All H-representation objects are incident.

The top-most element is the "full face". It is spanned by all V-representation objects. The incident H-representation objects are all equations and no inequalities.

In the case of a full-dimensional polytope, the "empty face" and the "full face" are the empty set (no vertices, all inequalities) and the full polytope (all vertices, no inequalities), respectively.

#### ALGORITHM:

See sage.geometry.polyhedron.combinatorial\_polyhedron.face\_iterator.

**Note:** The face lattice is not cached, as long as this creates a memory leak, see trac ticket #28982.

#### **EXAMPLES:**

```
sage: square = polytopes.hypercube(2)
sage: fl = square.face_lattice();fl
Finite lattice containing 10 elements
sage: list(f.ambient_V_indices() for f in fl)
[(), (0,), (1,), (0, 1), (2,), (1, 2), (3,), (0, 3), (2, 3), (0, 1, 2, 3)]
sage: poset_element = f1[5]
sage: a_face = poset_element
sage: a_face
A 1-dimensional face of a Polyhedron in ZZ^2 defined as the convex hull of 2.
→vertices
sage: a_face.ambient_V_indices()
sage: set(a_face.ambient_Vrepresentation()) ==
                                                           ....: set([square.
→Vrepresentation(1), square.Vrepresentation(2)])
sage: a_face.ambient_Vrepresentation()
(A vertex at (1, 1), A vertex at (-1, 1))
sage: a_face.ambient_Hrepresentation()
(An inequality (0, -1) \times + 1 \ge 0,)
```

A more complicated example:

```
sage: c5_10 = Polyhedron(vertices = [[i,i^2,i^3,i^4,i^5] for i in range(1,11)])
sage: c5_10_fl = c5_10.face_lattice()
sage: [len(x) for x in c5_10_fl.level_sets()]
[1, 10, 45, 100, 105, 42, 1]
```

Note that if the polyhedron contains lines then there is a dimension gap between the empty face and the first non-empty face in the face lattice:

```
sage: line = Polyhedron(vertices=[(0,)], lines=[(1,)])
sage: [ fl.dim() for fl in line.face_lattice() ]
[-1, 1]
```

## flag\_f\_vector(\*args)

Return the flag f-vector.

For each  $-1 < i_0 < \cdots < i_n < d$  the flag f-vector counts the number of flags  $F_0 \subset \cdots \subset F_n$  with  $F_j$  of dimension  $i_j$  for each  $0 \le j \le n$ , where d is the dimension of the polyhedron.

#### INPUT:

• args – integers (optional); specify an entry of the flag-f-vector; must be an increasing sequence of integers

## **OUTPUT**:

- a dictionary, if no arguments were given
- an Integer, if arguments were given

#### **EXAMPLES:**

Obtain the entire flag-f-vector:

```
sage: P = polytopes.twenty_four_cell()
sage: P.flag_f_vector()
    \{(-1,): 1,
     (0,): 24,
     (0, 1): 192,
     (0, 1, 2): 576,
     (0, 1, 2, 3): 1152,
     (0, 1, 3): 576,
     (0, 2): 288,
     (0, 2, 3): 576,
     (0, 3): 144,
     (1,):96,
     (1, 2): 288,
     (1, 2, 3): 576,
     (1, 3): 288,
     (2,):96,
     (2, 3): 192,
     (3,): 24,
     (4,): 1
```

Specify an entry:

```
sage: P.flag_f_vector(0,3)
144
sage: P.flag_f_vector(2)
96
```

Leading -1 and trailing entry of dimension are allowed:

```
sage: P.flag_f_vector(-1,0,3)
144
sage: P.flag_f_vector(-1,0,3,4)
144
```

One can get the number of trivial faces:

```
sage: P.flag_f_vector(-1)
1
sage: P.flag_f_vector(4)
1
```

Polyhedra with lines, have 0 entries accordingly:

```
sage: P = (Polyhedron(lines=[[1]]) * polytopes.cross_polytope(3))
sage: P.flag_f_vector()
{(-1,): 1,
   (0, 1): 0,
   (0, 1, 2): 0,
   (0, 1, 3): 0,
   (0, 2): 0,
   (0, 2, 3): 0,
   (0, 3): 0,
```

```
(0,): 0,

(1, 2): 24,

(1, 2, 3): 48,

(1, 3): 24,

(1,): 6,

(2, 3): 24,

(2,): 12,

(3,): 8,

4: 1}
```

If the arguments are not stricly increasing or out of range, a key error is raised:

```
sage: P.flag_f_vector(-1,0,3,6)
Traceback (most recent call last):
...
KeyError: (0, 3, 6)
sage: P.flag_f_vector(-1,3,0)
Traceback (most recent call last):
...
KeyError: (3, 0)
```

#### graph(\*\*kwds)

Return a graph in which the vertices correspond to vertices of the polyhedron, and edges to edges.

#### INPUT

- names boolean (default: True); if False, then the nodes of the graph are labeld by the indices of the Vrepresentation
- algorithm string (optional); specify whether the face generator starts with facets or vertices:
  - 'primal' start with the facets
  - 'dual' start with the vertices
  - None choose automatically

**Note:** The graph of a polyhedron with lines has no vertices, as the polyhedron has no vertices (0-faces).

The method *vertices()* returns the defining points in this case.

#### **EXAMPLES:**

```
sage: g3 = polytopes.hypercube(3).vertex_graph(); g3
Graph on 8 vertices
sage: g3.automorphism_group().cardinality()
48
sage: s4 = polytopes.simplex(4).vertex_graph(); s4
Graph on 5 vertices
sage: s4.is_eulerian()
True
```

The graph of an unbounded polyhedron is the graph of the bounded complex:

The graph of a polyhedron with lines has no vertices:

```
sage: line = Polyhedron(lines=[[0,1]])
sage: line.vertex_graph()
Graph on 0 vertices
```

## hasse\_diagram()

Return the Hasse diagram of the face lattice of self.

This is the Hasse diagram of the poset of the faces of self.

OUTPUT: a directed graph

**EXAMPLES:** 

Faces of an mutable polyhedron are not hashable. Hence those are not suitable as vertices of the hasse diagram. Use the combinatorial polyhedron instead:

```
sage: P = polytopes.regular_polygon(4).pyramid()
                                                                     # optional -
→ sage.rings.number_field
sage: parent = P.parent()
                                                                     # optional -
→ sage.rings.number_field
sage: parent = parent.change_ring(QQ, backend='ppl')
                                                                     # optional -
→ sage.rings.number_field
sage: Q = parent._element_constructor_(P, mutable=True)
                                                                     # optional -
→ sage.rings.number_field
sage: Q.hasse_diagram()
                                                                     # optional -
→ sage.rings.number_field
Traceback (most recent call last):
TypeError: mutable polyhedra are unhashable
sage: C = Q.combinatorial_polyhedron()
                                                                     # optional -
→ sage.rings.number_field
sage: D = C.hasse_diagram()
                                                                      # optional -
→ sage.rings.number_field
sage: set(D.vertices()) == set(range(20))
                                                                     # optional -
→ sage.rings.number_field
sage: def index_to_combinatorial_face(n):
          return C.face_by_face_lattice_index(n)
sage: D.relabel(index_to_combinatorial_face, inplace=True)
                                                                     # optional -
→ sage.rings.number_field
                                                                   (continues on next page)
```

```
sage: D.vertices()
                                                                     # optional -
→ sage.rings.number_field
[A -1-dimensional face of a 3-dimensional combinatorial polyhedron,
A 0-dimensional face of a 3-dimensional combinatorial polyhedron,
A 1-dimensional face of a 3-dimensional combinatorial polyhedron.
A 2-dimensional face of a 3-dimensional combinatorial polyhedron,
A 3-dimensional face of a 3-dimensional combinatorial polyhedron]
sage: D.degree_polynomial()
                                                                     # optional -
→ sage.rings.number_field
x^5 + x^4*y + x^4*y^4 + y^5 + 4^*x^3*y + 8^*x^2*y^2 + 4^*x^4y^3
```

## is\_combinatorially\_isomorphic(other, algorithm='bipartite\_graph')

Return whether the polyhedron is combinatorially isomorphic to another polyhedron.

We only consider bounded polyhedra. By definition, they are combinatorially isomorphic if their face lattices are isomorphic.

## INPUT:

- other a polyhedron object
- algorithm (default = 'bipartite\_graph') the algorithm to use. The other possible value is 'face\_lattice'.

#### **OUTPUT:**

- True if the two polyhedra are combinatorially isomorphic
- · False otherwise

#### See also:

```
combinatorial_automorphism_group(), vertex_facet_graph().
```

#### REFERENCES:

For the equivalence of the two algorithms see [KK1995], p. 877-878

## **EXAMPLES:**

The square is combinatorially isomorphic to the 2-dimensional cube:

All the faces of the 3-dimensional permutahedron are either combinatorially isomorphic to a square or a hexagon:

Checking that a regular simplex intersected with its reflection through the origin is combinatorially isomorphic to the intersection of a cube with a hyperplane perpendicular to its long diagonal:

```
sage: def simplex_intersection(k):
        S1 = Polyhedron([vector(v)-vector(polytopes.simplex(k).center()) for v_
→in polytopes.simplex(k).vertices_list()])
        S2 = Polyhedron([-vector(v) for v in S1.vertices_list()])
. . . . :
       return S1.intersection(S2)
sage: def cube_intersection(k):
         C = polytopes.hypercube(k+1)
         H = Polyhedron(eqns=[[0]+[1 for i in range(k+1)]])
. . . . :
         return C.intersection(H)
sage: [simplex_intersection(k).is_combinatorially_isomorphic(cube_
\rightarrowintersection(k)) for k in range(2,5)]
[True, True, True]
sage: simplex_intersection(2).is_combinatorially_isomorphic(polytopes.regular_
→polygon(6)) # optional - sage.rings.number_field
True
sage: simplex_intersection(3).is_combinatorially_isomorphic(polytopes.
→octahedron())
True
```

Two polytopes with the same f-vector, but different combinatorial types:

```
True
(1, 10, 45, 100, 105, 42, 1)
sage: C.is_combinatorially_isomorphic(P)
False
sage: S = polytopes.simplex(3)
sage: S = S.face_truncation(S.faces(0)[3])
sage: S = S.face_truncation(S.faces(0)[4])
sage: S = S.face_truncation(S.faces(0)[5])
sage: T = polytopes.simplex(3)
sage: T = T.face_truncation(T.faces(0)[3])
sage: T = T.face_truncation(T.faces(0)[4])
sage: T = T.face_truncation(T.faces(0)[4])
sage: T.is_combinatorially_isomorphic(S)
False
sage: T.f_vector(), S.f_vector()
((1, 10, 15, 7, 1), (1, 10, 15, 7, 1))
sage: C = polytopes.hypercube(5)
sage: C.is_combinatorially_isomorphic(C)
sage: C.is_combinatorially_isomorphic(C, algorithm='magic')
Traceback (most recent call last):
AssertionError: `algorithm` must be 'bipartite graph' or 'face_lattice'
sage: G = Graph()
sage: C.is_combinatorially_isomorphic(G)
Traceback (most recent call last):
AssertionError: input `other` must be a polyhedron
sage: H = Polyhedron(eqns=[[0,1,1,1,1]]); H
A 3-dimensional polyhedron in QQ^4 defined as the convex hull of 1 vertex and 3.
sage: C.is_combinatorially_isomorphic(H)
Traceback (most recent call last):
AssertionError: polyhedron `other` must be bounded
```

## is\_self\_dual()

Return whether the polytope is self-dual.

A polytope is self-dual if its face lattice is isomorphic to the face lattice of its dual polytope.

#### **EXAMPLES:**

```
sage: polytopes.simplex().is_self_dual()
True
sage: polytopes.twenty_four_cell().is_self_dual()
True
sage: polytopes.cube().is_self_dual()
False
```

```
sage: polytopes.hypersimplex(5,2).is_self_dual()
False
sage: P = Polyhedron(vertices=[[1/2, 1/3]], rays=[[1, 1]]).is_self_dual()
Traceback (most recent call last):
...
ValueError: polyhedron has to be compact
```

## restricted\_automorphism\_group(output='abstract')

Return the restricted automorphism group.

First, let the linear automorphism group be the subgroup of the affine group  $AGL(d, \mathbf{R}) = GL(d, \mathbf{R}) \ltimes \mathbf{R}^d$  preserving the d-dimensional polyhedron. The affine group acts in the usual way  $\vec{x} \mapsto A\vec{x} + b$  on the ambient space.

The restricted automorphism group is the subgroup of the linear automorphism group generated by permutations of the generators of the same type. That is, vertices can only be permuted with vertices, ray generators with ray generators, and line generators with line generators.

For example, take the first quadrant

$$Q = \left\{ (x, y) \middle| x \ge 0, \ y \ge 0 \right\} \subset \mathbf{Q}^2$$

Then the linear automorphism group is

$$\operatorname{Aut}(Q) = \left\{ \begin{pmatrix} a & 0 \\ 0 & b \end{pmatrix}, \; \begin{pmatrix} 0 & c \\ d & 0 \end{pmatrix} : \; a, b, c, d \in \mathbf{Q}_{>0} \right\} \subset GL(2, \mathbf{Q}) \subset E(d)$$

Note that there are no translations that map the quadrant Q to itself, so the linear automorphism group is contained in the general linear group (the subgroup of transformations preserving the origin). The restricted automorphism group is

$$\operatorname{Aut}(Q) = \left\{ \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \right\} \simeq \mathbf{Z}_2$$

## INPUT:

- output how the group should be represented:
  - "abstract" (default) return an abstract permutation group without further meaning.
  - "permutation" return a permutation group on the indices of the polyhedron generators. For example, the permutation (0,1) would correspond to swapping self.Vrepresentation(0) and self.Vrepresentation(1).
  - "matrix" return a matrix group representing affine transformations. When acting on affine vectors, you should append a 1 to every vector. If the polyhedron is not full dimensional, the returned matrices act as the identity on the orthogonal complement of the affine space spanned by the polyhedron.
  - "matrixlist" like matrix, but return the list of elements of the matrix group. Useful for fields without a good implementation of matrix groups or to avoid the overhead of creating the group.

## **OUTPUT**:

- For output="abstract" and output="permutation": a PermutationGroup.
- For output="matrix": a MatrixGroup().
- For output="matrixlist": a list of matrices.

## **REFERENCES:**

• [BSS2009]

#### **EXAMPLES:**

A cross-polytope example:

We test groups for equality in a fool-proof way; they can have different generators, etc:

```
sage: poly_g = P.restricted_automorphism_group(output="matrix")
sage: matrix_g = MatrixGroup([matrix(QQ,t) for t in mgens])
sage: all(t.matrix() in poly_g for t in matrix_g.gens())
True
sage: all(t.matrix() in matrix_g for t in poly_g.gens())
True
```

24-cell example:

Here is the quadrant example mentioned in the beginning:

Also, the polyhedron need not be full-dimensional:

```
sage: P = Polyhedron(vertices=[(1,2,3,4,5),(7,8,9,10,11)])
sage: P.restricted_automorphism_group()
Permutation Group with generators [(1,2)]
sage: G = P.restricted_automorphism_group(output="matrixlist")
sage: G
[1 0 0 0 0 0] [ -87/55 -82/55 -2/5 38/55 98/55 12/11]
```

```
[0 \ 1 \ 0 \ 0 \ 0 \ 0]
               [-142/55 -27/55
                                     -2/5
                                             38/55
                                                      98/55
                                                              12/11
[0 0 1 0 0 0] [-142/55
                          -82/55
                                      3/5
                                                      98/55
                                                              12/11
                                             38/55
                                     -2/5
[0 0 0 1 0 0] [-142/55 -82/55
                                             93/55
                                                      98/55
                                                              12/11]
                                      -2/5
[0 0 0 0 1 0] [-142/55 -82/55
                                             38/55 153/55
                                                              12/11]
[0 0 0 0 0 1], [
                                         0
                                                                   17
sage: g = AffineGroup(5, QQ)(G[1])
sage: g
      [ -87/55 -82/55 ]
                            -2/5
                                   38/55
                                            98/55]
                                                        [12/11]
      [-142/55 -27/55]
                            -2/5
                                   38/55
                                            98/55]
                                                        [12/11]
                                            98/55] x + [12/11]
                             3/5
                                   38/55
x \mid -> [-142/55 -82/55]
      [-142/55 -82/55
                           -2/5
                                   93/55
                                            98/55]
                                                        [12/11]
      [-142/55 -82/55
                           -2/5
                                   38/55 153/55]
                                                        [12/11]
sage: g^2
      [1 \ 0 \ 0 \ 0 \ 0]
                        [0]
      [0 1 0 0 0]
                        [0]
x \mid -> [0 \ 0 \ 1 \ 0 \ 0] \ x + [0]
      [0 0 0 1 0]
                        [0]
      [0 0 0 0 1]
                        [0]
sage: g(list(P.vertices()[0]))
(7, 8, 9, 10, 11)
sage: g(list(P.vertices()[1]))
(1, 2, 3, 4, 5)
```

Affine transformations do not change the restricted automorphism group. For example, any non-degenerate triangle has the dihedral group with 6 elements,  $D_6$ , as its automorphism group:

```
sage: initial_points = [vector([1,0]), vector([0,1]), vector([-2,-1])]
sage: points = initial_points
sage: Polyhedron(vertices=points).restricted_automorphism_group()
Permutation Group with generators [(2,3), (1,2)]
sage: points = [pt - initial_points[0] for pt in initial_points]
sage: Polyhedron(vertices=points).restricted_automorphism_group()
Permutation Group with generators [(2,3), (1,2)]
sage: points = [pt - initial_points[1] for pt in initial_points]
sage: Polyhedron(vertices=points).restricted_automorphism_group()
Permutation Group with generators [(2,3), (1,2)]
sage: points = [pt - 2*initial_points[1] for pt in initial_points]
sage: Polyhedron(vertices=points).restricted_automorphism_group()
Permutation Group with generators [(2,3), (1,2)]
```

The output="matrixlist" can be used over fields without a complete implementation of matrix groups:

Floating-point computations are supported with a simple fuzzy zero implementation:

## vertex\_digraph(f, increasing=True)

Return the directed graph of the polyhedron according to a linear form.

The underlying undirected graph is the graph of vertices and edges.

#### INPUT:

- f a linear form. The linear form can be provided as:
  - a vector space morphism with one-dimensional codomain, (see sage.modules. vector\_space\_morphism.linear\_transformation() and sage.modules. vector\_space\_morphism.VectorSpaceMorphism)
  - a vector; in this case the linear form is obtained by duality using the dot product: f(v) = v. dot\_product(f).
- increasing boolean (default True) whether to orient edges in the increasing or decreasing direction.

By default, an edge is oriented from v to w if  $f(v) \leq f(w)$ .

If f(v) = f(w), then two opposite edges are created.

## **EXAMPLES:**

```
sage: penta = Polyhedron([[0,0],[1,0],[0,1],[1,2],[3,2]])
sage: G = penta.vertex_digraph(vector([1,1])); G
Digraph on 5 vertices
sage: G.sinks()
[A vertex at (3, 2)]

sage: A = matrix(ZZ, [[1], [-1]])
sage: f = linear_transformation(A)
sage: G = penta.vertex_digraph(f) ; G
Digraph on 5 vertices
sage: G.is_directed_acyclic()
False
```

## See also:

```
vertex_graph()
```

## vertex\_facet\_graph(labels=True)

Return the vertex-facet graph.

This function constructs a directed bipartite graph. The nodes of the graph correspond to the vertices of the polyhedron and the facets of the polyhedron. There is an directed edge from a vertex to a face if and only if the vertex is incident to the face.

#### INPUT:

• labels – boolean (default: True); decide how the nodes of the graph are labelled. Either with the original vertices/facets of the Polyhedron or with integers.

# OUTPUT:

• a bipartite DiGraph. If labels is True, then the nodes of the graph will actually be the vertices and facets of self, otherwise they will be integers.

#### See also:

combinatorial\_automorphism\_group(), is\_combinatorially\_isomorphic().

#### **EXAMPLES:**

```
sage: P = polytopes.cube()
sage: G = P.vertex_facet_graph(); G
Digraph on 14 vertices
sage: G.vertices(key = lambda v: str(v))
[A vertex at (-1, -1, -1),
A vertex at (-1, -1, 1),
A vertex at (-1, 1, -1),
A vertex at (-1, 1, 1),
 A vertex at (1, -1, -1),
A vertex at (1, -1, 1),
 A vertex at (1, 1, -1),
 A vertex at (1, 1, 1),
 An inequality (-1, 0, 0) \times + 1 \ge 0,
 An inequality (0, -1, 0) x + 1 >= 0,
 An inequality (0, 0, -1) \times + 1 >= 0,
 An inequality (0, 0, 1) x + 1 >= 0,
 An inequality (0, 1, 0) x + 1 >= 0,
An inequality (1, 0, 0) x + 1 \ge 0
sage: G.automorphism_group().is_isomorphic(P.hasse_diagram().automorphism_

¬group())
True
sage: 0 = polytopes.octahedron(); 0
A 3-dimensional polyhedron in ZZ^3 defined as the convex hull of 6 vertices
sage: 0.vertex_facet_graph()
Digraph on 14 vertices
sage: H = 0.vertex_facet_graph()
sage: G.is_isomorphic(H)
False
sage: G2 = copy(G)
sage: G2.reverse_edges(G2.edges(sort=True))
sage: G2.is_isomorphic(H)
True
```

#### vertex\_graph(\*\*kwds)

Return a graph in which the vertices correspond to vertices of the polyhedron, and edges to edges.

#### INPUT:

- names boolean (default: True); if False, then the nodes of the graph are labeld by the indices of the Vrepresentation
- algorithm string (optional); specify whether the face generator starts with facets or vertices:
  - 'primal' start with the facets
  - 'dual' start with the vertices
  - None choose automatically

**Note:** The graph of a polyhedron with lines has no vertices, as the polyhedron has no vertices (0-faces).

The method *vertices()* returns the defining points in this case.

## **EXAMPLES:**

```
sage: g3 = polytopes.hypercube(3).vertex_graph(); g3
Graph on 8 vertices
sage: g3.automorphism_group().cardinality()
48
sage: s4 = polytopes.simplex(4).vertex_graph(); s4
Graph on 5 vertices
sage: s4.is_eulerian()
True
```

The graph of an unbounded polyhedron is the graph of the bounded complex:

The graph of a polyhedron with lines has no vertices:

```
sage: line = Polyhedron(lines=[[0,1]])
sage: line.vertex_graph()
Graph on 0 vertices
```

# 2.6.6 Base class for polyhedra: Methods for constructing new polyhedra

Except for affine hull and affine hull projection.

Bases: sage.geometry.polyhedron.base4.Polyhedron\_base4

Methods constructing new polyhedra except for affine hull and affine hull projection.

See sage.geometry.polyhedron.base.Polyhedron\_base.

#### bipyramid()

Return a polyhedron that is a bipyramid over the original.

## **EXAMPLES:**

```
sage: octahedron = polytopes.cross_polytope(3)
sage: cross_poly_4d = octahedron.bipyramid()
sage: cross_poly_4d.n_vertices()
8
sage: q = [list(v) for v in cross_poly_4d.vertex_generator()]
sage: q
[[-1, 0, 0, 0],
[0, -1, 0, 0],
```

```
[0, 0, -1, 0],

[0, 0, 0, -1],

[0, 0, 0, 1],

[0, 0, 1, 0],

[0, 1, 0, 0],

[1, 0, 0, 0]]
```

Now check that bipyramids of cross-polytopes are cross-polytopes:

```
sage: q2 = [list(v) for v in polytopes.cross_polytope(4).vertex_generator()]
sage: [v in q2 for v in q]
[True, True, True, True, True, True, True]
```

# cartesian\_product(other)

Return the Cartesian product.

INPUT:

• other - a Polyhedron\_base

**OUTPUT**:

The Cartesian product of self and other with a suitable base ring to encompass the two.

**EXAMPLES:** 

```
sage: P1 = Polyhedron([[0],[1]], base_ring=ZZ)
sage: P2 = Polyhedron([[0],[1]], base_ring=QQ)
sage: P1.product(P2)
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 4 vertices
```

The Cartesian product is the product in the semiring of polyhedra:

```
sage: P1 * P1
A 2-dimensional polyhedron in ZZ^2 defined as the convex hull of 4 vertices
sage: P1 * P2
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 4 vertices
sage: P2 * P2
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 4 vertices
sage: 2 * P1
A 1-dimensional polyhedron in ZZ^1 defined as the convex hull of 2 vertices
sage: P1 * 2.0
A 1-dimensional polyhedron in RDF^1 defined as the convex hull of 2 vertices
```

An alias is cartesian\_product():

```
sage: P1.cartesian_product(P2) == P1.product(P2)
True
```

#### convex\_hull(other)

Return the convex hull of the set-theoretic union of the two polyhedra.

INPUT:

• other – a Polyhedron

**OUTPUT**:

The convex hull.

#### **EXAMPLES:**

```
sage: a_simplex = polytopes.simplex(3, project=True)
sage: verts = a_simplex.vertices()
sage: verts = [[x[0]*3/5+x[1]*4/5, -x[0]*4/5+x[1]*3/5, x[2]] for x in verts]
sage: another_simplex = Polyhedron(vertices = verts)
sage: simplex_union = a_simplex.convex_hull(another_simplex)
sage: simplex_union.n_vertices()
7
```

## dilation(scalar)

Return the dilated (uniformly stretched) polyhedron.

#### INPUT:

• scalar – A scalar, not necessarily in base\_ring()

#### **OUTPUT**:

The polyhedron dilated by that scalar, possibly coerced to a bigger base ring.

#### **EXAMPLES:**

```
sage: p = Polyhedron(vertices = [[t,t^2,t^3] for t in srange(2,6)])
sage: next(p.vertex_generator())
A vertex at (2, 4, 8)
sage: p2 = p.dilation(2)
sage: next(p2.vertex_generator())
A vertex at (4, 8, 16)
sage: p.dilation(2) == p * 2
True
```

## direct\_sum(other)

Return the direct sum of self and other.

The direct sum of two polyhedron is the subdirect sum of the two, when they have the origin in their interior. To avoid checking if the origin is contained in both, we place the affine subspace containing other at the center of self.

## INPUT:

• other - a Polyhedron\_base

#### **EXAMPLES:**

```
sage: P1 = Polyhedron([[1],[2]], base_ring=ZZ)
sage: P2 = Polyhedron([[3],[4]], base_ring=QQ)
sage: ds = P1.direct_sum(P2);ds
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 4 vertices
sage: ds.vertices()
(A vertex at (1, 0),
A vertex at (2, 0),
A vertex at (3/2, -1/2),
A vertex at (3/2, 1/2))
```

## See also:

```
join() subdirect_sum()
```

# face\_split(face)

Return the face splitting of the face face.

Splitting a face correspond to the bipyramid (see bipyramid()) of self where the two new vertices are placed above and below the center of face instead of the center of the whole polyhedron. The two new vertices are placed in the new dimension at height -1 and 1.

#### INPUT:

face – a PolyhedronFace or a Vertex

#### **EXAMPLES:**

#### See also:

```
one_point_suspension()
```

**face\_truncation**(face, linear\_coefficients=None, cut\_frac=None)

Return a new polyhedron formed by truncating a face by an hyperplane.

By default, the normal vector of the hyperplane used to truncate the polyhedron is obtained by taking the barycenter vector of the cone corresponding to the truncated face in the normal fan of the polyhedron. It is possible to change the direction using the option linear\_coefficients.

To determine how deep the truncation is done, the method uses the parameter  $\mathtt{cut\_frac}$ . By default it is equal to  $\frac{1}{3}$ . Once the normal vector of the cutting hyperplane is chosen, the vertices of polyhedron are evaluated according to the corresponding linear function. The parameter  $\frac{1}{3}$  means that the cutting hyperplane is placed  $\frac{1}{3}$  of the way from the vertices of the truncated face to the next evaluated vertex.

# INPUT:

- face a PolyhedronFace
- linear\_coefficients tuple of integer. Specifies the coefficient of the normal vector of the cutting hyperplane used to truncate the face. The default direction is determined using the normal fan of the polyhedron.
- cut\_frac number between 0 and 1. Determines where the hyperplane cuts the polyhedron. A value close to 0 cuts very close to the face, whereas a value close to 1 cuts very close to the next vertex (according to the normal vector of the cutting hyperplane). Default is  $\frac{1}{3}$ .

# **OUTPUT**:

A Polyhedron object, truncated as described above.

### **EXAMPLES:**

```
sage: Cube = polytopes.hypercube(3)
sage: vertex_trunc1 = Cube.face_truncation(Cube.faces(0)[0])
sage: vertex_trunc1.f_vector()
(1, 10, 15, 7, 1)
```

```
sage: tuple(f.ambient_V_indices() for f in vertex_trunc1.faces(2))
((4, 5, 6, 7, 9),
(0, 3, 4, 8, 9),
(0, 1, 6, 7, 8),
(7, 8, 9),
 (2, 3, 4, 5),
(1, 2, 5, 6),
(0, 1, 2, 3))
sage: vertex_trunc1.vertices()
(A vertex at (1, -1, -1),
A vertex at (1, 1, -1),
A vertex at (1, 1, 1),
A vertex at (1, -1, 1),
A vertex at (-1, -1, 1),
A vertex at (-1, 1, 1),
A vertex at (-1, 1, -1),
A vertex at (-1, -1/3, -1),
A vertex at (-1/3, -1, -1),
A vertex at (-1, -1, -1/3)
sage: vertex_trunc2 = Cube.face_truncation(Cube.faces(0)[0],cut_frac=1/2)
sage: vertex_trunc2.f_vector()
(1, 10, 15, 7, 1)
sage: tuple(f.ambient_V_indices() for f in vertex_trunc2.faces(2))
((4, 5, 6, 7, 9),
 (0, 3, 4, 8, 9),
 (0, 1, 6, 7, 8),
 (7, 8, 9),
(2, 3, 4, 5),
 (1, 2, 5, 6),
(0, 1, 2, 3))
sage: vertex_trunc2.vertices()
(A vertex at (1, -1, -1),
A vertex at (1, 1, -1),
A vertex at (1, 1, 1),
A vertex at (1, -1, 1),
A vertex at (-1, -1, 1),
A vertex at (-1, 1, 1),
A vertex at (-1, 1, -1),
A vertex at (-1, 0, -1),
A vertex at (0, -1, -1),
A vertex at (-1, -1, 0)
sage: vertex_trunc3 = Cube.face_truncation(Cube.faces(0)[0],cut_frac=0.3)
sage: vertex_trunc3.vertices()
(A vertex at (-1.0, -1.0, 1.0),
A vertex at (-1.0, 1.0, -1.0),
A vertex at (-1.0, 1.0, 1.0),
A vertex at (1.0, 1.0, -1.0),
A vertex at (1.0, 1.0, 1.0),
A vertex at (1.0, -1.0, 1.0),
A vertex at (1.0, -1.0, -1.0),
A vertex at (-0.4, -1.0, -1.0),
A vertex at (-1.0, -0.4, -1.0),
```

```
A vertex at (-1.0, -1.0, -0.4))
sage: edge_trunc = Cube.face_truncation(Cube.faces(1)[11])
sage: edge_trunc.f_vector()
(1, 10, 15, 7, 1)
sage: tuple(f.ambient_V_indices() for f in edge_trunc.faces(2))
((0, 5, 6, 7),
(1, 4, 5, 6, 8),
 (6, 7, 8, 9),
 (0, 2, 3, 7, 9),
 (1, 2, 8, 9),
 (0, 3, 4, 5),
 (1, 2, 3, 4))
sage: face_trunc = Cube.face_truncation(Cube.faces(2)[2])
 sage: face_trunc.vertices()
 (A vertex at (1, -1, -1),
 A vertex at (1, 1, -1),
 A vertex at (1, 1, 1),
 A vertex at (1, -1, 1),
 A vertex at (-1/3, -1, 1),
 A vertex at (-1/3, 1, 1),
 A vertex at (-1/3, 1, -1),
 A vertex at (-1/3, -1, -1)
 sage: face_trunc.face_lattice().is_isomorphic(Cube.face_lattice())
True
```

### intersection(other)

Return the intersection of one polyhedron with another.

## INPUT:

• other - a Polyhedron

### OUTPUT:

The intersection.

Note that the intersection of two  $\mathbf{Z}$ -polyhedra might not be a  $\mathbf{Z}$ -polyhedron. In this case, a  $\mathbf{Q}$ -polyhedron is returned.

### **EXAMPLES:**

```
sage: cube = polytopes.hypercube(3)
sage: oct = polytopes.cross_polytope(3)
sage: cube.intersection(oct*2)
A 3-dimensional polyhedron in ZZ^3 defined as the convex hull of 12 vertices
```

As a shorthand, one may use:

```
sage: cube & oct*2
A 3-dimensional polyhedron in ZZ^3 defined as the convex hull of 12 vertices
```

The intersection of two **Z**-polyhedra is not necessarily a **Z**-polyhedron:

```
sage: P = Polyhedron([(0,0),(1,1)], base_ring=ZZ)
sage: P.intersection(P)
```

```
A 1-dimensional polyhedron in ZZ^2 defined as the convex hull of 2 vertices sage: Q = Polyhedron([(0,1),(1,0)], base_ring=ZZ) sage: P.intersection(Q)
A 0-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex sage: _.Vrepresentation()
(A vertex at (1/2, 1/2),)
```

## join(other)

Return the join of self and other.

The join of two polyhedra is obtained by first placing the two objects in two non-intersecting affine subspaces V, and W whose affine hull is the whole ambient space, and finally by taking the convex hull of their union. The dimension of the join is the sum of the dimensions of the two polyhedron plus 1.

### INPUT:

• other – a polyhedron

### **EXAMPLES:**

```
sage: P1 = Polyhedron([[0],[1]], base_ring=ZZ)
sage: P2 = Polyhedron([[0],[1]], base_ring=QQ)
sage: P1.join(P2)
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 4 vertices
sage: P1.join(P1)
A 3-dimensional polyhedron in ZZ^3 defined as the convex hull of 4 vertices
sage: P2.join(P2)
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 4 vertices
```

### An unbounded example:

## lawrence\_extension(v)

Return the Lawrence extension of self on the point v.

Let P be a polytope and v be a vertex of P or a point outside P. The Lawrence extension of P on v is the convex hull of (v, 1), (v, 2) and (u, 0) for all vertices u in P other than v if v is a vertex.

### INPUT:

• v - a vertex of self or a point outside it

#### **EXAMPLES:**

```
sage: P = polytopes.cube()
sage: P.lawrence_extension(P.vertices()[0])
A 4-dimensional polyhedron in ZZ^4 defined as the convex hull of 9 vertices
sage: P.lawrence_extension([-1,-1,-1])
A 4-dimensional polyhedron in ZZ^4 defined as the convex hull of 9 vertices
```

#### REFERENCES:

For more information, see Section 6.6 of [Zie2007].

# lawrence\_polytope()

Return the Lawrence polytope of self.

Let P be a d-polytope in  $\mathbb{R}^r$  with n vertices. The Lawrence polytope of P is the polytope whose vertices are the columns of the following (r+n)-by-2n matrix.

$$\begin{pmatrix} V & V \\ I_n & 2I_n \end{pmatrix},$$

where V is the r-by-n vertices matrix of P.

#### **EXAMPLES:**

### REFERENCES:

For more information, see Section 6.6 of [Zie2007].

## linear\_transformation(linear\_transf, new\_base\_ring=None)

Return the linear transformation of self.

### INPUT:

- linear\_transf a matrix, not necessarily in base\_ring()
- new\_base\_ring ring (optional); specify the new base ring; may avoid coercion failure

# OUTPUT:

The polyhedron transformed by that matrix, possibly coerced to a bigger base ring.

#### **EXAMPLES:**

```
sage: b3 = polytopes.Birkhoff_polytope(3)
sage: proj_mat=matrix([[0,1,0,0,0,0,0,0,0],[0,0,0,1,0,0,0,0,0],[0,0,0,0,0,1,0,0,
\leftarrow 0], [0,0,0,0,0,0,0,1,0]])
sage: b3_proj = proj_mat * b3; b3_proj
A 3-dimensional polyhedron in ZZ^4 defined as the convex hull of 5 vertices
sage: square = polytopes.regular_polygon(4)
                                                                      # optional -
→ sage.rings.number_field
sage: square.vertices_list()
                                                                      # optional -
→ sage.rings.number_field
[[0, -1], [1, 0], [-1, 0], [0, 1]]
sage: transf = matrix([[1,1],[0,1]])
                                                                      # optional -
→ sage.rings.number_field
sage: sheared = transf * square
                                                                      # optional -
→ sage.rings.number_field
```

Specifying the new base ring may avoid coercion failure:

```
sage: K.<sqrt2> = QuadraticField(2)
                                                                     # optional -
→ sage.rings.number_field
sage: L.<sqrt3> = QuadraticField(3)
                                                                     # optional -
→ sage.rings.number_field
sage: P = polytopes.cube()*sqrt2
                                                                      # optional -
→ sage.rings.number_field
sage: M = matrix([[sqrt3, 0, 0], [0, sqrt3, 0], [0, 0, 1]])
                                                                     # optional -
→ sage.rings.number_field
sage: P.linear_transformation(M, new_base_ring=K.composite_fields(L)[0])
→optional - sage.rings.number_field
A 3-dimensional polyhedron in (Number Field in sqrt2sqrt3 with defining
\rightarrow polynomial x^4 - 10*x^2 + 1 with sqrt2sqrt3 = 0.3178372451957823?)^3 defined
→as the convex hull of 8 vertices
```

Linear transformation without specified new base ring fails in this case:

### minkowski\_difference(other)

Return the Minkowski difference.

Minkowski subtraction can equivalently be defined via Minkowski addition (see minkowski\_sum()) or as set-theoretic intersection via

$$X\ominus Y=(X^c\oplus Y)^c=\bigcap_{y\in Y}(X-y)$$

where superscript-"c" means the complement in the ambient vector space. The Minkowski difference of convex sets is convex, and the difference of polyhedra is again a polyhedron. We only consider the case of polyhedra in the following. Note that it is not quite the inverse of addition. In fact:

- (X + Y) Y = X for any polyhedra X, Y.
- $(X-Y)+Y\subseteq X$
- (X Y) + Y = X if and only if Y is a Minkowski summand of X.

INPUT:

• other - a Polyhedron\_base

### **OUTPUT**:

The Minkowski difference of self and other. Also known as Minkowski subtraction of other from self.

### **EXAMPLES:**

```
sage: X = polytopes.hypercube(3)
sage: Y = Polyhedron(vertices=[(0,0,0), (0,0,1), (0,1,0), (1,0,0)]) / 2
sage: (X+Y)-Y == X
True
sage: (X-Y)+Y < X
True</pre>
```

The polyhedra need not be full-dimensional:

```
sage: X2 = Polyhedron(vertices=[(-1,-1,0),(1,-1,0),(-1,1,0),(1,1,0)])
sage: Y2 = Polyhedron(vertices=[(0,0,0), (0,1,0), (1,0,0)]) / 2
sage: (X2+Y2)-Y2 == X2
True
sage: (X2-Y2)+Y2 < X2
True</pre>
```

Minus sign is really an alias for minkowski\_difference()

Coercion of the base ring works:

# minkowski\_sum(other)

Return the Minkowski sum.

Minkowski addition of two subsets of a vector space is defined as

$$X \oplus Y = \bigcup_{y \in Y} (X+y) = \bigcup_{x \in X, y \in Y} (x+y)$$

See *minkowski\_difference()* for a partial inverse operation.

#### INPUT:

• other - a Polyhedron\_base

# OUTPUT:

The Minkowski sum of self and other

### **EXAMPLES:**

```
sage: X = polytopes.hypercube(3)
sage: Y = Polyhedron(vertices=[(0,0,0), (0,0,1/2), (0,1/2,0), (1/2,0,0)])
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 13 vertices
sage: four_cube = polytopes.hypercube(4)
sage: four_simplex = Polyhedron(vertices = [[0, 0, 0, 1], [0, 0, 1, 0], [0, 1, ...])
\rightarrow 0, 0], [1, 0, 0, 0]])
sage: four_cube + four_simplex
A 4-dimensional polyhedron in ZZ^4 defined as the convex hull of 36 vertices
sage: four_cube.minkowski_sum(four_simplex) == four_cube + four_simplex
True
sage: poly_spam = Polyhedron([[3,4,5,2],[1,0,0,1],[0,0,0,0],[0,4,3,2],[-3,-3,-3,
\rightarrow-3]], base_ring=ZZ)
sage: poly_eggs = Polyhedron([[5,4,5,4],[-4,5,-4,5],[4,-5,4,-5],[0,0,0,0]],__
→base_ring=QQ)
sage: poly_spam + poly_spam + poly_eggs
A 4-dimensional polyhedron in QQ^4 defined as the convex hull of 12 vertices
```

# one\_point\_suspension(vertex)

Return the one-point suspension of self by splitting the vertex vertex.

The resulting polyhedron has one more vertex and its dimension increases by one.

## INPUT:

• vertex - a Vertex of self

# **EXAMPLES:**

```
sage: cube = polytopes.cube()
sage: v = cube.vertices()[0]
sage: ops_cube = cube.one_point_suspension(v)
sage: ops_cube.f_vector()
(1, 9, 24, 24, 9, 1)
sage: pentagon = polytopes.regular_polygon(5)
                                                                     # optional -
→ sage.rings.number_field
sage: v = pentagon.vertices()[0]
                                                                     # optional -
→ sage.rings.number_field
sage: ops_pentagon = pentagon.one_point_suspension(v)
                                                                     # optional -
→ sage.rings.number_field
sage: ops_pentagon.f_vector()
                                                                     # optional -
→ sage.rings.number_field
(1, 6, 12, 8, 1)
```

It works with a polyhedral face as well:

```
sage: vv = cube.faces(0)[1]
sage: ops_cube2 = cube.one_point_suspension(vv)
sage: ops_cube == ops_cube2
True
```

### See also:

```
face_split()
```

```
polar(in_affine_span=False)
```

Return the polar (dual) polytope.

The original vertices are translated so that their barycenter is at the origin, and then the vertices are used as the coefficients in the polar inequalities.

The polytope must be full-dimensional, unless in\_affine\_span is True. If in\_affine\_span is True, then the operation will be performed in the linear/affine span of the polyhedron (after translation).

#### **EXAMPLES:**

in\_affine\_span somewhat ignores equations, performing the polar in the spanned subspace (after translating barycenter to origin):

```
sage: P = polytopes.simplex(3, base_ring=QQ)
sage: P.polar(in_affine_span=True)
A 3-dimensional polyhedron in QQ^4 defined as the convex hull of 4 vertices
```

Embedding the polytope in a higher dimension, commutes with polar in this case:

```
sage: point = Polyhedron([[0]])
sage: P = polytopes.cube().change_ring(QQ)
sage: (P*point).polar(in_affine_span=True) == P.polar()*point
True
```

## prism()

Return a prism of the original polyhedron.

# **EXAMPLES:**

```
sage: square = polytopes.hypercube(2)
sage: cube = square.prism()
sage: cube
A 3-dimensional polyhedron in ZZ^3 defined as the convex hull of 8 vertices
sage: hypercube = cube.prism()
sage: hypercube.n_vertices()
16
```

# product(other)

Return the Cartesian product.

### INPUT:

• other - a Polyhedron\_base

### **OUTPUT**:

The Cartesian product of self and other with a suitable base ring to encompass the two.

#### **EXAMPLES:**

```
sage: P1 = Polyhedron([[0],[1]], base_ring=ZZ)
sage: P2 = Polyhedron([[0],[1]], base_ring=QQ)
sage: P1.product(P2)
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 4 vertices
```

The Cartesian product is the product in the semiring of polyhedra:

```
sage: P1 * P1
A 2-dimensional polyhedron in ZZ^2 defined as the convex hull of 4 vertices
sage: P1 * P2
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 4 vertices
sage: P2 * P2
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 4 vertices
sage: 2 * P1
A 1-dimensional polyhedron in ZZ^1 defined as the convex hull of 2 vertices
sage: P1 * 2.0
A 1-dimensional polyhedron in RDF^1 defined as the convex hull of 2 vertices
```

An alias is cartesian\_product():

```
sage: P1.cartesian_product(P2) == P1.product(P2)
True
```

#### pyramid()

Return a polyhedron that is a pyramid over the original.

# **EXAMPLES:**

```
sage: square = polytopes.hypercube(2); square
A 2-dimensional polyhedron in ZZ^2 defined as the convex hull of 4 vertices
sage: egyptian_pyramid = square.pyramid(); egyptian_pyramid
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 5 vertices
sage: egyptian_pyramid.n_vertices()
5
sage: for v in egyptian_pyramid.vertex_generator(): print(v)
A vertex at (0, -1, -1)
A vertex at (0, -1, 1)
A vertex at (0, 1, -1)
A vertex at (0, 1, 0)
```

### stack(face, position=None)

Return a new polyhedron formed by stacking onto a face. Stacking a face adds a new vertex located slightly outside of the designated face.

## INPUT:

• face – a PolyhedronFace

• position – a positive number. Determines a relative distance from the barycenter of face. A value close to 0 will place the new vertex close to the face and a large value further away. Default is 1. If the given value is too large, an error is returned.

## **OUTPUT**:

A Polyhedron object

### **EXAMPLES:**

```
sage: cube = polytopes.cube()
sage: square_face = cube.facets()[2]
sage: stacked_square = cube.stack(square_face)
sage: stacked_square.f_vector()
(1, 9, 16, 9, 1)
sage: edge_face = cube.faces(1)[3]
sage: stacked_edge = cube.stack(edge_face)
sage: stacked_edge.f_vector()
(1, 9, 17, 10, 1)
sage: cube.stack(cube.faces(0)[0])
Traceback (most recent call last):
ValueError: cannot stack onto a vertex
sage: stacked_square_half = cube.stack(square_face,position=1/2)
sage: stacked_square_half.f_vector()
(1, 9, 16, 9, 1)
sage: stacked_square_large = cube.stack(square_face,position=10)
sage: hexaprism = polytopes.regular_polygon(6).prism()
                                                                     # optional -
→ sage.rings.number_field
sage: hexaprism.f_vector()
                                                                     # optional -
→ sage.rings.number_field
(1, 12, 18, 8, 1)
sage: square_face = hexaprism.faces(2)[2]
                                                                     # optional -
→ sage.rings.number_field
sage: stacked_hexaprism = hexaprism.stack(square_face)
                                                                     # optional -
→ sage.rings.number_field
sage: stacked_hexaprism.f_vector()
                                                                     # optional -
→ sage.rings.number_field
(1, 13, 22, 11, 1)
sage: hexaprism.stack(square_face,position=4)
                                                                     # optional -
→ sage.rings.number_field
Traceback (most recent call last):
ValueError: the chosen position is too large
sage: s = polytopes.simplex(7)
sage: f = s.faces(3)[69]
sage: sf = s.stack(f); sf
A 7-dimensional polyhedron in QQ^8 defined as the convex hull of 9 vertices
sage: sf.vertices()
```

```
(A vertex at (-4, -4, -4, -4, 17/4, 17/4, 17/4, 17/4),

A vertex at (0, 0, 0, 0, 0, 0, 0, 1),

A vertex at (0, 0, 0, 0, 0, 0, 1, 0),

A vertex at (0, 0, 0, 0, 0, 1, 0, 0),

A vertex at (0, 0, 0, 0, 1, 0, 0, 0),

A vertex at (0, 0, 0, 1, 0, 0, 0, 0),

A vertex at (0, 0, 1, 0, 0, 0, 0, 0),

A vertex at (0, 1, 0, 0, 0, 0, 0),

A vertex at (1, 0, 0, 0, 0, 0, 0))
```

It is possible to stack on unbounded faces:

```
sage: Q = Polyhedron(vertices=[[0,1],[1,0]],rays=[[1,1]])
sage: E = Q.faces(1)
sage: Q.stack(E[0],1/2).Vrepresentation()
(A vertex at (0, 1),
A vertex at (1, 0),
A ray in the direction (1, 1),
A vertex at (2, 0)
sage: Q.stack(E[1],1/2).Vrepresentation()
(A vertex at (0, 1),
A vertex at (0, 2),
A vertex at (1, 0),
A ray in the direction (1, 1))
sage: Q.stack(E[2],1/2).Vrepresentation()
(A vertex at (0, 0),
A vertex at (0, 1),
A vertex at (1, 0),
A ray in the direction (1, 1))
```

Stacking requires a proper face:

```
sage: Q.stack(Q.faces(2)[0])
Traceback (most recent call last):
...
ValueError: can only stack on proper face
```

### subdirect\_sum(other)

Return the subdirect sum of self and other.

The subdirect sum of two polyhedron is a projection of the join of the two polytopes. It is obtained by placing the two objects in orthogonal subspaces intersecting at the origin.

## INPUT:

• other – a Polyhedron\_base

### **EXAMPLES:**

```
sage: P1 = Polyhedron([[1],[2]], base_ring=ZZ)
sage: P2 = Polyhedron([[3],[4]], base_ring=QQ)
sage: sds = P1.subdirect_sum(P2);sds
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 4
vertices
sage: sds.vertices()
```

```
(A vertex at (0, 3),
A vertex at (0, 4),
A vertex at (1, 0),
A vertex at (2, 0))
```

### See also:

```
join() direct_sum()
```

### translation(displacement)

Return the translated polyhedron.

### INPUT:

 displacement – a displacement vector or a list/tuple of coordinates that determines a displacement vector

### **OUTPUT**:

The translated polyhedron.

### **EXAMPLES:**

```
sage: P = Polyhedron([[0,0],[1,0],[0,1]], base_ring=ZZ)
sage: P.translation([2,1])
A 2-dimensional polyhedron in ZZ^2 defined as the convex hull of 3 vertices
sage: P.translation( vector(QQ,[2,1]) )
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 3 vertices
```

# truncation(cut\_frac=None)

Return a new polyhedron formed from two points on each edge between two vertices.

# INPUT:

• cut\_frac – integer, how deeply to cut into the edge. Default is  $\frac{1}{3}$ .

### **OUTPUT**:

A Polyhedron object, truncated as described above.

## **EXAMPLES:**

```
sage: cube = polytopes.hypercube(3)
sage: trunc_cube = cube.truncation()
sage: trunc_cube.n_vertices()
24
sage: trunc_cube.n_inequalities()
14
```

### wedge(face, width=1)

Return the wedge over a face of the polytope self.

The wedge over a face F of a polytope P with width  $w \neq 0$  is defined as:

$$(P \times \mathbb{R}) \cap \{a^{\top}x + |wx_{d+1}| \le b\}$$

where  $\{x|a^{\top}x=b\}$  is a supporting hyperplane defining F.

## INPUT:

• face – a PolyhedronFace of self, the face which we take the wedge over

• width – a nonzero number (default: 1); specifies how wide the wedge will be

### **OUTPUT**:

A (bounded) polyhedron

**EXAMPLES:** 

```
sage: P_4 = polytopes.regular_polygon(4)
        # optional - sage.rings.number_field
sage: W1 = P_4.wedge(P_4.faces(1)[0]); W1
        # optional - sage.rings.number_field
A 3-dimensional polyhedron in AA^3 defined as the convex hull of 6 vertices
sage: triangular_prism = polytopes.regular_polygon(3).prism()
        # optional - sage.rings.number_field
sage: W1.is_combinatorially_isomorphic(triangular_prism) # optional - sage.
⊶graphs
            # optional - sage.rings.number_field
True
sage: Q = polytopes.hypersimplex(4,2)
sage: W2 = Q.wedge(Q.faces(2)[7]); W2
A 4-dimensional polyhedron in QQ^5 defined as the convex hull of 9 vertices
sage: W2.vertices()
(A vertex at (1, 1, 0, 0, 1),
A vertex at (1, 1, 0, 0, -1),
A vertex at (1, 0, 1, 0, 1),
A vertex at (1, 0, 1, 0, -1),
A vertex at (1, 0, 0, 1, 1),
A vertex at (1, 0, 0, 1, -1),
A vertex at (0, 0, 1, 1, 0),
A vertex at (0, 1, 1, 0, 0),
A vertex at (0, 1, 0, 1, 0))
sage: W3 = Q.wedge(Q.faces(1)[11]); W3
A 4-dimensional polyhedron in QQ^5 defined as the convex hull of 10 vertices
sage: W3.vertices()
(A vertex at (1, 1, 0, 0, -2),
A vertex at (1, 1, 0, 0, 2),
A vertex at (1, 0, 1, 0, -2),
A vertex at (1, 0, 1, 0, 2),
A vertex at (1, 0, 0, 1, 1),
A vertex at (1, 0, 0, 1, -1),
A vertex at (0, 1, 0, 1, 0),
A vertex at (0, 1, 1, 0, 1),
A vertex at (0, 0, 1, 1, 0),
A vertex at (0, 1, 1, 0, -1)
sage: C_3_7 = polytopes.cyclic_polytope(3,7)
sage: P_6 = polytopes.regular_polygon(6)
        # optional - sage.rings.number_field
sage: W4 = P_6.wedge(P_6.faces(1)[0])
        # optional - sage.rings.number_field
sage: W4.is_combinatorially_isomorphic(C_3_7.polar())
                                                           # optional - sage.
            # optional - sage.rings.number_field
\hookrightarrow graphs
True
```

### **REFERENCES:**

For more information, see Chapter 15 of [HoDaCG17].

# 2.6.7 Base class for polyhedra: Methods for plotting and affine hull projection

Bases: sage.geometry.polyhedron.base5.Polyhedron\_base5

Methods related to plotting including affine hull projection.

```
affine_hull(*args, **kwds)
```

Return the affine hull of self as a polyhedron.

### **EXAMPLES:**

```
sage: half_plane_in_space = Polyhedron(ieqs=[(0,1,0,0)], eqns=[(0,0,0,1)])
sage: half_plane_in_space.affine_hull().Hrepresentation()
(An equation (0, 0, 1) x + 0 == 0,)
sage: polytopes.cube().affine_hull().is_universe()
True
```

**affine\_hull\_manifold**(name=None, latex\_name=None, start\_index=0, ambient\_space=None, ambient\_chart=None, names=None, \*\*kwds)

Return the affine hull of self as a manifold.

If self is full-dimensional, it is just the ambient Euclidean space. Otherwise, it is a Riemannian submanifold of the ambient Euclidean space.

## INPUT:

- ambient\_space a EuclideanSpace of the ambient dimension (default: the manifold of ambient\_chart, if provided; otherwise, a new instance of EuclideanSpace).
- ambient\_chart a chart on ambient\_space.
- names names for the coordinates on the affine hull.
- optional arguments accepted by affine\_hull\_projection().

The default chart is determined by the optional arguments of affine\_hull\_projection().

### **EXAMPLES:**

```
sage: triangle = Polyhedron([(1,0,0), (0,1,0), (0,0,1)]); triangle
A 2-dimensional polyhedron in ZZ^3 defined as the convex hull of 3 vertices
sage: A = triangle.affine_hull_manifold(name='A'); A
2-dimensional Riemannian submanifold A embedded in the Euclidean space E^3
sage: A.embedding().display()
A → E^3
    (x0, x1) ↦ (x, y, z) = (t0 + x0, t0 + x1, t0 - x0 - x1 + 1)
sage: A.embedding().inverse().display()
E^3 → A
    (x, y, z) ↦ (x0, x1) = (x, y)
sage: A.adapted_chart()
```

```
[Chart (E^3, (x0_E3, x1_E3, t0_E3))]

sage: A.normal().display()

n = 1/3*sqrt(3) e_x + 1/3*sqrt(3) e_y + 1/3*sqrt(3) e_z

sage: A.induced_metric() # Need to call this before volume_form

Riemannian metric gamma on the 2-dimensional Riemannian submanifold A embedded_
in the Euclidean space E^3

sage: A.volume_form()

2-form eps_gamma on the 2-dimensional Riemannian submanifold A embedded in the_
Euclidean space E^3
```

### Orthogonal version:

```
sage: A = triangle.affine_hull_manifold(name='A', orthogonal=True); A
2-dimensional Riemannian submanifold A embedded in the Euclidean space E^3
sage: A.embedding().display()
A \rightarrow E^3
   (x0, x1) \mapsto (x, y, z) = (t0 - 1/2*x0 - 1/3*x1 + 1, t0 + 1/2*x0 - 1/3*x1, t0_\(\dots\) \(\dots\) + 2/3*x1)
sage: A.embedding().inverse().display()
E^3 \rightarrow A
   (x, y, z) \mapsto (x0, x1) = (-x + y + 1, -1/2*x - 1/2*y + z + 1/2)
```

Arrangement of affine hull of facets:

```
sage: D = polytopes.dodecahedron()
                                                                      # optional -
→ sage.rings.number_field
sage: E3 = EuclideanSpace(3)
                                                                      # optional -
→ sage.rings.number_field
sage: submanifolds = [
                                                                      # optional -
→ sage.rings.number_field
          F.as_polyhedron().affine_hull_manifold(name=f'F{i}', orthogonal=True,_
. . . . . .
→ambient_space=E3)
          for i, F in enumerate(D.facets())]
. . . . :
sage: sum(FM.plot({}, srange(-2, 2, 0.1), srange(-2, 2, 0.1), opacity=0.2)
→not tested # optional - sage.plot # optional - sage.rings.number_field
          for FM in submanifolds) + D.plot()
. . . . :
Graphics3d Object
```

# Full-dimensional case:

```
sage: cube = polytopes.cube(); cube
A 3-dimensional polyhedron in ZZ^3 defined as the convex hull of 8 vertices
sage: cube.affine_hull_manifold()
Euclidean space E^3
```

**affine\_hull\_projection**(as\_polyhedron, as\_affine\_map=None, orthogonal=False, orthonormal=False, extend=False, minimal=False, return\_all\_data=False, as\_convex\_set=False)

Return the polyhedron projected into its affine hull.

Each polyhedron is contained in some smallest affine subspace (possibly the entire ambient space) – its affine hull. We provide an affine linear map that projects the ambient space of the polyhedron to the standard Euclidean space of dimension of the polyhedron, which restricts to a bijection from the affine hull.

The projection map is not unique; some parameters control the choice of the map. Other parameters control

the output of the function.

### INPUT:

- as\_polyhedron (or as\_convex\_set) (boolean or the default None) and
- as\_affine\_map (boolean, default False) control the output

The default as\_polyhedron=None translates to as\_polyhedron=not as\_affine\_map, therefore to as\_polyhedron=True if nothing is specified.

If exactly one of either as\_polyhedron or as\_affine\_map is set, then either a polyhedron or the affine transformation is returned. The affine transformation sends the embedded polytope to a full dimensional one. It is given as a pair (A, b), where A is a linear transformation and b is a vector, and the affine transformation sends v to A(v)+b.

If both as\_polyhedron and as\_affine\_map are set, then both are returned, encapsulated in an instance of AffineHullProjectionData.

• return\_all\_data - (boolean, default False)

If set, then as\_polyhedron and as\_affine\_map will set (possibly overridden) and additional (internal) data concerning the transformation is returned. Everything is encapsulated in an instance of AffineHullProjectionData in this case.

- orthogonal boolean (default: False); if True, provide an orthogonal transformation.
- orthonormal boolean (default: False); if True, provide an orthonormal transformation. If the base ring does not provide the necessary square roots, the extend parameter needs to be set to True.
- extend boolean (default: False); if True, allow base ring to be extended if necessary. This becomes relevant when requiring an orthonormal transformation.
- minimal boolean (default: False); if True, when doing an extension, it computes the minimal base ring of the extension, otherwise the base ring is AA.

#### **OUTPUT:**

A full-dimensional polyhedron or an affine transformation, depending on the parameters as\_polyhedron and as\_affine\_map, or an instance of *AffineHullProjectionData* containing all data (parameter return\_all\_data).

If the output is an instance of AffineHullProjectionData, the following fields may be set:

- image the projection of the original polyhedron
- projection\_map the affine map as a pair whose first component is a linear transformation and its second component a shift; see above.
- section\_map an affine map as a pair whose first component is a linear transformation and its second component a shift. It maps the codomain of affine\_map to the affine hull of self. It is a right inverse of projection\_map.

Note that all of these data are compatible.

### Todo:

• make the parameters orthogonal and orthonormal work with unbounded polyhedra.

# **EXAMPLES:**

```
sage: triangle = Polyhedron([(1,0,0), (0,1,0), (0,0,1)]); triangle
A 2-dimensional polyhedron in ZZ^3 defined as the convex hull of 3 vertices
sage: triangle.affine_hull_projection()
A 2-dimensional polyhedron in ZZ^2 defined as the convex hull of 3 vertices
sage: half3d = Polyhedron(vertices=[(3,2,1)], rays=[(1,0,0)])
sage: half3d.affine_hull_projection().Vrepresentation()
(A ray in the direction (1), A vertex at (3))
```

The resulting affine hulls depend on the parameter orthogonal and orthonormal:

```
sage: L = Polyhedron([[1,0],[0,1]]); L
A 1-dimensional polyhedron in ZZ^2 defined as the convex hull of 2 vertices
sage: A = L.affine_hull_projection(); A
A 1-dimensional polyhedron in ZZ^1 defined as the convex hull of 2 vertices
sage: A.vertices()
(A vertex at (0), A vertex at (1))
sage: A = L.affine_hull_projection(orthogonal=True); A
A 1-dimensional polyhedron in QQ^1 defined as the convex hull of 2 vertices
sage: A.vertices()
(A vertex at (0), A vertex at (2))
sage: A = L.affine_hull_projection(orthonormal=True)
        # optional - sage.rings.number_field
Traceback (most recent call last):
ValueError: the base ring needs to be extended; try with "extend=True"
sage: A = L.affine_hull_projection(orthonormal=True, extend=True); A
        # optional - sage.rings.number_field
A 1-dimensional polyhedron in AA^1 defined as the convex hull of 2 vertices
sage: A.vertices()
        # optional - sage.rings.number_field
(A vertex at (1.414213562373095?), A vertex at (0.?e-18))
```

More generally:

```
sage: S = polytopes.simplex(); S
A 3-dimensional polyhedron in ZZ^4 defined as the convex hull of 4 vertices
sage: S.vertices()
(A vertex at (0, 0, 0, 1),
A vertex at (0, 0, 1, 0),
A vertex at (0, 1, 0, 0),
A vertex at (1, 0, 0, 0)
sage: A = S.affine_hull_projection(); A
A 3-dimensional polyhedron in ZZ^3 defined as the convex hull of 4 vertices
sage: A.vertices()
(A vertex at (0, 0, 0),
A vertex at (0, 0, 1),
A vertex at (0, 1, 0),
A vertex at (1, 0, 0)
sage: A = S.affine_hull_projection(orthogonal=True); A
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 4 vertices
sage: A.vertices()
(A vertex at (0, 0, 0),
```

```
A vertex at (2, 0, 0),
A vertex at (1, 3/2, 0),
A vertex at (1, 1/2, 4/3))

sage: A = S.affine_hull_projection(orthonormal=True, extend=True); A

A 3-dimensional polyhedron in AA^3 defined as the convex hull of 4 vertices

sage: A.vertices()

(A vertex at (0.7071067811865475?, 0.4082482904638630?, 1.154700538379252?),
A vertex at (0.7071067811865475?, 1.224744871391589?, 0.?e-18),
A vertex at (1.414213562373095?, 0.?e-18, 0.?e-18),
A vertex at (0.?e-18, 0.?e-18, 0.?e-18))
```

With the parameter minimal one can get a minimal base ring:

More examples with the orthonormal parameter:

```
sage: P = polytopes.permutahedron(3); P
                                                          # optional - sage.
→combinat # optional - sage.rings.number_field
A 2-dimensional polyhedron in ZZ^3 defined as the convex hull of 6 vertices
sage: set([F.as_polyhedron().affine_hull_projection(orthonormal=True,_
-extend=True).volume() for F in P.affine_hull_projection().faces(1)]) == {1,...
→sqrt(AA(2))} # optional - sage.combinat # optional - sage.rings.number_field
sage: set([F.as_polyhedron().affine_hull_projection(orthonormal=True,_
→extend=True).volume() for F in P.affine_hull_projection(orthonormal=True, __
→extend=True).faces(1)]) == {sqrt(AA(2))} # optional - sage.combinat #_
→optional - sage.rings.number_field
True
sage: D = polytopes.dodecahedron()
       # optional - sage.rings.number_field
sage: F = D.faces(2)[0].as_polyhedron()
        # optional - sage.rings.number_field
sage: F.affine_hull_projection(orthogonal=True)
        # optional - sage.rings.number_field
A 2-dimensional polyhedron in (Number Field in sqrt5 with defining polynomial x^
-2 - 5 with sqrt5 = 2.236067977499790?)^2 defined as the convex hull of 5.
→vertices
sage: F.affine_hull_projection(orthonormal=True, extend=True)
        # optional - sage.rings.number_field
A 2-dimensional polyhedron in AA^2 defined as the convex hull of 5 vertices
sage: K.<sqrt2> = QuadraticField(2)
       # optional - sage.rings.number_field
                                                                  (continues on next page)
```

```
sage: P = Polyhedron([2*[K.zero()],2*[sqrt2]]); P
        # optional - sage.rings.number_field
A 1-dimensional polyhedron in (Number Field in sqrt2 with defining polynomial x^
-2 - 2 with sqrt2 = 1.414213562373095?)^2 defined as the convex hull of ^2
_vertices
sage: P.vertices()
        # optional - sage.rings.number_field
(A vertex at (0, 0), A vertex at (sqrt2, sqrt2))
sage: A = P.affine_hull_projection(orthonormal=True); A
        # optional - sage.rings.number_field
A 1-dimensional polyhedron in (Number Field in sqrt2 with defining polynomial x^
\rightarrow 2 - 2 with sqrt2 = 1.414213562373095?) 1 defined as the convex hull of 2.
→vertices
sage: A.vertices()
        # optional - sage.rings.number_field
(A vertex at (0), A vertex at (2))
sage: K.<sqrt3> = QuadraticField(3)
        # optional - sage.rings.number_field
sage: P = Polyhedron([2*[K.zero()],2*[sqrt3]]); P
        # optional - sage.rings.number_field
A 1-dimensional polyhedron in (Number Field in sqrt3 with defining polynomial x^
-2 - 3 with sqrt3 = 1.732050807568878?) ^2 defined as the convex hull of ^2
→vertices
sage: P.vertices()
        # optional - sage.rings.number_field
(A vertex at (0, 0), A vertex at (sqrt3, sqrt3))
sage: A = P.affine_hull_projection(orthonormal=True)
        # optional - sage.rings.number_field
Traceback (most recent call last):
ValueError: the base ring needs to be extended; try with "extend=True"
sage: A = P.affine_hull_projection(orthonormal=True, extend=True); A
        # optional - sage.rings.number_field
A 1-dimensional polyhedron in AA^1 defined as the convex hull of 2 vertices
sage: A.vertices()
        # optional - sage.rings.number_field
(A vertex at (0), A vertex at (2.449489742783178?))
sage: sqrt(6).n()
        # optional - sage.rings.number_field
2.44948974278318
```

The affine hull is combinatorially equivalent to the input:

```
sage: P.is_combinatorially_isomorphic(P.affine_hull_projection())

# optional - sage.rings.number_field
True
sage: P.is_combinatorially_isomorphic(P.affine_hull_
projection(orthogonal=True)) # optional - sage.rings.number_field
True
sage: P.is_combinatorially_isomorphic(P.affine_hull_projection(orthonormal=True,
extend=True)) # optional - sage.rings.number_field
```

True

The orthonormal=True parameter preserves volumes; it provides an isometric copy of the polyhedron:

```
sage: Pentagon = polytopes.dodecahedron().faces(2)[0].as_polyhedron()
        # optional - sage.rings.number_field
sage: P = Pentagon.affine_hull_projection(orthonormal=True, extend=True)
        # optional - sage.rings.number_field
sage: _, c= P.is_inscribed(certificate=True)
        # optional - sage.rings.number_field
sage: c
        # optional - sage.rings.number_field
(0.4721359549995794?, 0.6498393924658126?)
sage: circumradius = (c-vector(P.vertices()[0])).norm()
        # optional - sage.rings.number_field
sage: p = polytopes.regular_polygon(5)
        # optional - sage.rings.number_field
sage: p.volume()
        # optional - sage.rings.number_field
2.377641290737884?
sage: P.volume()
        # optional - sage.rings.number_field
1.53406271079097?
sage: p.volume()*circumradius^2
        # optional - sage.rings.number_field
1.534062710790965?
sage: P.volume() == p.volume()*circumradius^2
        # optional - sage.rings.number_field
True
```

One can also use orthogonal parameter to calculate volumes; in this case we don't need to switch base rings. One has to divide by the square root of the determinant of the linear part of the affine transformation times its transpose:

```
sage: Pentagon = polytopes.dodecahedron().faces(2)[0].as_polyhedron()
        # optional - sage.rings.number_field
sage: Pnormal = Pentagon.affine_hull_projection(orthonormal=True, extend=True)
       # optional - sage.rings.number_field
sage: Pgonal = Pentagon.affine_hull_projection(orthogonal=True)
        # optional - sage.rings.number_field
sage: A, b = Pentagon.affine_hull_projection(orthogonal=True, as_affine_
→map=True)
                # optional - sage.rings.number_field
sage: Adet = (A.matrix().transpose()*A.matrix()).det()
        # optional - sage.rings.number_field
sage: Pnormal.volume()
        # optional - sage.rings.number_field
1.53406271079097?
sage: Pgonal.volume()/Adet.sqrt(extend=True)
        # optional - sage.rings.number_field
-80*(55*sqrt(5) - 123)/sqrt(-6368*sqrt(5) + 14240)
sage: Pgonal.volume()/AA(Adet).sqrt().n(digits=20)
        # optional - sage.rings.number_field
```

```
1.5340627107909646813

sage: AA(Pgonal.volume()^2) == (Pnormal.volume()^2)*AA(Adet)

# optional - sage.rings.number_field

True
```

Another example with as\_affine\_map=True:

For unbounded, non full-dimensional polyhedra, the orthogonal=True and orthonormal=True is not implemented:

Setting as\_affine\_map to True without orthogonal or orthonormal set to True:

```
sage: S = polytopes.simplex()
sage: S.affine_hull_projection(as_affine_map=True)
(Vector space morphism represented by the matrix:
  [1 0 0]
  [0 1 0]
  [0 0 1]
  [0 0 0]
Domain: Vector space of dimension 4 over Rational Field
Codomain: Vector space of dimension 3 over Rational Field,
  (0, 0, 0))
```

If the polyhedron is full-dimensional, it is returned:

```
sage: polytopes.cube().affine_hull_projection()
A 3-dimensional polyhedron in ZZ^3 defined as the convex hull of 8 vertices
sage: polytopes.cube().affine_hull_projection(as_affine_map=True)
(Vector space morphism represented by the matrix:
  [1 0 0]
  [0 1 0]
  [0 0 1]
Domain: Vector space of dimension 3 over Rational Field
Codomain: Vector space of dimension 3 over Rational Field,
  (0, 0, 0))
```

Return polyhedron and affine map:

```
sage: S = polytopes.simplex(2)
sage: data = S.affine_hull_projection(orthogonal=True,
. . . . :
                                       as_polyhedron=True,
                                       as_affine_map=True); data
. . . . :
AffineHullProjectionData(image=A 2-dimensional polyhedron in QQ^2
        defined as the convex hull of 3 vertices,
    projection_linear_map=Vector space morphism represented by the matrix:
        [-1 - 1/2]
           1 -1/2]
            0
                 17
        Domain: Vector space of dimension 3 over Rational Field
        Codomain: Vector space of dimension 2 over Rational Field,
    projection_translation=(1, 1/2),
    section_linear_map=None,
    section_translation=None)
```

Return all data:

```
sage: data = S.affine_hull_projection(orthogonal=True, return_all_data=True);
AffineHullProjectionData(image=A 2-dimensional polyhedron in QQ^2
        defined as the convex hull of 3 vertices,
   projection_linear_map=Vector space morphism represented by the matrix:
        [-1 - 1/2]
           1 - 1/2
        0
                 17
        Domain: Vector space of dimension 3 over Rational Field
        Codomain: Vector space of dimension 2 over Rational Field,
   projection_translation=(1, 1/2),
   section_linear_map=Vector space morphism represented by the matrix:
        [-1/2  1/2]
                      70
        [-1/3 - 1/3 2/3]
        Domain: Vector space of dimension 2 over Rational Field
        Codomain: Vector space of dimension 3 over Rational Field, section_
\rightarrowtranslation=(1, 0, 0))
```

The section map is a right inverse of the projection map:

Same without orthogonal=True:

```
sage: data = S.affine_hull_projection(return_all_data=True); data
AffineHullProjectionData(image=A 2-dimensional polyhedron in ZZ^2
        defined as the convex hull of 3 vertices,
    projection_linear_map=Vector space morphism represented by the matrix:
        [0 1]
        [0 0]
        Domain: Vector space of dimension 3 over Rational Field
        Codomain: Vector space of dimension 2 over Rational Field, projection_
\rightarrowtranslation=(0.0).
    section_linear_map=Vector space morphism represented by the matrix:
        [1 \quad 0 \quad -1]
        [0 \ 1 \ -1]
        Domain: Vector space of dimension 2 over Rational Field
        Codomain: Vector space of dimension 3 over Rational Field, section_
\rightarrowtranslation=(0, 0, 1))
sage: data.image.linear_transformation(data.section_linear_map.matrix().
→transpose()) + data.section_translation == S
```

```
sage: P0 = Polyhedron(
          ieqs=[(0, -1, 0, 1, 1, 1), (0, 1, 1, 0, -1, -1), (0, -1, 1, 1, 0, 0),
                (0, 1, 0, 0, 0, 0), (0, 0, 1, 1, -1, -1), (0, 0, 0, 0, 0, 1),
. . . . .
                (0, 0, 0, 0, 1, 0), (0, 0, 0, 1, 0, -1), (0, 0, 1, 0, 0, 0)])
. . . . :
sage: P = P0.intersection(Polyhedron(eqns=[(-1, 1, 1, 1, 1, 1)]))
sage: P.dim()
sage: P.affine_hull_projection(orthogonal=True, as_affine_map=True)[0]
Vector space morphism represented by the matrix:
    0
          0
                 0
                     1/3]
[-2/3 -1/6]
                 0 - 1/12
  1/3 -1/6
             1/2 -1/12]
       1/2
                 0 - 1/12
[ 1/3 -1/6 -1/2 -1/12]
Domain: Vector space of dimension 5 over Rational Field
Codomain: Vector space of dimension 4 over Rational Field
```

# gale\_transform()

Return the Gale transform of a polytope as described in the reference below.

### **OUTPUT**:

A list of vectors, the Gale transform. The dimension is the dimension of the affine dependencies of the vertices of the polytope.

#### **EXAMPLES:**

This is from the reference, for a triangular prism:

```
sage: p = Polyhedron(vertices = [[0,0],[0,1],[1,0]])
sage: p2 = p.prism()
sage: p2.gale_transform()
((-1, 0), (0, -1), (1, 1), (-1, -1), (1, 0), (0, 1))
```

#### REFERENCES:

Lectures in Geometric Combinatorics, R.R.Thomas, 2006, AMS Press.

### See also:

```
gale_transform_to_polyhedron().
```

### INPUT:

- point, line, polygon Parameters to pass to point (0d), line (1d), and polygon (2d) plot commands. Allowed values are:
  - A Python dictionary to be passed as keywords to the plot commands.
  - A string or triple of numbers: The color. This is equivalent to passing the dictionary {'color':...}.
  - False: Switches off the drawing of the corresponding graphics object
- wireframe, fill Similar to point, line, and polygon, but fill is used for the graphics objects in the dimension of the polytope (or of dimension 2 for higher dimensional polytopes) and wireframe is used for all lower-dimensional graphics objects (default: 'green' for fill and 'blue' for wireframe)
- position positive number; the position to take the projection point in Schlegel diagrams.
- orthonormal Boolean (default: True); whether to use orthonormal projections.
- \*\*kwds optional keyword parameters that are passed to all graphics objects.

### **OUTPUT**:

A (multipart) graphics object.

# **EXAMPLES:**

```
sage: square = polytopes.hypercube(2)
sage: point = Polyhedron([[1,1]])
sage: line = Polyhedron([[1,1],[2,1]])
sage: cube = polytopes.hypercube(3)
sage: hypercube = polytopes.hypercube(4)
```

By default, the wireframe is rendered in blue and the fill in green:

```
sage: square.plot() # optional - sage.plot
Graphics object consisting of 6 graphics primitives
sage: point.plot() # optional - sage.plot
Graphics object consisting of 1 graphics primitive
sage: line.plot() # optional - sage.plot
Graphics object consisting of 2 graphics primitives
sage: cube.plot() # optional - sage.plot
Graphics3d Object
```

```
sage: hypercube.plot() # optional - sage.plot
Graphics3d Object
```

Draw the lines in red and nothing else:

Draw points in red, no lines, and a blue polygon:

If we instead use the fill and wireframe options, the coloring depends on the dimension of the object:

```
sage: square.plot(fill='green', wireframe='red') # optional - sage.plot
Graphics object consisting of 6 graphics primitives
sage: point.plot(fill='green', wireframe='red') # optional - sage.plot
Graphics object consisting of 1 graphics primitive
sage: line.plot(fill='green', wireframe='red') # optional - sage.plot
Graphics object consisting of 2 graphics primitives
sage: cube.plot(fill='green', wireframe='red') # optional - sage.plot
Graphics3d Object
sage: hypercube.plot(fill='green', wireframe='red') # optional - sage.plot
Graphics3d Object
```

It is possible to draw polyhedra up to dimension 4, no matter what the ambient dimension is:

```
sage: hcube = polytopes.hypercube(5)
sage: facet = hcube.facets()[0].as_polyhedron();facet
```

```
A 4-dimensional polyhedron in ZZ^5 defined as the convex hull of 16 vertices sage: facet.plot() # optional - sage.plot
Graphics3d Object
```

For a 3d plot, we may draw the polygons with rainbow colors, using any of the following ways:

```
sage: cube.plot(polygon='rainbow') # optional - sage.plot
Graphics3d Object
sage: cube.plot(polygon={'color':'rainbow'}) # optional - sage.plot
Graphics3d Object
sage: cube.plot(fill='rainbow') # optional - sage.plot
Graphics3d Object
```

For a 3d plot, the size of a point, the thickness of a line and the width of an arrow are controlled by the respective parameters:

### projection(projection=None)

Return a projection object.

#### INPUT:

• proj – a projection function

# OUTPUT:

The identity projection. This is useful for plotting polyhedra.

## See also:

schlegel\_projection() for a more interesting projection.

#### **EXAMPLES:**

```
sage: p = polytopes.hypercube(3)
sage: proj = p.projection()
sage: proj
The projection of a polyhedron into 3 dimensions
```

# render\_solid(\*\*kwds)

Return a solid rendering of a 2- or 3-d polytope.

### **EXAMPLES:**

```
sage: p = polytopes.hypercube(3)
sage: p_solid = p.render_solid(opacity = .7)
sage: type(p_solid)
<class 'sage.plot.plot3d.index_face_set.IndexFaceSet'>
```

## render\_wireframe(\*\*kwds)

For polytopes in 2 or 3 dimensions, return the edges as a list of lines.

### **EXAMPLES:**

```
sage: p = Polyhedron([[1,2,],[1,1],[0,0]])
sage: p_wireframe = p.render_wireframe()
sage: p_wireframe._objects
[Line defined by 2 points, Line defined by 2 points, Line defined by 2 points]
```

## schlegel\_projection(facet=None, position=None)

Return the Schlegel projection.

- The facet is orthonormally transformed into its affine hull.
- The position specifies a point coming out of the barycenter of the facet from which the other vertices will be projected into the facet.

### **INPUT:**

- facet a PolyhedronFace. The facet into which the Schlegel diagram is created. The default is the
  first facet.
- position a positive number. Determines a relative distance from the barycenter of facet. A value close to 0 will place the projection point close to the facet and a large value further away. Default is 1. If the given value is too large, an error is returned.

#### **OUTPUT:**

A Projection object.

### **EXAMPLES:**

```
sage: p = polytopes.hypercube(3)
sage: sch_proj = p.schlegel_projection()
sage: schlegel_edge_indices = sch_proj.lines
sage: schlegel_edges = [sch_proj.coordinates_of(x) for x in schlegel_edge_
indices]
sage: len([x for x in schlegel_edges if x[0][0] > 0])
8
```

The Schlegel projection preserves the convexity of facets, see trac ticket #30015:

The same truncated cube but see inside the tetrahedral facet:

```
sage: tfcube.facets()[4]
A 3-dimensional face of a Polyhedron in QQ^4 defined as the convex hull of 4
    vertices
sage: sp = tfcube.schlegel_projection(tfcube.facets()[4])
sage: sp.plot() # optional - sage.plot
Graphics3d Object
```

A different values of position changes the projection:

```
sage: sp = tfcube.schlegel_projection(tfcube.facets()[4],1/2)
sage: sp.plot() # optional - sage.plot
Graphics3d Object
sage: sp = tfcube.schlegel_projection(tfcube.facets()[4],4)
sage: sp.plot() # optional - sage.plot
Graphics3d Object
```

A value which is too large give a projection point that sees more than one facet resulting in a error:

```
sage: sp = tfcube.schlegel_projection(tfcube.facets()[4],5)
Traceback (most recent call last):
...
ValueError: the chosen position is too large
```

#### show(\*\*kwds)

Display graphics immediately

This method attempts to display the graphics immediately, without waiting for the currently running code (if any) to return to the command line. Be careful, calling it from within a loop will potentially launch a large number of external viewer programs.

#### INPUT:

• kwds – optional keyword arguments. See plot() for the description of available options.

## **OUTPUT**:

This method does not return anything. Use *plot()* if you want to generate a graphics object that can be saved or further transformed.

### **EXAMPLES:**

```
sage: square = polytopes.hypercube(2)
sage: square.show(point='red') # optional - sage.plot
```

tikz(view=[0, 0, 1], angle=0, scale=1, edge\_color='blue!95!black', facet\_color='blue!95!black', opacity=0.8, vertex\_color='green', axis=False)

Return a string tikz\_pic consisting of a tikz picture of self according to a projection view and an angle angle obtained via the threejs viewer. self must be bounded.

### INPUT:

- view list (default: [0,0,1]) representing the rotation axis (see note below).
- angle integer (default: 0) angle of rotation in degree from 0 to 360 (see note below).
- scale integer (default: 1) specifying the scaling of the tikz picture.
- edge\_color string (default: 'blue!95!black') representing colors which tikz recognize.
- facet\_color string (default: 'blue!95!black') representing colors which tikz recognize.
- vertex\_color string (default: 'green') representing colors which tikz recognize.
- opacity real number (default: 0.8) between 0 and 1 giving the opacity of the front facets.
- axis Boolean (default: False) draw the axes at the origin or not.

#### **OUTPUT**:

• LatexExpr – containing the TikZ picture.

**Note:** This is a wrapper of a method of the projection object self.projection(). See tikz() for more detail

The inputs view and angle can be obtained by visualizing it using .show(aspect\_ratio=1). This will open an interactive view in your default browser, where you can rotate the polytope. Once the desired view angle is found, click on the information icon in the lower right-hand corner and select *Get Viewpoint*. This will copy a string of the form '[x,y,z],angle' to your local clipboard. Go back to Sage and type Img = P.tikz([x,y,z],angle).

The inputs view and angle can also be obtained from the viewer Jmol:

```
    Right click on the image
    Select ``Console``
    Select the tab ``State``
    Scroll to the line ``moveto``
```

It reads something like:

```
moveto 0.0 {x y z angle} Scale
```

The view is then [x,y,z] and angle is angle. The following number is the scale.

Jmol performs a rotation of angle degrees along the vector [x,y,z] and show the result from the z-axis.

#### **EXAMPLES:**

```
sage: co = polytopes.cuboctahedron()
sage: Img = co.tikz([0,0,1], 0)
sage: print('\n'.join(Img.splitlines()[:9]))
\begin{tikzpicture}%
    [x=\{(1.000000cm, 0.000000cm)\},
    y = \{(0.000000 cm, 1.000000 cm)\},\
    z=\{(0.000000cm, 0.000000cm)\},
    scale=1.000000,
    back/.style={loosely dotted, thin},
    edge/.style={color=blue!95!black, thick},
    facet/.style={fill=blue!95!black,fill opacity=0.800000},
    vertex/.style={inner sep=1pt,circle,draw=green!25!black,fill=green!75!black,
→thick}]
sage: print('\n'.join(Img.splitlines()[12:21]))
%% with the command: ._tikz_3d_in_3d and parameters:
\%\% view = [0, 0, 1]
%% angle = 0
%% scale = 1
%% edge_color = blue!95!black
%% facet_color = blue!95!black
%% opacity = 0.8
%% vertex_color = green
%% axis = False
sage: print('\n'.join(Img.splitlines()[22:26]))
%% Coordinate of the vertices:
%%
\coordinate (-1.00000, -1.00000, 0.00000) at (-1.00000, -1.00000, 0.00000);
\coordinate (-1.00000, 0.00000, -1.00000) at (-1.00000, 0.00000, -1.00000);
```

# 2.6.8 Base class for polyhedra: Methods for triangulation and volume computation

Bases: sage.geometry.polyhedron.base6.Polyhedron\_base6

Methods related to triangulation and volume.

```
centroid(engine='auto', **kwds)
```

Return the center of the mass of the polytope.

The mass is taken with respect to the induced Lebesgue measure, see *volume()*.

If the polyhedron is not compact, a NotImplementedError is raised.

# INPUT:

- engine either 'auto' (default), 'internal', 'TOPCOM', or 'normaliz'. The 'internal' and 'TOPCOM' instruct this package to always use its own triangulation algorithms or TOPCOM's algorithms, respectively. By default ('auto'), TOPCOM is used if it is available and internal routines otherwise.
- \*\*kwds keyword arguments that are passed to the triangulation engine (see triangulate()).

OUTPUT: The centroid as vector.

#### ALGORITHM:

We triangulate the polytope and find the barycenter of the simplices. We add the individual barycenters weighted by the fraction of the total mass.

### **EXAMPLES:**

```
sage: P = polytopes.hypercube(2).pyramid()
sage: P.centroid()
(1/4, 0, 0)

sage: P = polytopes.associahedron(['A',2])
sage: P.centroid()
(2/21, 2/21)

sage: P = polytopes.permutahedron(4, backend='normaliz') # optional -u
-pynormaliz
sage: P.centroid() # optional -u
-pynormaliz
(5/2, 5/2, 5/2, 5/2, 5/2)
```

The method is not implemented for unbounded polyhedra:

```
sage: P = Polyhedron(vertices=[(0,0)],rays=[(1,0),(0,1)])
sage: P.centroid()
Traceback (most recent call last):
...
NotImplementedError: the polyhedron is not compact
```

The centroid of an empty polyhedron is not defined:

```
sage: Polyhedron().centroid()
Traceback (most recent call last):
```

```
...
ZeroDivisionError: rational division by zero
```

integrate(function, measure='ambient', \*\*kwds)

Return the integral of function over this polytope.

### INPUT:

- self Polyhedron
- function a multivariate polynomial or a valid LattE description string for polynomials
- measure string, the measure to use

Allowed values are:

- ambient (default): Lebesgue measure of ambient space,
- induced: Lebesgue measure of the affine hull,
- induced\_nonnormalized: Lebesgue measure of the affine hull without the normalization by  $\sqrt{\det(A^{\top}A)}$  (with A being the affine transformation matrix; see affine\_hull()).
- \*\*kwds additional keyword arguments that are passed to the engine

#### **OUTPUT:**

The integral of the polynomial over the polytope

**Note:** The polytope triangulation algorithm is used. This function depends on LattE (i.e., the latte\_int optional package).

## **EXAMPLES:**

```
sage: P = polytopes.cube()
sage: x, y, z = polygens(QQ, 'x, y, z')
sage: P.integrate(x^2*y^2*z^2) # optional - latte_int
8/27
```

If the polyhedron has floating point coordinates, an inexact result can be obtained if we transform to rational coordinates:

Integral over a non full-dimensional polytope:

```
sage: x, y = polygens(QQ, 'x, y')
sage: P = Polyhedron(vertices=[[0,0],[1,1]])
sage: P.integrate(x*y) # optional - latte_int
0
sage: ixy = P.integrate(x*y, measure='induced'); ixy # optional - latte_int
0.4714045207910317?
```

```
sage: ixy.parent() # optional - latte_int
Algebraic Real Field
```

Convert to a symbolic expression:

```
sage: ixy.radical_expression() # optional - latte_int
1/3*sqrt(2)
```

Another non full-dimensional polytope integration:

Computing the mass center:

**triangulate**(*engine='auto'*, *connected=True*, *fine=False*, *regular=None*, *star=None*)
Return a triangulation of the polytope.

## INPUT:

• engine – either 'auto' (default), 'internal', 'TOPCOM', or 'normaliz'. The 'internal' and 'TOPCOM' instruct this package to always use its own triangulation algorithms or TOPCOM's algorithms, respectively. By default ('auto'), TOPCOM is used if it is available and internal routines otherwise.

The remaining keyword parameters are passed through to the *PointConfiguration* constructor:

- connected boolean (default: True). Whether the triangulations should be connected to the regular triangulations via bistellar flips. These are much easier to compute than all triangulations.
- fine boolean (default: False). Whether the triangulations must be fine, that is, make use of all points of the configuration.
- regular boolean or None (default: None). Whether the triangulations must be regular. A regular triangulation is one that is induced by a piecewise-linear convex support function. In other words, the shadows of the faces of a polyhedron in one higher dimension.
  - True: Only regular triangulations.
  - False: Only non-regular triangulations.
  - None (default): Both kinds of triangulation.

• star – either None (default) or a point. Whether the triangulations must be star. A triangulation is star if all maximal simplices contain a common point. The central point can be specified by its index (an integer) in the given points or by its coordinates (anything iterable.)

### **OUTPUT**:

A triangulation of the convex hull of the vertices as a *Triangulation*. The indices in the triangulation correspond to the *Vrepresentation()* objects.

#### **EXAMPLES:**

```
sage: cube = polytopes.hypercube(3)
sage: triangulation = cube.triangulate(
....: engine='internal') # to make doctest independent of TOPCOM
sage: triangulation
(<0,1,2,7>, <0,1,5,7>, <0,2,3,7>, <0,3,4,7>, <0,4,5,7>, <1,5,6,7>)
sage: simplex_indices = triangulation[0]; simplex_indices
(0, 1, 2, 7)
sage: simplex_vertices = [ cube.Vrepresentation(i) for i in simplex_indices ]
sage: simplex_vertices
[A vertex at (1, -1, -1),
    A vertex at (1, 1, -1),
    A vertex at (1, 1, 1)]
sage: Polyhedron(simplex_vertices)
A 3-dimensional polyhedron in ZZ^3 defined as the convex hull of 4 vertices
```

It is possible to use 'normaliz' as an engine. For this, the polyhedron should have the backend set to normaliz:

The normaliz engine can triangulate pointed cones:

They can also be affine cones:

**volume**(*measure='ambient'*, *engine='auto'*, \*\*kwds)

Return the volume of the polytope.

### INPUT:

- measure string. The measure to use. Allowed values are:
  - ambient (default): Lebesgue measure of ambient space (volume)
  - induced: Lebesgue measure of the affine hull (relative volume)
  - induced\_rational: Scaling of the Lebesgue measure for rational polytopes, such that the unit hypercube has volume 1
  - induced\_lattice: Scaling of the Lebesgue measure, such that the volume of the hypercube is factorial(n)
- engine string. The backend to use. Allowed values are:
  - 'auto' (default): choose engine according to measure
  - 'internal': see triangulate()
  - 'TOPCOM': see triangulate()
  - 'lrs': use David Avis's lrs program (optional)
  - 'latte': use LattE integrale program (optional)
  - 'normaliz': use Normaliz program (optional)
- \*\*kwds keyword arguments that are passed to the triangulation engine

## **OUTPUT**:

The volume of the polytope

### **EXAMPLES:**

```
sage: polytopes.hypercube(3).volume()
8
sage: (polytopes.hypercube(3)*2).volume()
64
sage: polytopes.twenty_four_cell().volume()
2
```

Volume of the same polytopes, using the optional package Irslib (which requires a rational polytope):

```
sage: I3 = polytopes.hypercube(3)
sage: I3.volume(engine='lrs')  # optional - lrslib
8
sage: C24 = polytopes.twenty_four_cell()
sage: C24.volume(engine='lrs')  # optional - lrslib
2
```

If the base ring is exact, the answer is exact:

When considering lower-dimensional polytopes, we can ask for the ambient (full-dimensional), the induced measure (of the affine hull) or, in the case of lattice polytopes, for the induced rational measure. This is controlled by the parameter measure. Different engines may have different ideas on the definition of volume of a lower-dimensional object:

```
sage: P = Polyhedron([[0, 0], [1, 1]])
sage: P.volume()
0
sage: P.volume(measure='induced')
1.414213562373095?
sage: P.volume(measure='induced_rational') # optional -- latte_int
sage: S = polytopes.regular_polygon(6); S
                                                                     # optional -
→ sage.rings.number_field
A 2-dimensional polyhedron in AA^2 defined as the convex hull of 6 vertices
sage: edge = S.faces(1)[4].as_polyhedron()
                                                                     # optional -
→ sage.rings.number_field
sage: edge.vertices()
                                                                     # optional -
→ sage.rings.number_field
(A vertex at (0.866025403784439?, 1/2), A vertex at (0, 1))
sage: edge.volume()
                                                                     # optional -
→ sage.rings.number_field
sage: edge.volume(measure='induced')
                                                                     # optional -
→ sage.rings.number_field
1
sage: P = Polyhedron(backend='normaliz',vertices=[[1,0,0],[0,0,1],[-1,1],[-1,
\rightarrow 2,0]]) # optional - pynormaliz
sage: P.volume() # optional - pynormaliz
sage: P.volume(measure='induced') # optional - pynormaliz
                                                                     # optional -
→ sage.rings.number_field
2.598076211353316?
sage: P.volume(measure='induced',engine='normaliz') # optional - pynormaliz
2.598076211353316
sage: P.volume(measure='induced_rational') # optional - pynormaliz, latte_int
sage: P.volume(measure='induced_rational',engine='normaliz') # optional -_
→pynormaliz
                                                                   (continues on next page)
```

```
3/2
sage: P.volume(measure='induced_lattice') # optional - pynormaliz
3
```

The same polytope without normaliz backend:

```
sage: P = Polyhedron(vertices=[[1,0,0],[0,0,1],[-1,1,1],[-1,2,0]])
sage: P.volume(measure='induced_lattice',engine='latte') # optional - latte_int
3
sage: Dexact = polytopes.dodecahedron()
                                                                     # optional -
→ sage.rings.number_field
sage: v = Dexact.faces(2)[0].as_polyhedron().volume(measure='induced', engine=
→ 'internal'); v # optional - sage.rings.number_field
1.53406271079097?
sage: v = Dexact.faces(2)[4].as_polyhedron().volume(measure='induced', engine=
→'internal'); v # optional - sage.rings.number_field
1.53406271079097?
sage: RDF(v)
               # abs tol 1e-9
                                                                     # optional -
→ sage.rings.number_field
1.53406271079044
sage: Dinexact = polytopes.dodecahedron(exact=False)
sage: w = Dinexact.faces(2)[2].as_polyhedron().volume(measure='induced', engine=
→'internal'); RDF(w) # abs tol 1e-9
1.5340627082974878
sage: [polytopes.simplex(d).volume(measure='induced') for d in range(1,5)] ==_
\rightarrow [sqrt(d+1)/factorial(d) for d in range(1,5)]
True
sage: I = Polyhedron([[-3, 0], [0, 9]])
sage: I.volume(measure='induced')
                                                                     # optional -
→ sage.rings.number_field
9.48683298050514?
sage: I.volume(measure='induced_rational') # optional -- latte_int
sage: T = Polyhedron([[3, 0, 0], [0, 4, 0], [0, 0, 5]])
sage: T.volume(measure='induced')
                                                                     # optional -
→ sage.rings.number_field
13.86542462386205?
sage: T.volume(measure='induced_rational') # optional -- latte_int
1/2
sage: Q = Polyhedron(vertices=[(0, 0, 1, 1), (0, 1, 1, 0), (1, 1, 0, 0)])
sage: Q.volume(measure='induced')
sage: Q.volume(measure='induced_rational') # optional -- latte_int
1/2
```

The volume of a full-dimensional unbounded polyhedron is infinity:

```
sage: P = Polyhedron(vertices = [[1, 0], [0, 1]], rays = [[1, 1]])
sage: P.volume()
+Infinity
```

The volume of a non full-dimensional unbounded polyhedron depends on the measure used:

The volume in 0-dimensional space is taken by counting measure:

```
sage: P = Polyhedron(vertices=[[]]); P
A 0-dimensional polyhedron in ZZ^0 defined as the convex hull of 1 vertex
sage: P.volume()
1
sage: P = Polyhedron(vertices=[]); P
The empty polyhedron in ZZ^0
sage: P.volume()
0
```

# 2.6.9 Base class for polyhedra: Miscellaneous methods

Bases: sage.geometry.polyhedron.base7.Polyhedron\_base7

Base class for Polyhedron objects

# INPUT:

- parent the parent, an instance of *Polyhedra*.
- Vrep a list [vertices, rays, lines] or None. The V-representation of the polyhedron. If None, the polyhedron is determined by the H-representation.
- Hrep a list [ieqs, eqns] or None. The H-representation of the polyhedron. If None, the polyhedron is determined by the V-representation.
- Vrep\_minimal (optional) see below
- Hrep\_minimal (optional) see below

- pref\_rep string (default: None); one of Vrep or Hrep to pick this in case the backend cannot initialize
  from complete double description
- mutable ignored

If both Vrep and Hrep are provided, then Vrep\_minimal and Hrep\_minimal must be set to True.

#### barycentric\_subdivision(subdivision\_frac=None)

Return the barycentric subdivision of a compact polyhedron.

#### **DEFINITION:**

The barycentric subdivision of a compact polyhedron is a standard way to triangulate its faces in such a way that maximal faces correspond to flags of faces of the starting polyhedron (i.e. a maximal chain in the face lattice of the polyhedron). As a simplicial complex, this is known as the order complex of the face lattice of the polyhedron.

### REFERENCE:

See Wikipedia article Barycentric\_subdivision

Section 6.6, Handbook of Convex Geometry, Volume A, edited by P.M. Gruber and J.M. Wills. 1993, North-Holland Publishing Co..

#### INPUT:

• subdivision\_frac – number. Gives the proportion how far the new vertices are pulled out of the polytope. Default is  $\frac{1}{3}$  and the value should be smaller than  $\frac{1}{2}$ . The subdivision is computed on the polar polyhedron.

#### **OUTPUT:**

A Polyhedron object, subdivided as described above.

# **EXAMPLES:**

```
sage: P = polytopes.hypercube(3)
sage: P.barycentric_subdivision()
A 3-dimensional polyhedron in QQ<sup>3</sup> defined as the convex hull
of 26 vertices
sage: P = Polyhedron(vertices=[[0,0,0],[0,1,0],[1,0,0],[0,0,1]])
sage: P.barycentric_subdivision()
A 3-dimensional polyhedron in QQ^3 defined as the convex hull
of 14 vertices
sage: P = Polyhedron(vertices=[[0,1,0],[0,0,1],[1,0,0]])
sage: P.barycentric_subdivision()
A 2-dimensional polyhedron in QQ^3 defined as the convex hull
of 6 vertices
sage: P = polytopes.regular_polygon(4, base_ring=QQ)
                                                                      # optional -
→ sage.rings.number_field
sage: P.barycentric_subdivision()
                                                                      # optional -
→ sage.rings.number_field
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 8
vertices
```

#### boundary\_complex()

Return the simplicial complex given by the boundary faces of self, if it is simplicial.

# **OUTPUT**:

A (spherical) simplicial complex

### **EXAMPLES:**

The boundary complex of the octahedron:

```
sage: oc = polytopes.octahedron()
sage: sc_oc = oc.boundary_complex()
sage: fl_oc = oc.face_lattice()
sage: fl_sc = sc_oc.face_poset()
sage: [len(x) for x in fl_oc.level_sets()]
[1, 6, 12, 8, 1]
sage: [len(x) for x in fl_sc.level_sets()]
[6, 12, 8]
sage: sc_oc.euler_characteristic()
2
sage: sc_oc.homology()
{0: 0, 1: 0, 2: Z}
```

The polyhedron should be simplicial:

```
sage: c = polytopes.cube()
sage: c.boundary_complex()
Traceback (most recent call last):
...
NotImplementedError: this function is only implemented for simplicial polytopes
```

# bounding\_box(integral=False, integral\_hull=False)

Return the coordinates of a rectangular box containing the non-empty polytope.

### INPUT:

- integral Boolean (default: False). Whether to only allow integral coordinates in the bounding box.
- integral\_hull Boolean (default: False). If True, return a box containing the integral points of the polytope, or None, None if it is known that the polytope has no integral points.

## **OUTPUT**:

A pair of tuples (box\_min, box\_max) where box\_min are the coordinates of a point bounding the coordinates of the polytope from below and box\_max bounds the coordinates from above.

# **EXAMPLES:**

```
sage: Polyhedron([ (1/3,2/3), (2/3, 1/3) ]).bounding_box()
((1/3, 1/3), (2/3, 2/3))
sage: Polyhedron([ (1/3,2/3), (2/3, 1/3) ]).bounding_box(integral=True)
((0, 0), (1, 1))
sage: Polyhedron([ (1/3,2/3), (2/3, 1/3) ]).bounding_box(integral_hull=True)
(None, None)
sage: Polyhedron([ (1/3,2/3), (3/3, 4/3) ]).bounding_box(integral_hull=True)
((1, 1), (1, 1))
sage: polytopes.buckyball(exact=False).bounding_box()
((-0.8090169944, -0.8090169944, -0.8090169944), (0.8090169944, 0.8090169944, 0.
--8090169944))
```

# center()

Return the average of the vertices.

### See also:

```
sage.geometry.polyhedron.base1.Polyhedron_base1.representative_point().
```

### **OUTPUT**:

The center of the polyhedron. All rays and lines are ignored. Raises a ZeroDivisionError for the empty polytope.

# **EXAMPLES:**

```
sage: p = polytopes.hypercube(3)
sage: p = p + vector([1,0,0])
sage: p.center()
(1, 0, 0)
```

# face\_fan()

Return the face fan of a compact rational polyhedron.

### **OUTPUT**:

A fan of the ambient space as a RationalPolyhedralFan.

# See also:

```
normal fan().
```

# **EXAMPLES:**

```
sage: T = polytopes.cuboctahedron()
sage: T.face_fan()
Rational polyhedral fan in 3-d lattice M
```

The polytope should contain the origin in the interior:

```
sage: P = Polyhedron(vertices = [[1/2, 1], [1, 1/2]])
sage: P.face_fan()
Traceback (most recent call last):
...
ValueError: face fans are defined only for polytopes containing the origin as_
an interior point!

sage: Q = Polyhedron(vertices = [[-1, 1/2], [1, -1/2]])
sage: Q.contains([0,0])
True
sage: FF = Q.face_fan(); FF
Rational polyhedral fan in 2-d lattice M
```

The polytope has to have rational coordinates:

**REFERENCES:** 

For more information, see Chapter 7 of [Zie2007].

# hyperplane\_arrangement()

Return the hyperplane arrangement defined by the equations and inequalities.

#### **OUTPUT:**

A *hyperplane arrangement* consisting of the hyperplanes defined by the *Hrepresentation()*. If the polytope is full-dimensional, this is the hyperplane arrangement spanned by the facets of the polyhedron.

#### **EXAMPLES:**

```
sage: p = polytopes.hypercube(2)
sage: p.hyperplane_arrangement()
Arrangement <-t0 + 1 | -t1 + 1 | t1 + 1 | t0 + 1>
```

# is\_inscribed(certificate=False)

This function tests whether the vertices of the polyhedron are inscribed on a sphere.

The polyhedron is expected to be compact and full-dimensional. A full-dimensional compact polytope is inscribed if there exists a point in space which is equidistant to all its vertices.

#### ALGORITHM:

The function first computes the circumsphere of a full-dimensional simplex with vertices of self. It is found by lifting the points on a paraboloid to find the hyperplane on which the circumsphere is lifted. Then, it checks if all other vertices are equidistant to the circumcenter of that simplex.

# INPUT:

• certificate – (default: False) boolean; specifies whether to return the circumcenter, if found.

# **OUTPUT**:

If certificate is true, returns a tuple containing:

- 1. Boolean.
- 2. The circumcenter of the polytope or None.

If certificate is false:

· a Boolean.

# **EXAMPLES:**

```
sage: truncated_cube = cube.face_truncation(cube.faces(0)[0])
sage: truncated_cube.is_inscribed()
False
```

The method is not implemented for non-full-dimensional polytope or unbounded polyhedra:

# is\_minkowski\_summand(Y)

Test whether Y is a Minkowski summand.

```
See minkowski_sum().
```

### **OUTPUT:**

Boolean. Whether there exists another polyhedron Z such that self can be written as  $Y \oplus Z$ .

## **EXAMPLES**:

```
sage: A = polytopes.hypercube(2)
sage: B = Polyhedron(vertices=[(0,1), (1/2,1)])
sage: C = Polyhedron(vertices=[(1,1)])
sage: A.is_minkowski_summand(B)
True
sage: A.is_minkowski_summand(C)
True
sage: B.is_minkowski_summand(C)
True
sage: B.is_minkowski_summand(A)
False
sage: C.is_minkowski_summand(A)
False
sage: C.is_minkowski_summand(B)
False
```

# normal\_fan(direction='inner')

Return the normal fan of a compact full-dimensional rational polyhedron.

This returns the inner normal fan of self. For the outer normal fan, use direction='outer'.

### INPUT:

• direction – either 'inner' (default) or 'outer'; if set to 'inner', use the inner normal vectors to span the cones of the fan, if set to 'outer', use the outer normal vectors.

## **OUTPUT**:

A complete fan of the ambient space as a RationalPolyhedralFan.

### See also:

```
face_fan().
```

#### **EXAMPLES:**

```
sage: S = Polyhedron(vertices = [[0, 0], [1, 0], [0, 1]])
sage: S.normal_fan()
Rational polyhedral fan in 2-d lattice N

sage: C = polytopes.hypercube(4)
sage: NF = C.normal_fan(); NF
Rational polyhedral fan in 4-d lattice N
```

Currently, it is only possible to get the normal fan of a bounded rational polytope:

```
sage: P = Polyhedron(rays = [[1, 0], [0, 1]])
sage: P.normal_fan()
Traceback (most recent call last):
NotImplementedError: the normal fan is only supported for polytopes (compact.
→polyhedra).
sage: Q = Polyhedron(vertices = [[1, 0, 0], [0, 1, 0], [0, 0, 1]])
sage: Q.normal_fan()
Traceback (most recent call last):
ValueError: the normal fan is only defined for full-dimensional polytopes
sage: R = Polyhedron(vertices=[[0, 0], [AA(sqrt(2)), 0], [0, AA(sqrt(2))]])
→optional - sage.rings.number_field
sage: R.normal_fan()
                                                                               #__
→optional - sage.rings.number_field
Traceback (most recent call last):
NotImplementedError: normal fan handles only polytopes over the rationals
sage: P = Polyhedron(vertices=[[0,0],[2,0],[0,2],[2,1],[1,2]])
sage: P.normal_fan(direction=None)
Traceback (most recent call last):
TypeError: the direction should be 'inner' or 'outer'
sage: inner_nf = P.normal_fan()
sage: inner_nf.rays()
N(1, 0),
N(0, -1),
N(0, 1),
N(-1, 0),
N(-1, -1)
in 2-d lattice N
```

```
sage: outer_nf = P.normal_fan(direction='outer')
sage: outer_nf.rays()
N( 1,  0),
N( 1,  1),
N( 0,  1),
N( 0,  -1)
in 2-d lattice N
```

#### REFERENCES:

For more information, see Chapter 7 of [Zie2007].

# permutations\_to\_matrices(conj\_class\_reps, acting\_group=None, additional\_elts=None)

Return a dictionary between different representations of elements in the acting\_group, with group elements represented as permutations of the vertices of this polytope (keys) or matrices (values).

The dictionary has entries for the generators of the acting\_group and the representatives of conjugacy classes in conj\_class\_reps. By default, the acting\_group is the restricted\_automorphism\_group() of the polytope. Each element in additional\_elts also becomes a key.

### INPUT:

- conj\_class\_reps list. A list of representatives of the conjugacy classes of the acting\_group.
- acting\_group a subgroup of polytope's restricted\_automorphism\_group().
- additional\_elts list (default=None). A subset of the restricted\_automorphism\_group() of the polytope expressed as permutations.

# **OUTPUT**:

A dictionary between elements of the acting\_group expressed as permutations (keys) and matrices (values).

#### **EXAMPLES:**

This example shows the dictionary between permutations and matrices for the generators of the restricted\_automorphism\_group of the  $\pm 1$  2-dimensional square. The permutations are written in terms of the vertices of the square:

```
sage: square = Polyhedron(vertices=[[1,1],[-1,1],[-1,-1],[1,-1]], backend=
→ 'normaliz') # optional - pynormaliz
sage: square.vertices() # optional - pynormaliz
(A vertex at (-1, -1),
A vertex at (-1, 1),
A vertex at (1, -1),
A vertex at (1, 1)
sage: aut_square = square.restricted_automorphism_group(output = 'permutation')_
        # optional - pynormaliz
sage: conj_reps = aut_square.conjugacy_classes_representatives()
        # optional - pynormaliz
sage: gens_dict = square.permutations_to_matrices(conj_reps);
        # optional - pynormaliz
sage: conj_reps[1],gens_dict[conj_reps[1]]
        # optional - pynormaliz
(
```

```
[0 1 0]
[1 0 0]
(1,2), [0 0 1]
```

This example tests the functionality for additional elements:

```
sage: C = polytopes.cross_polytope(2)
sage: G = C.restricted_automorphism_group(output = 'permutation')
sage: conj_reps = G.conjugacy_classes_representatives()
sage: add_elt = G[6]; add_elt
(0,2,3,1)
sage: dict = C.permutations_to_matrices(conj_reps,additional_elts = [add_elt])
sage: dict[add_elt]
[ 0  1  0]
[-1  0  0]
[ 0  0  1]
```

### radius()

Return the maximal distance from the center to a vertex. All rays and lines are ignored.

### **OUTPUT:**

The radius for a rational polyhedron is, in general, not rational. use *radius\_square()* if you need a rational distance measure.

### **EXAMPLES:**

```
sage: p = polytopes.hypercube(4)
sage: p.radius()
2
```

# radius\_square()

Return the square of the maximal distance from the center() to a vertex. All rays and lines are ignored.

### **OUTPUT**:

The square of the radius, which is in base\_ring().

# **EXAMPLES:**

```
sage: p = polytopes.permutahedron(4, project = False)
sage: p.radius_square()
5
```

# to\_linear\_program(solver=None, return\_variable=False, base\_ring=None)

Return a linear optimization problem over the polyhedron in the form of a MixedIntegerLinearProgram.

# INPUT:

- solver select a solver (MIP backend). See the documentation of for MixedIntegerLinearProgram. Set to None by default.
- return\_variable (default: False) If True, return a tuple (p, x), where p is the MixedIntegerLinearProgram object and x is the vector-valued MIP variable in this problem, indexed from 0. If False, only return p.

• base\_ring – select a field over which the linear program should be set up. Use RDF to request a fast inexact (floating point) solver even if self is exact.

Note that the MixedIntegerLinearProgram object will have the null function as an objective to be maximized.

### See also:

polyhedron() - return the polyhedron associated with a MixedIntegerLinearProgram object.

#### **EXAMPLES:**

Exact rational linear program:

```
sage: p = polytopes.cube()
sage: p.to_linear_program()
Linear Program (no objective, 3 variables, 6 constraints)
sage: lp, x = p.to_linear_program(return_variable=True)
sage: lp.set_objective(2*x[0] + 1*x[1] + 39*x[2])
sage: lp.solve()
42
sage: lp.get_values(x[0], x[1], x[2])
[1, 1, 1]
```

Floating-point linear program:

```
sage: lp, x = p.to_linear_program(return_variable=True, base_ring=RDF)
sage: lp.set_objective(2*x[0] + 1*x[1] + 39*x[2])
sage: lp.solve()
42.0
```

Irrational algebraic linear program over an embedded number field:

Same example with floating point:

Same example with a specific floating point solver:

Irrational algebraic linear program over AA:

sage.geometry.polyhedron.base.is\_Polyhedron(X)

Test whether X is a Polyhedron.

INPUT:

• X – anything.

**OUTPUT:** 

Boolean.

**EXAMPLES:** 

```
sage: p = polytopes.hypercube(2)
sage: from sage.geometry.polyhedron.base import is_Polyhedron
sage: is_Polyhedron(p)
True
sage: is_Polyhedron(123456)
False
```

# 2.6.10 Base class for polyhedra over Q

Bases: sage.geometry.polyhedron.base.Polyhedron\_base

Base class for Polyhedra over Q

Hstar\_function(acting\_group=None, output=None)

Return  $H^*$  as a rational function in t with coefficients in the ring of class functions of the acting\_group of this polytope.

Here,  $H^*(t) = \sum_m \chi_{mself} t^m \det(Id - \rho(t))$ . The irreducible characters of acting\_group form an orthonormal basis for the ring of class functions with values in  $\mathbf{C}$ . The coefficients of  $H^*(t)$  are expressed in this basis.

# INPUT:

- acting\_group (default=None) a permgroup object. A subgroup of the polytope's restricted\_automorphism\_group. If None, it is set to the full restricted\_automorphism\_group of the polytope. The acting group should always use output='permutation'.
- output string. an output option. The allowed values are:
  - None (default): returns the rational function  $H^*(t)$ .  $H^*$  is a rational function in t with coefficients in the ring of class functions.
  - 'e\_series\_list': Returns a list of the ehrhart\_series for the fixed\_subpolytopes of each conjugacy class representative.
  - 'determinant\_vec': Returns a list of the determinants of  $Id \rho * t$  for each conjugacy class representative.
  - 'Hstar\_as\_lin\_comb': Returns a vector of the coefficients of the irreducible representations in the expression of  $H^*$ .
  - 'prod\_det\_es': Returns a vector of the product of determinants and the Ehrhart series.
  - 'complete': Returns a list with Hstar, Hstar\_as\_lin\_comb, character table of the acting group, and whether Hstar is effective.

### **OUTPUT**:

The default output is the rational function  $H^*$ .  $H^*$  is a rational function in t with coefficients in the ring of class functions. There are several output options to see the intermediary outputs of the function.

### **EXAMPLES:**

The  $H^*$ -polynomial of the standard (d-1)-dimensional simplex  $S=conv(e_1,\ldots,e_d)$  under its restricted\_automorphism\_group is equal to  $1=\chi_{trivial}$  (Prop 6.1 [Stap2011]). Here is the computation for the 3-dimensional standard simplex:

```
sage: S = polytopes.simplex(3, backend = 'normaliz'); S
                                                                     # optional_
→- pynormaliz
A 3-dimensional polyhedron in ZZ^4 defined as the convex hull of 4 vertices
sage: G = S.restricted_automorphism_group(output = 'permutation'); G # optional_
→- pynormaliz
Permutation Group with generators [(2,3), (1,2), (0,1)]
sage: len(G)
                                                                     # optional_
→- pynormaliz
24
sage: Hstar = S._Hstar_function_normaliz(G); Hstar
                                                                     # optional_
→- pynormaliz
chi_4
sage: G.character_table()
                                                                     # optional_
→- pynormaliz
[1 -1 1 1 -1]
Γ 3 -1 0 -1 1]
[ 2 0 -1 2 0]
[ 3 1 0 -1 -1]
[1 \ 1 \ 1 \ 1 \ 1]
```

The next example is Example 7.6 in [Stap2011], and shows that  $H^*$  is not always a polynomial. Let P be the polytope with vertices  $\pm (0,0,1), \pm (1,0,1), \pm (0,1,1), \pm (1,1,1)$  and let  $G = \mathbb{Z}/2\mathbb{Z}$  act on P as follows:

```
sage: P = Polyhedron(vertices=[[0,0,1],[0,0,-1],[1,0,1],[-1,0,-1],[0,1,1],
→optional - pynormaliz
....: [0,-1,-1],[1,1,1],[-1,-1,-1]],backend='normaliz')
                                                                                  #.
→optional - pynormaliz
sage: K = P.restricted_automorphism_group(output = 'permutation')
                                                                                  #_
→optional - pynormaliz
sage: G = K.subgroup(gens = [K[6]]); G
                                                                                  #.
→optional - pynormaliz
Subgroup generated by [(0,2)(1,3)(4,6)(5,7)] of (Permutation Group with...
\rightarrowgenerators [(2,4)(3,5), (1,2)(5,6), (0,1)(2,3)(4,5)(6,7), (0,7)(1,3)(2,5)(4,
sage: conj_reps = G.conjugacy_classes_representatives()
                                                                                  #_
→optional - pynormaliz
sage: Dict = P.permutations_to_matrices(conj_reps, acting_group = G)
→optional - pynormaliz
sage: list(Dict.keys())[0]
                                                                                  #_
→optional - pynormaliz
(0,2)(1,3)(4,6)(5,7)
sage: list(Dict.values())[0]
                                                                                  #_
→optional - pynormaliz
[-1 \ 0 \ 1 \ 0]
[0 1 0 0]
[0 \ 0 \ 1 \ 0]
[0 0 0 1]
sage: len(G)
                                                                                  #__
→optional - pynormaliz
sage: G.character_table()
                                                                                  #_
→optional - pynormaliz
Γ 1 1<sub>]</sub>
\begin{bmatrix} 1 & -1 \end{bmatrix}
```

Then we calculate the rational function  $H^*(t)$ :

```
sage: Hst = P._Hstar_function_normaliz(G); Hst # optional - pynormaliz
(chi_0*t^4 + (3*chi_0 + 3*chi_1)*t^3 + (8*chi_0 + 2*chi_1)*t^2 + (3*chi_0 + ...
→3*chi_1)*t + chi_0)/(t + 1)
```

To see the exact as written in [Stap2011], we can format it as 'Hstar\_as\_lin\_comb'. The first coordinate is the coefficient of the trivial character; the second is the coefficient of the sign character:

```
sage: lin = P._Hstar_function_normaliz(G,output = 'Hstar_as_lin_comb'); lin #\_
\hookrightarrow optional - pynormaliz
((t^4 + 3*t^3 + 8*t^2 + 3*t + 1)/(t + 1), (3*t^3 + 2*t^2 + 3*t)/(t + 1))
```

Return the Ehrhart polynomial of this polyhedron.

The polyhedron must be a lattice polytope. Let P be a lattice polytope in  $\mathbf{R}^d$  and define  $L(P,t) = \#(tP \cap \mathbf{Z}^d)$ . Then E. Ehrhart proved in 1962 that L coincides with a rational polynomial of degree d for integer t. L is called the *Ehrhart polynomial* of P. For more information see the Wikipedia article Ehrhart\_polynomial.

The Ehrhart polynomial may be computed using either LattE Integrale or Normaliz by setting engine to 'latte' or 'normaliz' respectively.

#### INPUT:

- engine string; The backend to use. Allowed values are:
  - None (default); When no input is given the Ehrhart polynomial is computed using LattE Integrale (optional)
  - 'latte'; use LattE integrale program (optional)
  - 'normaliz'; use Normaliz program (optional package pynormaliz). The backend of self must be set to 'normaliz'.
- variable string (default: 't'); The variable in which the Ehrhart polynomial should be expressed.
- When the engine is 'latte', the additional input values are:
  - verbose boolean (default: False); If True, print the whole output of the LattE command.

The following options are passed to the LattE command, for details consult the LattE documentation:

- dual boolean; triangulate and signed-decompose in the dual space
- irrational\_primal boolean; triangulate in the dual space, signed-decompose in the primal space using irrationalization.
- irrational\_all\_primal boolean; triangulate and signed-decompose in the primal space using irrationalization.
- maxdet integer; decompose down to an index (determinant) of maxdet instead of index 1 (unimodular cones).
- no\_decomposition boolean; do not signed-decompose simplicial cones.
- compute\_vertex\_cones string; either 'cdd' or 'lrs' or '4ti2'
- smith\_form string; either 'ilio' or 'lidia'
- dualization string; either 'cdd' or '4ti2'
- triangulation string; 'cddlib', '4ti2' or 'topcom'
- triangulation\_max\_height integer; use a uniform distribution of height from 1 to this number

### **OUTPUT:**

A univariate polynomial in variable over a rational field.

### See also:

latte the interface to LattE Integrale PyNormaliz

# **EXAMPLES:**

To start, we find the Ehrhart polynomial of a three-dimensional simplex, first using engine='latte'. Leaving the engine unspecified sets the engine to 'latte' by default:

```
6
sage: len(simplex.integral_points())  # optional - latte_int
6
sage: poly(2)  # optional - latte_int
36
sage: len((2*simplex).integral_points())  # optional - latte_int
36
```

Now we find the same Ehrhart polynomial, this time using engine='normaliz'. To use the Normaliz engine, the simplex must be defined with backend='normaliz':

If the engine='normaliz', the backend should be 'normaliz', otherwise it returns an error:

```
sage: simplex = Polyhedron(vertices=[(0,0,0),(3,3,3),(-3,2,1),(1,-1,-2)])
sage: simplex = simplex.change_ring(QQ)
sage: simplex.ehrhart_polynomial(engine='normaliz') # optional - pynormaliz
Traceback (most recent call last):
...
TypeError: The backend of the polyhedron should be 'normaliz'
```

The polyhedron should be compact:

The polyhedron should have integral vertices:

**ehrhart\_quasipolynomial**(variable='t', engine=None, verbose=False, dual=None,

irrational\_primal=None, irrational\_all\_primal=None, maxdet=None, no\_decomposition=None, compute\_vertex\_cones=None, smith\_form=None, dualization=None, triangulation=None, triangulation\_max\_height=None, \*\*kwds)

Compute the Ehrhart quasipolynomial of this polyhedron with rational vertices.

If the polyhedron is a lattice polytope, returns the Ehrhart polynomial, a univariate polynomial in variable over a rational field. If the polyhedron has rational, nonintegral vertices, returns a tuple of polynomials in variable over a rational field. The Ehrhart counting function of a polytope P with rational vertices is given by a *quasipolynomial*. That is, there exists a positive integer l and l polynomials  $ehr_{P,i}$  for  $i \in \{1, \ldots, l\}$  such that if t is equivalent to i mod l then  $tP \cap \mathbb{Z}^d = ehr_{P,i}(t)$ .

#### INPUT:

- variable string (default: 't'); The variable in which the Ehrhart polynomial should be expressed.
- engine string; The backend to use. Allowed values are:
  - None (default); When no input is given the Ehrhart polynomial is computed using Normaliz (optional)
  - 'latte'; use LattE Integrale program (requires optional package 'latte\_int')
  - 'normaliz'; use the Normaliz program (requires optional package 'pynormaliz'). The backend of self must be set to 'normaliz'.
- When the engine is 'latte', the additional input values are:
  - verbose boolean (default: False); If True, print the whole output of the LattE command.

The following options are passed to the LattE command, for details consult the LattE documentation:

- dual boolean; triangulate and signed-decompose in the dual space
- irrational\_primal boolean; triangulate in the dual space, signed-decompose in the primal space using irrationalization.
- irrational\_all\_primal boolean; triangulate and signed-decompose in the primal space using irrationalization.
- maxdet integer; decompose down to an index (determinant) of maxdet instead of index 1 (unimodular cones).
- no\_decomposition boolean; do not signed-decompose simplicial cones.
- compute\_vertex\_cones string; either 'cdd' or 'lrs' or '4ti2'
- smith\_form string; either 'ilio' or 'lidia'
- dualization string; either 'cdd' or '4ti2'
- triangulation string; 'cddlib', '4ti2' or 'topcom'
- triangulation\_max\_height integer; use a uniform distribution of height from 1 to this number

### **OUTPUT**:

A univariate polynomial over a rational field or a tuple of such polynomials.

# See also:

latte the interface to LattE Integrale PyNormaliz

Warning: If the polytope has rational, non integral vertices, it must have backend='normaliz'.

### **EXAMPLES:**

As a first example, consider the line segment [0,1/2]. If we dilate this line segment by an even integral factor k, then the dilated line segment will contain k/2+1 lattice points. If k is odd then there will be k/2+1/2 lattice points in the dilated line segment. Note that it is necessary to set the backend of the polytope to 'normaliz':

For a more exciting example, let us look at the subpolytope of the 3 dimensional permutahedron fixed by the reflection across the hyperplane  $x_1 = x_4$ :

```
sage: verts = [[3/2, 3, 4, 3/2],
[3/2, 4, 3, 3/2],
[5/2, 1, 4, 5/2],
[5/2, 4, 1, 5/2],
[7/2, 1, 2, 7/2],
[7/2, 2, 1, 7/2]]
sage: subpoly = Polyhedron(vertices=verts, backend='normaliz') # optional -_
→pynormaliz
sage: eq = subpoly.ehrhart_quasipolynomial()
                                               # optional - pynormaliz
                                                # optional - pynormaliz
sage: eq
(4*t^2 + 3*t + 1, 4*t^2 + 2*t)
sage: eq = subpoly.ehrhart_quasipolynomial()
                                               # optional - pynormaliz
                                                # optional - pynormaliz
sage: eq
(4*t^2 + 3*t + 1, 4*t^2 + 2*t)
sage: even_ep = eq[0]
                                               # optional - pynormaliz
                                                # optional - pynormaliz
sage: odd_ep = eq[1]
sage: even_ep(2)
                                                # optional - pynormaliz
23
                                               # optional - pynormaliz
sage: ts = 2*subpoly
sage: ts.integral_points_count()
                                                # optional - pynormaliz latte_
→int
23
                                               # optional - pynormaliz
sage: odd_ep(1)
sage: subpoly.integral_points_count()
                                               # optional - pynormaliz latte_
\hookrightarrow int
```

A polytope with rational nonintegral vertices must have backend='normaliz':

```
sage: line_seg = Polyhedron(vertices=[[0],[1/2]])
sage: line_seg.ehrhart_quasipolynomial()
```

```
Traceback (most recent call last):
...
TypeError: The backend of the polyhedron should be 'normaliz'
```

The polyhedron should be compact:

If the polytope happens to be a lattice polytope, the Ehrhart polynomial is returned:

# fixed\_subpolytope(vertex\_permutation)

Return the fixed subpolytope of this polytope by the cyclic action of vertex\_permutation.

The fixed subpolytope of this polytope under the vertex\_permutation is the subset of this polytope that is fixed pointwise.

# INPUT:

• vertex\_permutation – permutation; a permutation of the vertices of self.

#### **OUTPUT:**

A subpolytope of self.

**Note:** The vertex\_permutation is obtained as a permutation of the vertices represented as a permutation. For example, vertex\_permutation = self.restricted\_automorphism\_group(output='permutation').

Requiring a lattice polytope as opposed to a rational polytope as input is purely conventional.

# **EXAMPLES:**

The fixed subpolytopes of the cube can be obtained as follows:

```
sage: reprs = AG.conjugacy_classes_representatives() # optional -
    pynormaliz
```

The fixed subpolytope of the identity element of the group is the entire cube:

```
sage: reprs[0]
                                                                     # optional -
→ pynormaliz
()
sage: Cube.fixed_subpolytope(vertex_permutation = reprs[0])
                                                                     # optional -
→ pynormaliz
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 8
sage: _.vertices()
                                                                      # optional -
→ pynormaliz
(A vertex at (-1, -1, -1),
A vertex at (-1, -1, 1),
A vertex at (-1, 1, -1),
A vertex at (-1, 1, 1),
A vertex at (1, -1, -1),
A vertex at (1, -1, 1),
A vertex at (1, 1, -1),
A vertex at (1, 1, 1))
```

You can obtain non-trivial examples:

```
sage: fsp1 = Cube.fixed_subpolytope(reprs[8]);fsp1
                                                                     # optional -
→ pynormaliz
A 0-dimensional polyhedron in QQ^3 defined as the convex hull of 1 vertex
sage: fsp1.vertices()
                                                                     # optional -
→ pynormaliz
(A vertex at (0, 0, 0),)
sage: fsp2 = Cube.fixed_subpolytope(reprs[3]);fsp2
                                                                     # optional -
→ pynormaliz
A 2-dimensional polyhedron in QQ^3 defined as the convex hull of 4 vertices
sage: fsp2.vertices()
→ pynormaliz
(A vertex at (-1, -1, 0),
A vertex at (-1, 1, 0),
A vertex at (1, -1, 0),
A vertex at (1, 1, 0)
```

The next example shows that fixed\_subpolytope works for rational polytopes:

```
Permutation Group with generators [(1,2), (0,1)(2,3), (0,3)]
sage: len(G)
                                                                      # optional_
→- pynormaliz
sage: G[2]
                                                                      # optional_
→- pynormaliz
(0,1)(2,3)
sage: fixed_set = P.fixed_subpolytope(G[2]); fixed_set
                                                                      # optional_
→- pynormaliz
A 1-dimensional polyhedron in QQ^2 defined as the convex hull of 2 vertices
sage: fixed_set.vertices()
                                                                      # optional_
→- pynormaliz
(A vertex at (0, 3/4), A vertex at (3/2, 3/4))
```

# fixed\_subpolytopes(conj class reps)

Return the fixed subpolytopes of this polytope under the actions of the given conjugacy class representatives.

The conj\_class\_reps are representatives of the conjugacy classes of a subgroup of the automorphism group of this polytope. For an element of the automorphism group, the fixed subpolytope is the subset of this polytope that is fixed pointwise.

#### INPUT:

• conj\_class\_reps - a list of representatives of the conjugacy classes of the subgroup of the restricted\_automorphism\_group of the polytope. Each element is written as a permutation of the vertices of the polytope.

### **OUTPUT**:

A dictionary where the elements of conj\_class\_reps are keys and the fixed subpolytopes are values.

**Note:** Two elements in the same conjugacy class fix lattice-isomorphic subpolytopes.

# **EXAMPLES:**

Here is an example for the square:

```
sage: p = polytopes.hypercube(2, backend = 'normaliz'); p
→optional - pynormaliz
A 2-dimensional polyhedron in ZZ^2 defined as the convex hull of 4 vertices
sage: aut_p = p.restricted_automorphism_group(output = 'permutation')
→optional - pynormaliz
sage: aut_p.order()
                                                                        #__
→optional - pynormaliz
sage: conj_list = aut_p.conjugacy_classes_representatives(); conj_list
→optional - pynormaliz
[(), (1,2), (0,1)(2,3), (0,1,3,2), (0,3)(1,2)]
sage: p.fixed_subpolytopes(conj_list)
                                                                        #_
→optional - pynormaliz
{(): A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 4_
→vertices,
(1,2): A 1-dimensional polyhedron in QQ^2 defined as the convex hull of 2.
→vertices.
```

```
(0,1)(2,3): A 1-dimensional polyhedron in QQ^2 defined as the convex hull of 2... →vertices, (0,1,3,2): A 0-dimensional polyhedron in QQ^2 defined as the convex hull of 1... →vertex, (0,3)(1,2): A 0-dimensional polyhedron in QQ^2 defined as the convex hull of 1... →vertex}
```

```
integral_points_count(verbose=False, use_Hrepresentation=False,
```

explicit\_enumeration\_threshold=1000, preprocess=True, \*\*kwds)

Return the number of integral points in the polyhedron.

This method uses the optional package latte\_int if an estimate for lattice points based on bounding boxes exceeds explicit\_enumeration\_threshold.

### INPUT:

- verbose (boolean; False by default) whether to display verbose output.
- ullet use\_Hrepresentation (boolean; False by default) whether to send the H or V representation to LattE
- preprocess (boolean; True by default) whether, if the integral hull is known to lie in a coordinate hyperplane, to tighten bounds to reduce dimension

#### See also:

latte the interface to LattE interfaces

### **EXAMPLES:**

We enlarge the polyhedron to force the use of the generating function methods implemented in LattE integrale, rather than explicit enumeration.

We shrink the polyhedron a little bit:

Unbounded polyhedra (with or without lattice points) are not supported:

```
sage: P = Polyhedron(vertices=[[1/2, 1/3]], rays=[[1, 1]])
sage: P.integral_points_count()
Traceback (most recent call last):
```

```
NotImplementedError: ...
sage: P = Polyhedron(vertices=[[1, 1]], rays=[[1, 1]])
sage: P.integral_points_count()
Traceback (most recent call last):
...
NotImplementedError: ...
```

"Fibonacci" knapsacks (preprocessing helps a lot):

# is\_effective(Hstar, Hstar\_as\_lin\_comb)

Test for the effectiveness of the Hstar series of this polytope.

The Hstar series of the polytope is determined by the action of a subgroup of the polytope's restricted\_automorphism\_group. The Hstar series is effective if it is a polynomial in t and the coefficient of each  $t^i$  is an effective character in the ring of class functions of the acting group. A character  $\rho$  is effective if the coefficients of the irreducible representations in the expression of  $\rho$  are non-negative integers.

# INPUT:

- Hstar a rational function in t with coefficients in the ring of class functions.
- Hstar\_as\_lin\_comb vector. The coefficients of the irreducible representations of the acting group in the expression of Hstar as a linear combination of irreducible representations with coefficients in the field of rational functions in t.

# **OUTPUT**:

Boolean. Whether the Hstar series is effective.

## See also:

Hstar\_function()

#### **EXAMPLES:**

The  $H^*$  series of the two-dimensional permutahedron under the action of the symmetric group is effective:

```
sage: [Hstar, Hlin] = [p2.Hstar_function(H), p2.Hstar_function(H, output =
    'Hstar_as_lin_comb')] # optional - pynormaliz
sage: p2.is_effective(Hstar,Hlin) # optional - pynormaliz
True
```

If the  $H^*$ -series is not polynomial, then it is not effective:

```
sage: P = Polyhedron(vertices=[[0,0,1],[0,0,-1],[1,0,1],[-1,0,-1],[0,1,1], #_J)
→optional - pynormaliz
....: [0,-1,-1],[1,1,1],[-1,-1,-1]],backend='normaliz')
                                                                               #_
\hookrightarrowoptional - pynormaliz
sage: G = P.restricted_automorphism_group(output = 'permutation')
                                                                               #. .
→optional - pynormaliz
sage: H = G.subgroup(gens = [G[6]])
→optional - pynormaliz
sage: Hstar = P.Hstar_function(H); Hstar
→optional - pynormaliz
(chi_0*t^4 + (3*chi_0 + 3*chi_1)*t^3 + (8*chi_0 + 2*chi_1)*t^2 + (3*chi_0 + ...)
\rightarrow3*chi_1)*t + chi_0)/(t + 1)
sage: Hstar_lin = P.Hstar_function(H, output = 'Hstar_as_lin_comb')
→optional - pynormaliz
sage: P.is_effective(Hstar, Hstar_lin)
                                                                         # optional_
→- pynormaliz
False
```

# 2.6.11 Base class for polyhedra over ${\bf Z}$

Bases: sage.geometry.polyhedron.base\_QQ.Polyhedron\_QQ

Base class for Polyhedra over Z

Return the Ehrhart polynomial of this polyhedron.

Let P be a lattice polytope in  $\mathbf{R}^d$  and define  $L(P,t)=\#(tP\cap\mathbf{Z}^d)$ . Then E. Ehrhart proved in 1962 that L coincides with a rational polynomial of degree d for integer t. L is called the *Ehrhart polynomial* of P. For more information see the Wikipedia article Ehrhart\_polynomial.

The Ehrhart polynomial may be computed using either LattE Integrale or Normaliz by setting engine to 'latte' or 'normaliz' respectively.

#### INPUT:

- engine string; The backend to use. Allowed values are:
  - None (default); When no input is given the Ehrhart polynomial is computed using LattE Integrale (optional)
  - 'latte'; use LattE integrale program (optional)

- 'normaliz'; use Normaliz program (optional). The backend of self must be set to 'normaliz'.
- variable string (default: 't'); The variable in which the Ehrhart polynomial should be expressed.
- When the engine is 'latte' or None, the additional input values are:
  - verbose boolean (default: False); if True, print the whole output of the LattE command.

The following options are passed to the LattE command, for details consult the LattE documentation:

- dual boolean; triangulate and signed-decompose in the dual space
- irrational\_primal boolean; triangulate in the dual space, signed-decompose in the primal space using irrationalization.
- irrational\_all\_primal boolean; Triangulate and signed-decompose in the primal space using irrationalization.
- maxdet integer; decompose down to an index (determinant) of maxdet instead of index 1 (unimodular cones).
- no\_decomposition boolean; do not signed-decompose simplicial cones.
- compute\_vertex\_cones string; either 'cdd' or 'lrs' or '4ti2'
- smith\_form string; either 'ilio' or 'lidia'
- dualization string; either 'cdd' or '4ti2'
- triangulation string; 'cddlib', '4ti2' or 'topcom'
- triangulation\_max\_height integer; use a uniform distribution of height from 1 to this number

### **OUTPUT**:

The Ehrhart polynomial as a univariate polynomial in variable over a rational field.

#### See also:

latte the interface to LattE Integrale PyNormaliz

## **EXAMPLES:**

To start, we find the Ehrhart polynomial of a three-dimensional simplex, first using engine='latte'. Leaving the engine unspecified sets the engine to 'latte' by default:

```
sage: simplex = Polyhedron(vertices=[(0,0,0),(3,3,3),(-3,2,1),(1,-1,-2)])
sage: poly = simplex.ehrhart_polynomial(engine = 'latte') # optional - latte_
→int
sage: poly
                                                            # optional - latte_
→int
7/2*t^3 + 2*t^2 - 1/2*t + 1
                                                            # optional - latte_
sage: poly(1)
→int
sage: len(simplex.integral_points())
                                                            # optional - latte_
⊶int
                                                            # optional - latte_
sage: poly(2)
→int
36
```

```
sage: len((2*simplex).integral_points()) # optional - latte_
    int
36
```

Now we find the same Ehrhart polynomial, this time using engine='normaliz'. To use the Normaliz engine, the simplex must be defined with backend='normaliz':

If the engine='normaliz', the backend should be 'normaliz', otherwise it returns an error:

Now we find the Ehrhart polynomials of the unit hypercubes of dimensions three through six. They are computed first with engine='latte' and then with engine='normaliz'. The degree of the Ehrhart polynomial matches the dimension of the hypercube, and the coefficient of the leading monomial equals the volume of the unit hypercube:

```
sage: from itertools import product
sage: def hypercube(d):
         return Polyhedron(vertices=list(product([0,1],repeat=d)))
sage: hypercube(3).ehrhart_polynomial() # optional - latte_int
t^3 + 3*t^2 + 3*t + 1
sage: hypercube(4).ehrhart_polynomial() # optional - latte_int
t^4 + 4*t^3 + 6*t^2 + 4*t + 1
sage: hypercube(5).ehrhart_polynomial()
                                          # optional - latte_int
t^5 + 5^*t^4 + 10^*t^3 + 10^*t^2 + 5^*t + 1
sage: hypercube(6).ehrhart_polynomial()
                                         # optional - latte_int
t^6 + 6^*t^5 + 15^*t^4 + 20^*t^3 + 15^*t^2 + 6^*t + 1
sage: def hypercube(d):
         return Polyhedron(vertices=list(product([0,1],repeat=d)),backend=
→ 'normaliz') # optional - pynormaliz
sage: hypercube(3).ehrhart_polynomial(engine='normaliz') # optional - pynormaliz
t^3 + 3*t^2 + 3*t + 1
sage: hypercube(4).ehrhart_polynomial(engine='normaliz') # optional - pynormaliz
t^4 + 4*t^3 + 6*t^2 + 4*t + 1
sage: hypercube(5).ehrhart_polynomial(engine='normaliz') # optional - pynormaliz
t^5 + 5^*t^4 + 10^*t^3 + 10^*t^2 + 5^*t + 1
sage: hypercube(6).ehrhart_polynomial(engine='normaliz') # optional - pynormaliz
t^6 + 6^*t^5 + 15^*t^4 + 20^*t^3 + 15^*t^2 + 6^*t + 1
```

An empty polyhedron:

```
sage: p = Polyhedron(ambient_dim=3, vertices=[])
sage: p.ehrhart_polynomial()
0
sage: parent(_)
Univariate Polynomial Ring in t over Rational Field
```

The polyhedron should be compact:

```
sage: C = Polyhedron(rays=[[1,2],[2,1]])
sage: C.ehrhart_polynomial()
Traceback (most recent call last):
...
ValueError: Ehrhart polynomial only defined for compact polyhedra
```

# fibration\_generator(dim)

Generate the lattice polytope fibrations.

For the purposes of this function, a lattice polytope fiber is a sub-lattice polytope. Projecting the plane spanned by the subpolytope to a point yields another lattice polytope, the base of the fibration.

### INPUT:

• dim – integer. The dimension of the lattice polytope fiber.

#### **OUTPUT:**

A generator yielding the distinct lattice polytope fibers of given dimension.

### **EXAMPLES:**

# find\_translation(translated\_polyhedron)

Return the translation vector to translated\_polyhedron.

### INPUT:

• translated\_polyhedron – a polyhedron.

# **OUTPUT**:

A **Z**-vector that translates self to translated\_polyhedron. A ValueError is raised if translated\_polyhedron is not a translation of self, this can be used to check that two polyhedra are not translates of each other.

## **EXAMPLES:**

```
sage: X = polytopes.cube()
sage: X.find_translation(X + vector([2,3,5]))
(2, 3, 5)
sage: X.find_translation(2*X)
Traceback (most recent call last):
...
ValueError: polyhedron is not a translation of self
```

### has\_IP\_property()

Test whether the polyhedron has the IP property.

The IP (interior point) property means that

- self is compact (a polytope).
- self contains the origin as an interior point.

This implies that

- self is full-dimensional.
- The dual polyhedron is again a polytope (that is, a compact polyhedron), though not necessarily a lattice polytope.

#### **EXAMPLES:**

```
sage: Polyhedron([(1,1),(1,0),(0,1)], base_ring=ZZ).has_IP_property()
False
sage: Polyhedron([(0,0),(1,0),(0,1)], base_ring=ZZ).has_IP_property()
False
sage: Polyhedron([(-1,-1),(1,0),(0,1)], base_ring=ZZ).has_IP_property()
True
```

### REFERENCES:

• [PALP]

# is\_lattice\_polytope()

Return whether the polyhedron is a lattice polytope.

# OUTPUT:

True if the polyhedron is compact and has only integral vertices, False otherwise.

# **EXAMPLES:**

## is\_reflexive()

A lattice polytope is reflexive if it contains the origin in its interior and its polar with respect to the origin is a lattice polytope.

Equivalently, it is reflexive if it is of the form  $\{x \in \mathbb{R}^d : Ax \leq 1\}$  for some integer matrix A and d the ambient dimension.

## **EXAMPLES:**

```
sage: p = Polyhedron(vertices=[(1,0,0),(0,1,0),(0,0,1),(-1,-1,-1)], base_
    ring=ZZ)
sage: p.is_reflexive()
True
sage: polytopes.hypercube(4).is_reflexive()
True
sage: p = Polyhedron(vertices=[(1,0), (0,2), (-1,0), (0,-1)], base_ring=ZZ)
sage: p.is_reflexive()
```

```
False
sage: p = Polyhedron(vertices=[(1,0), (0,2), (-1,0)], base_ring=ZZ)
sage: p.is_reflexive()
False
```

An error is raised, if the polyhedron is not compact:

```
sage: p = Polyhedron(rays=[(1,)], base_ring=ZZ)
sage: p.is_reflexive()
Traceback (most recent call last):
...
ValueError: the polyhedron is not compact
```

# minkowski\_decompositions()

Return all Minkowski sums that add up to the polyhedron.

### **OUTPUT**:

A tuple consisting of pairs (X,Y) of **Z**-polyhedra that add up to self. All pairs up to exchange of the summands are returned, that is, (Y,X) is not included if (X,Y) already is.

### **EXAMPLES:**

```
sage: square = Polyhedron(vertices=[(0,0),(1,0),(0,1),(1,1)])
sage: square.minkowski_decompositions()
((A 0-dimensional polyhedron in ZZ^2 defined as the convex hull of 1 vertex,
   A 2-dimensional polyhedron in ZZ^2 defined as the convex hull of 4 vertices),
   (A 1-dimensional polyhedron in ZZ^2 defined as the convex hull of 2 vertices,
   A 1-dimensional polyhedron in ZZ^2 defined as the convex hull of 2 vertices))
```

Example from http://cgi.di.uoa.gr/~amantzaf/geo/

```
sage: Q = Polyhedron(vertices=[(4,0), (6,0), (0,3), (4,3)])
 sage: R = Polyhedron(vertices=[(0,0), (5,0), (8,4), (3,2)])
 sage: (Q+R).minkowski_decompositions()
 ((A 0-dimensional polyhedron in ZZ^2 defined as the convex hull of 1 vertex,
  A 2-dimensional polyhedron in ZZ^2 defined as the convex hull of 7 vertices),
  (A 2-dimensional polyhedron in ZZ^2 defined as the convex hull of 4 vertices,
  A 2-dimensional polyhedron in ZZ^2 defined as the convex hull of 4 vertices),
  (A 1-dimensional polyhedron in ZZ^2 defined as the convex hull of 2 vertices,
  A 2-dimensional polyhedron in ZZ^2 defined as the convex hull of 7 vertices),
  (A 2-dimensional polyhedron in ZZ^2 defined as the convex hull of 5 vertices,
  A 2-dimensional polyhedron in ZZ^2 defined as the convex hull of 4 vertices),
  (A 1-dimensional polyhedron in ZZ^2 defined as the convex hull of 2 vertices,
  A 2-dimensional polyhedron in ZZ^2 defined as the convex hull of 7 vertices),
  (A 2-dimensional polyhedron in ZZ^2 defined as the convex hull of 5 vertices,
  A 2-dimensional polyhedron in ZZ^2 defined as the convex hull of 3 vertices),
  (A 1-dimensional polyhedron in ZZ^2 defined as the convex hull of 2 vertices,
  A 2-dimensional polyhedron in ZZ^2 defined as the convex hull of 7 vertices),
  (A 1-dimensional polyhedron in ZZ^2 defined as the convex hull of 2 vertices,
  A 2-dimensional polyhedron in ZZ^2 defined as the convex hull of 6 vertices))
sage: [ len(square.dilation(i).minkowski_decompositions())
        for i in range(6) ]
```

```
[1, 2, 5, 8, 13, 18]
sage: [ integer_ceil((i^2 + 2*i - 1) / 2) + 1 for i in range(10) ]
[1, 2, 5, 8, 13, 18, 25, 32, 41, 50]
```

## polar()

Return the polar (dual) polytope.

The polytope must have the IP-property (see *has\_IP\_property()*), that is, the origin must be an interior point. In particular, it must be full-dimensional.

#### **OUTPUT:**

The polytope whose vertices are the coefficient vectors of the inequalities of self with inhomogeneous term normalized to unity.

### **EXAMPLES:**

# 2.6.12 Base class for polyhedra over RDF

Bases: sage.geometry.polyhedron.base.Polyhedron\_base

Base class for polyhedra over RDF.

# 2.7 Backends for Polyhedra

# 2.7.1 The cdd backend for polyhedral computations

base\_QQ.Polyhedron\_QQ
Polyhedra over QQ with cdd

# INPUT:

- parent the parent, an instance of *Polyhedra*.
- Vrep a list [vertices, rays, lines] or None.
- Hrep a list [ieqs, eqns] or None.

**EXAMPLES:** 

```
sage: from sage.geometry.polyhedron.parent import Polyhedra
sage: parent = Polyhedra(QQ, 2, backend='cdd')
sage: from sage.geometry.polyhedron.backend_cdd import Polyhedron_QQ_cdd
sage: Polyhedron_QQ_cdd(parent, [ [(1,0),(0,1),(0,0)], [], []], None, verbose=False)
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 3 vertices
```

 $\textbf{class} \texttt{ sage.geometry.polyhedron.backend\_cdd.Polyhedron\_cdd}(\textit{parent}, \textit{Vrep}, \textit{Hrep}, \textit{Polyhedron\_cdd}(\textit{parent}, \textit{Vrep}, \textit{Polyhedron\_cdd}(\textit{parent}, \textit{Vrep}, \textit{Hrep}, \textit{Polyhedron\_cdd}(\textit{parent}, \textit{Vrep}, \textit{$ 

Vrep\_minimal=None, Hrep\_minimal=None, pref\_rep=None, mutable=False, \*\*kwds)

Bases: sage.geometry.polyhedron.base.Polyhedron\_base

Base class for the cdd backend.

# 2.7.2 The cdd backend for polyhedral computations, floating point version

class sage.geometry.polyhedron.backend\_cdd\_rdf.Polyhedron\_RDF\_cdd(parent, Vrep, Hrep, \*\*kwds)
 Bases: sage.geometry.polyhedron.backend\_cdd.Polyhedron\_cdd, sage.geometry.polyhedron.
 base\_RDF.Polyhedron\_RDF

Polyhedra over RDF with cdd

#### INPUT:

- ambient\_dim integer. The dimension of the ambient space.
- Vrep a list [vertices, rays, lines] or None.
- Hrep a list [ieqs, eqns] or None.

# EXAMPLES:

# 2.7.3 The Python backend

While slower than specialized C/C++ implementations, the implementation is general and works with any exact field in Sage that allows you to define polyhedra.

# **EXAMPLES:**

class sage.geometry.polyhedron.backend\_field.Polyhedron\_field(parent, Vrep, Hrep,

Vrep\_minimal=None, Hrep\_minimal=None, pref\_rep=None, mutable=False, \*\*kwds)

Bases: sage.geometry.polyhedron.base.Polyhedron\_base

Polyhedra over all fields supported by Sage

# INPUT:

- Vrep a list [vertices, rays, lines] or None.
- Hrep a list [ieqs, eqns] or None.

#### **EXAMPLES:**

# 2.7.4 The Normaliz backend for polyhedral computations

Note: This backend requires PyNormaliz. To install PyNormaliz, type sage -i pynormaliz in the terminal.

#### **AUTHORS:**

- Matthias Köppe (2016-12): initial version
- Jean-Philippe Labbé (2019-04): Expose normaliz features and added functionalities

class sage.geometry.polyhedron.backend\_normaliz.Polyhedron\_QQ\_normaliz(parent, Vrep, Hrep,

normaliz\_cone=None, normaliz\_data=None, normaliz\_field=None, \*\*kwds)

Bases: sage.geometry.polyhedron.backend\_normaliz.Polyhedron\_normaliz, sage.geometry.polyhedron.base\_QQ.Polyhedron\_QQ

Polyhedra over **Q** with normaliz.

### INPUT:

- Vrep a list [vertices, rays, lines] or None
- Hrep a list [ieqs, eqns] or None

### **EXAMPLES:**

### ehrhart\_series(variable='t')

Return the Ehrhart series of a compact rational polyhedron.

The Ehrhart series is the generating function where the coefficient of  $t^k$  is number of integer lattice points inside the k-th dilation of the polytope.

### INPUT:

• variable – string (default: 't')

### **OUTPUT**:

A rational function.

#### **EXAMPLES:**

```
sage: S = Polyhedron(vertices=[[0,1],[1,0]], backend='normaliz') # optional -_
→pynormaliz
sage: ES = S.ehrhart_series()
                                                                      # optional -_
→pynormaliz
sage: ES.numerator()
                                                                      # optional -_
→pynormaliz
1
sage: ES.denominator().factor()
                                                                      # optional -_
\hookrightarrowpynormaliz
(t - 1)^2
sage: C = Polyhedron(vertices = [[0,0,0],[0,0,1],[0,1,0],[0,1,1],[1,0,0],[1,0,
\hookrightarrow1],[1,1,0],[1,1,1]],backend='normaliz') # optional - pynormaliz
sage: ES = C.ehrhart_series()
                                           # optional - pynormaliz
                                           # optional - pynormaliz
sage: ES.numerator()
t^2 + 4*t + 1
sage: ES.denominator().factor()
                                           # optional - pynormaliz
(t - 1)^4
```

The following example is from the Normaliz manual contained in the file rational.in:

The polyhedron should be compact:

### See also:

hilbert\_series()

### hilbert\_series(grading, variable='t')

Return the Hilbert series of the polyhedron with respect to grading.

# INPUT:

- grading vector. The grading to use to form the Hilbert series
- variable string (default: 't')

#### **OUTPUT**:

A rational function.

### **EXAMPLES:**

By changing the grading, you can get the Ehrhart series of the square lifted at height 1:

```
sage: C.hilbert_series([0,0,1]) # optional - pynormaliz
(t + 1)/(-t^3 + 3*t^2 - 3*t + 1)
```

Here is an example 2cone.in from the Normaliz manual:

```
sage: C = Polyhedron(backend='normaliz',rays=[[1,3],[2,1]]) # optional -□
□ pynormaliz
sage: HS = C.hilbert_series([1,1]) # optional - pynormaliz
sage: HS.numerator() # optional - pynormaliz
t^5 + t^4 + t^3 + t^2 + 1
sage: HS.denominator().factor() # optional - pynormaliz
(t + 1) * (t - 1)^2 * (t^2 + 1) * (t^2 + t + 1)

sage: HS = C.hilbert_series([1,2]) # optional - pynormaliz
sage: HS.numerator() # optional - pynormaliz
t^8 + t^6 + t^5 + t^3 + 1
sage: HS.denominator().factor() # optional - pynormaliz
(t + 1) * (t - 1)^2 * (t^2 + 1) * (t^6 + t^5 + t^4 + t^3 + t^2 + t + 1)
```

Here is the magic square example form the Normaliz manual:

#### See also:

ehrhart\_series()

### integral\_points(threshold=10000)

Return the integral points in the polyhedron.

Uses either the naive algorithm (iterate over a rectangular bounding box) or triangulation + Smith form.

# INPUT:

 threshold – integer (default: 10000); use the naïve algorithm as long as the bounding box is smaller than this

#### **OUTPUT:**

The list of integral points in the polyhedron. If the polyhedron is not compact, a ValueError is raised.

# **EXAMPLES:**

The polyhedron need not be full-dimensional:

Here is a simplex where the naive algorithm of running over all points in a rectangular bounding box no longer works fast enough:

A rather thin polytope for which the bounding box method would be a very bad idea (note this is a rational (non-lattice) polytope, so the other backends use the bounding box method):

Finally, the 3-d reflexive polytope number 4078:

```
sage: v = [(1,0,0), (0,1,0), (0,0,1), (0,0,-1), (0,-2,1),
           (-1,2,-1), (-1,2,-2), (-1,1,-2), (-1,-1,2), (-1,-3,2)
sage: P = Polyhedron(v, backend='normaliz')
                                                                # optional -_
→pynormaliz
sage: pts1 = P.integral_points()
                                                                # optional -_
→pynormaliz
sage: all(P.contains(p) for p in pts1)
                                                                # optional -_
→pynormaliz
True
sage: pts2 = LatticePolytope(v).points() # optional - palp
sage: for p in pts1: p.set_immutable()
                                                                # optional -_
\hookrightarrowpynormaliz
                                             # optional - palp # optional -_
sage: set(pts1) == set(pts2)
→pynormaliz
True
sage: timeit('Polyhedron(v, backend='normaliz').integral_points()')
→tested - random
```

```
625 loops, best of 3: 1.41 ms per loop

sage: timeit('LatticePolytope(v).points()')  # not tested - random
25 loops, best of 3: 17.2 ms per loop
```

### integral\_points\_generators()

Return the integral points generators of the polyhedron.

Every integral point in the polyhedron can be written as a (unique) non-negative linear combination of integral points contained in the three defining parts of the polyhedron: the integral points (the compact part), the recession cone, and the lineality space.

### **OUTPUT**:

A tuple consisting of the integral points, the Hilbert basis of the recession cone, and an integral basis for the lineality space.

### **EXAMPLES:**

Normaliz gives a nonnegative integer basis of the lineality space:

```
sage: P = Polyhedron(backend='normaliz',lines=[[2,2]]) # optional - pynormaliz
sage: P.integral_points_generators() # optional - pynormaliz
(((0, 0),), (), ((1, 1),))
```

A recession cone generated by two rays:

Empty polyhedron:

```
sage: P = Polyhedron(backend='normaliz') # optional - pynormaliz
sage: P.integral_points_generators() # optional - pynormaliz
((), (), ())
```

Bases: sage.geometry.polyhedron.backend\_normaliz.Polyhedron\_QQ\_normaliz, sage.geometry.polyhedron.base\_ZZ.Polyhedron\_ZZ

Polyhedra over **Z** with normaliz.

# INPUT:

- Vrep a list [vertices, rays, lines] or None
- Hrep a list [ieqs, eqns] or None

Bases: sage.geometry.polyhedron.base.Polyhedron\_base

Polyhedra with normaliz

### INPUT:

- parent *Polyhedra* the parent
- Vrep a list [vertices, rays, lines] or None; the V-representation of the polyhedron; if None, the polyhedron is determined by the H-representation
- $\bullet$  Hrep a list [ieqs, eqns] or None; the H-representation of the polyhedron; if None, the polyhedron is determined by the V-representation
- normaliz\_cone a PyNormaliz wrapper of a normaliz cone

Only one of Vrep, Hrep, or normaliz\_cone can be different from None.

### **EXAMPLES:**

Two ways to get the full space:

A lower-dimensional affine cone; we test that there are no mysterious inequalities coming in from the homogenization:

```
1
sage: P.equations()
\rightarrow pynormaliz
(An equation (1, 0) x - 1 == 0,)
```

The empty polyhedron:

```
sage: P=Polyhedron(ieqs=[[-2, 1, 1], [-3, -1, -1], [-4, 1, -2]],
                                                                       # optional -
→pynormaliz
. . . . :
                    backend='normaliz')
sage: P
                                                                         # optional -_
\rightarrowpynormaliz
The empty polyhedron in QQ^2
sage: P.Vrepresentation()
                                                                         # optional -_
→pynormaliz
sage: P.Hrepresentation()
                                                                         # optional -_
\rightarrowpynormaliz
(An equation -1 == 0,)
```

### integral\_hull()

Return the integral hull in the polyhedron.

This is a new polyhedron that is the convex hull of all integral points.

#### **EXAMPLES:**

Unbounded example from Normaliz manual, "a dull polyhedron":

Nonpointed case:

Empty polyhedron:

# 2.7.5 The polymake backend for polyhedral computations

Note: This backend requires polymake. To install it, type sage -i polymake in the terminal.

### **AUTHORS:**

• Matthias Köppe (2017-03): initial version

Bases:  $sage.geometry.polyhedron.backend_polymake.Polyhedron_polymake, sage.geometry.polyhedron.base_QQ.Polyhedron_QQ$ 

Polyhedra over **Q** with polymake.

### INPUT:

- $\bullet$  Vrep a list [vertices, rays, lines] or None
- Hrep a list [ieqs, eqns] or None

### **EXAMPLES:**

make\_polytope=None,
\*\*kwds)

 $Bases: sage.geometry.polyhedron.backend\_polymake.Polyhedron\_polymake, sage.geometry.polyhedron.base\_ZZ.Polyhedron\_ZZ$ 

Polyhedra over **Z** with polymake.

### INPUT:

- Vrep a list [vertices, rays, lines] or None
- Hrep a list [ieqs, eqns] or None

Bases: sage.geometry.polyhedron.base.Polyhedron\_base

Polyhedra with polymake

INPUT:

- parent Polyhedra the parent
- Vrep a list [vertices, rays, lines] or None; the V-representation of the polyhedron; if None, the polyhedron is determined by the H-representation
- Hrep a list [ieqs, eqns] or None; the H-representation of the polyhedron; if None, the polyhedron is determined by the V-representation
- polymake\_polytope a polymake polytope object

Only one of Vrep, Hrep, or polymake\_polytope can be different from None.

**EXAMPLES:** 

A lower-dimensional affine cone; we test that there are no mysterious inequalities coming in from the homogenization:

```
sage: P = Polyhedron(vertices=[(1, 1)], rays=[(0, 1)],  # optional -
    jupymake
    backend='polymake')
sage: P.n_inequalities()  # optional -
    jupymake
1
sage: P.equations()  # optional -
    jupymake
(An equation (1, 0) x - 1 == 0,)
```

The empty polyhedron:

```
sage: Polyhedron(eqns=[[1, 0, 0]], backend='polymake') # optional -
    jupymake
The empty polyhedron in QQ^2
```

It can also be obtained differently:

```
sage: P=Polyhedron(ieqs=[[-2, 1, 1], [-3, -1, -1], [-4, 1, -2]], # optional -_
→ jupymake
. . . . :
                   backend='polymake')
sage: P
                                                                     # optional -_
→ jupymake
The empty polyhedron in QQ^2
sage: P.Vrepresentation()
                                                                     # optional -_
→ jupymake
()
                                                                     # optional -_
sage: P.Hrepresentation()
→ jupymake
(An equation -1 == 0,)
```

# The full polyhedron:

### Ouadratic fields work:

# 2.7.6 The PPL (Parma Polyhedra Library) backend for polyhedral computations

 $Bases: sage.geometry.polyhedron.backend\_ppl.Polyhedron\_ppl, sage.geometry.polyhedron.base\_QQ.Polyhedron\_QQ$ 

Polyhedra over **Q** with ppl

INPUT:

- Vrep a list [vertices, rays, lines] or None.
- Hrep a list [ieqs, eqns] or None.

 $\textbf{class} \ \, \textbf{sage.geometry.polyhedron.backend\_ppl.Polyhedron\_ZZ\_ppl} (\textit{parent}, \textit{Vrep}, \textit{Hrep}, \textit{Polyhedron}) (\textit{parent}, \textit{Polyhedron}) ($ 

ppl\_polyhedron=None,
mutable=False, \*\*kwds)

 $Bases: sage.geometry.polyhedron.backend\_ppl.Polyhedron\_ppl, sage.geometry.polyhedron.base\_ZZ.Polyhedron\_ZZ$ 

Polyhedra over **Z** with ppl

#### **INPUT:**

- Vrep a list [vertices, rays, lines] or None.
- Hrep a list [ieqs, eqns] or None.

### **EXAMPLES:**

class sage.geometry.polyhedron.backend\_ppl.Polyhedron\_ppl(parent, Vrep, Hrep,

ppl\_polyhedron=None, mutable=False,
\*\*kwds)

Bases: sage.geometry.polyhedron.base\_mutable.Polyhedron\_mutable

Polyhedra with ppl

# INPUT:

- Vrep a list [vertices, rays, lines] or None.
- Hrep a list [ieqs, eqns] or None.

#### **EXAMPLES:**

### Hrepresentation(index=None)

Return the objects of the H-representation. Each entry is either an inequality or a equation.

#### INPUT:

• index – either an integer or None

# OUTPUT:

The optional argument is an index running from 0 to self.n\_Hrepresentation()-1. If present, the H-representation object at the given index will be returned. Without an argument, returns the list of all H-representation objects.

## **EXAMPLES:**

```
sage: p = polytopes.hypercube(3)
sage: p.Hrepresentation(0)
An inequality (-1, 0, 0) x + 1 >= 0
```

```
sage: p.Hrepresentation(0) == p.Hrepresentation()[0]
True
```

```
sage: P = p.parent()
sage: p = P._element_constructor_(p, mutable=True)
sage: p.Hrepresentation(0)
An inequality (0, 0, -1) x + 1 >= 0
sage: p._clear_cache()
sage: p.Hrepresentation(0)
An inequality (0, 0, -1) x + 1 >= 0
sage: TestSuite(p).run()
```

### Vrepresentation(index=None)

Return the objects of the V-representation. Each entry is either a vertex, a ray, or a line.

See sage.geometry.polyhedron.constructor for a definition of vertex/ray/line.

#### INPUT:

• index – either an integer or None

#### **OUTPUT**:

The optional argument is an index running from 0 to self.n\_Vrepresentation()-1. If present, the V-representation object at the given index will be returned. Without an argument, returns the list of all V-representation objects.

### **EXAMPLES:**

```
sage: p = polytopes.cube()
sage: p.Vrepresentation(0)
A vertex at (1, -1, -1)
```

```
sage: P = p.parent()
sage: p = P._element_constructor_(p, mutable=True)
sage: p.Vrepresentation(0)
A vertex at (-1, -1, -1)
sage: p._clear_cache()
sage: p.Vrepresentation(0)
A vertex at (-1, -1, -1)
sage: TestSuite(p).run()
```

# set\_immutable()

Make this polyhedron immutable. This operation cannot be undone.

```
sage: p = Polyhedron([[1, 1]], mutable=True)
sage: p.is_mutable()
True
sage: hasattr(p, "_Vrepresentation")
False
sage: p.set_immutable()
sage: hasattr(p, "_Vrepresentation")
True
```

# 2.7.7 Double Description Algorithm for Cones

This module implements the double description algorithm for extremal vertex enumeration in a pointed cone following [FP1996]. With a little bit of preprocessing (see *double\_description\_inhomogeneous*) this defines a backend for polyhedral computations. But as far as this module is concerned, *inequality* always means without a constant term and the origin is always a point of the cone.

### **EXAMPLES:**

The implementation works over any exact field that is embedded in **R**, for example:

 $\begin{tabular}{ll} \textbf{class} & sage. \texttt{geometry.polyhedron.double\_description.DoubleDescriptionPair}(problem, A\_rows, \\ & R\_cols) \end{tabular}$ 

Bases: object

Base class for a double description pair (A, R)

**Warning:** You should use the *Problem.initial\_pair()* or *Problem.run()* to generate double description pairs for a set of inequalities, and not generate DoubleDescriptionPair instances directly.

### INPUT:

- problem instance of *Problem*.
- A\_rows list of row vectors of the matrix A. These encode the inequalities.
- $R\_cols$  list of column vectors of the matrix R. These encode the rays.

# R\_by\_sign(a)

Classify the rays into those that are positive, zero, and negative on a.

### INPUT:

• a – vector. Coefficient vector of a homogeneous inequality.

### **OUTPUT:**

A triple consisting of the rays (columns of R) that are positive, zero, and negative on a. In that order.

#### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.double_description import StandardAlgorithm
sage: A = matrix(QQ, [(1,0,1), (0,1,1), (-1,-1,1)])
sage: DD, _ = StandardAlgorithm(A).initial_pair()
sage: DD.R_by_sign(vector([1,-1,0]))
([(2/3, -1/3, 1/3)], [(-1/3, -1/3, 1/3)], [(-1/3, 2/3, 1/3)])
sage: DD.R_by_sign(vector([1,1,1]))
([(2/3, -1/3, 1/3), (-1/3, 2/3, 1/3)], [], [(-1/3, -1/3, 1/3)])
```

### are\_adjacent(r1, r2)

Return whether the two rays are adjacent.

### INPUT:

• r1, r2 – two rays.

#### **OUTPUT:**

Boolean. Whether the two rays are adjacent.

### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.double_description import StandardAlgorithm
sage: A = matrix(QQ, [(0,1,0), (1,0,0), (0,-1,1), (-1,0,1)])
sage: DD = StandardAlgorithm(A).run()
sage: DD.are_adjacent(DD.R[0], DD.R[1])
True
sage: DD.are_adjacent(DD.R[0], DD.R[2])
True
sage: DD.are_adjacent(DD.R[0], DD.R[3])
False
```

### cone()

Return the cone defined by A.

This method is for debugging only. Assumes that the base ring is **Q**.

### **OUTPUT**:

The cone defined by the inequalities as a *Polyhedron()*, using the PPL backend.

```
sage: from sage.geometry.polyhedron.double_description import StandardAlgorithm
sage: A = matrix(QQ, [(1,0,1), (0,1,1), (-1,-1,1)])
sage: DD, _ = StandardAlgorithm(A).initial_pair()
sage: DD.cone().Hrepresentation()
(An inequality (-1, -1, 1) \times + 0 >= 0,
An inequality (0, 1, 1) \times + 0 >= 0,
An inequality (1, 0, 1) \times + 0 >= 0
```

### dual()

Return the dual.

**OUTPUT:** 

For the double description pair (A, R) this method returns the dual double description pair  $(R^T, A^T)$ 

### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.double_description import Problem
sage: A = matrix(QQ, [(0,1,0), (1,0,0), (0,-1,1), (-1,0,1)])
sage: DD, _ = Problem(A).initial_pair()
sage: DD
Double description pair (A, R) defined by
    [0 1 0]
                       [0 \ 1 \ 0]
A = [1 \quad 0 \quad 0],
                   R = [1 \ 0 \ 0]
    [ 0 -1 1]
                  [1 0 1]
sage: DD.dual()
Double description pair (A, R) defined by
    [0 \ 1 \ 1]
                   [ 0 1 0]
A = [1 \ 0 \ 0], \quad R = [1 \ 0 \ -1]
    [0 \ 0 \ 1]
                    [0 \ 0 \ 1]
```

# first\_coordinate\_plane()

Restrict to the first coordinate plane.

**OUTPUT**:

A new double description pair with the constraint  $x_0 = 0$  added.

### **EXAMPLES:**

### inner\_product\_matrix()

Return the inner product matrix between the rows of A and the columns of R.

**OUTPUT**:

A matrix over the base ring. There is one row for each row of A and one column for each column of R.

### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.double_description import StandardAlgorithm
sage: A = matrix(QQ, [(1,0,1), (0,1,1), (-1,-1,1)])
sage: alg = StandardAlgorithm(A)
```

```
sage: DD, _ = alg.initial_pair()
sage: DD.inner_product_matrix()
[1 0 0]
[0 1 0]
[0 0 1]
```

# is\_extremal(ray)

Test whether the ray is extremal.

#### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.double_description import StandardAlgorithm
sage: A = matrix(QQ, [(0,1,0), (1,0,0), (0,-1,1), (-1,0,1)])
sage: DD = StandardAlgorithm(A).run()
sage: DD.is_extremal(DD.R[0])
True
```

### matrix\_space(nrows, ncols)

Return a matrix space of size nrows and ncols over the base ring of self.

These matrix spaces are cached to avoid their creation in the very demanding add\_inequality() and more precisely  $are\_adjacent()$ .

#### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.double_description import Problem
sage: A = matrix(QQ, [(1,0,1), (0,1,1), (-1,-1,1)])
sage: DD, _ = Problem(A).initial_pair()
sage: DD.matrix_space(2,2)
Full MatrixSpace of 2 by 2 dense matrices over Rational Field
sage: DD.matrix_space(3,2)
Full MatrixSpace of 3 by 2 dense matrices over Rational Field
                                           # optional - sage.rings.number_field
sage: K.<sqrt2> = QuadraticField(2)
sage: A = matrix([[1,sqrt2],[2,0]])
                                           # optional - sage.rings.number_field
sage: DD, _ = Problem(A).initial_pair()
                                           # optional - sage.rings.number_field
                                           # optional - sage.rings.number_field
sage: DD.matrix_space(1,2)
Full MatrixSpace of 1 by 2 dense matrices
over Number Field in sqrt2 with defining polynomial x^2 - 2 with sqrt2 = 1.
→414213562373095?
```

### verify()

Validate the double description pair.

This method used the PPL backend to check that the double description pair is valid. An assertion is triggered if it is not. Does nothing if the base ring is not  $\mathbf{Q}$ .

# **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.double_description import \
...:     DoubleDescriptionPair, Problem
sage: A = matrix(QQ, [(1,0,1), (0,1,1), (-1,-1,1)])
sage: alg = Problem(A)
sage: DD = DoubleDescriptionPair(alg,
...:     [(1, 0, 3), (0, 1, 1), (-1, -1, 1)],
```

```
[(2/3, -1/3, 1/3), (-1/3, 2/3, 1/3), (-1/3, -1/3, 1/3)])

sage: DD.verify()

Traceback (most recent call last):
...
assert A_cone == R_cone
AssertionError
```

### zero\_set(ray)

Return the zero set (active set) Z(r).

INPUT:

• ray – a ray vector.

**OUTPUT**:

A set containing the inequality vectors that are zero on ray.

**EXAMPLES:** 

```
sage: from sage.geometry.polyhedron.double_description import Problem
sage: A = matrix(QQ, [(1,0,1), (0,1,1), (-1,-1,1)])
sage: DD, _ = Problem(A).initial_pair()
sage: r = DD.R[0]; r
(2/3, -1/3, 1/3)
sage: DD.zero_set(r)
{(-1, -1, 1), (0, 1, 1)}
```

# class sage.geometry.polyhedron.double\_description.Problem(A)

Bases: object

Base class for implementations of the double description algorithm

It does not make sense to instantiate the base class directly, it just provides helpers for implementations.

### INPUT:

• A – a matrix. The rows of the matrix are interpreted as homogeneous inequalities  $Ax \ge 0$ . Must have maximal rank.

**A**()

Return the rows of the defining matrix A.

**OUTPUT**:

The matrix A whose rows are the inequalities.

**EXAMPLES:** 

```
sage: A = matrix([(1, 1), (-1, 1)])
sage: from sage.geometry.polyhedron.double_description import Problem
sage: Problem(A).A()
((1, 1), (-1, 1))
```

### A\_matrix()

Return the defining matrix A.

OUTPUT:

Matrix whose rows are the inequalities.

### **EXAMPLES:**

```
sage: A = matrix([(1, 1), (-1, 1)])
sage: from sage.geometry.polyhedron.double_description import Problem
sage: Problem(A).A_matrix()
[ 1  1]
[-1  1]
```

### base\_ring()

Return the base field.

OUTPUT:

A field.

### **EXAMPLES:**

```
sage: A = matrix(AA, [(1, 1), (-1, 1)]) # optional - sage.rings.number_field
sage: from sage.geometry.polyhedron.double_description import Problem
sage: Problem(A).base_ring() # optional - sage.rings.number_field
Algebraic Real Field
```

### dim()

Return the ambient space dimension.

**OUTPUT**:

Integer. The ambient space dimension of the cone.

### **EXAMPLES:**

```
sage: A = matrix(QQ, [(1, 1), (-1, 1)])
sage: from sage.geometry.polyhedron.double_description import Problem
sage: Problem(A).dim()
2
```

# initial\_pair()

Return an initial double description pair.

Picks an initial set of rays by selecting a basis. This is probably the most efficient way to select the initial set.

### INPUT:

• pair\_class - subclass of DoubleDescriptionPair.

### **OUTPUT**:

A pair consisting of a <code>DoubleDescriptionPair</code> instance and the tuple of remaining unused inequalities.

### **EXAMPLES:**

```
sage: A = matrix([(-1, 1), (-1, 2), (1/2, -1/2), (1/2, 2)])
sage: from sage.geometry.polyhedron.double_description import Problem
sage: DD, remaining = Problem(A).initial_pair()
sage: DD.verify()
sage: remaining
[(1/2, -1/2), (1/2, 2)]
```

# pair\_class

alias of DoubleDescriptionPair

# class sage.geometry.polyhedron.double\_description.StandardAlgorithm(A)

Bases: sage.geometry.polyhedron.double\_description.Problem

Standard implementation of the double description algorithm

See [FP1996] for the definition of the "Standard Algorithm".

### **EXAMPLES:**

```
sage: A = matrix(QQ, [(1, 1), (-1, 1)])
sage: from sage.geometry.polyhedron.double_description import StandardAlgorithm
sage: DD = StandardAlgorithm(A).run()
sage: DD.R  # the extremal rays
[(1/2, 1/2), (-1/2, 1/2)]
```

### pair\_class

 $alias \ of \ Standard Double Description Pair$ 

### run()

Run the Standard Algorithm.

### **OUTPUT**:

A double description pair (A, R) of all inequalities as a *DoubleDescriptionPair*. By virtue of the double description algorithm, the columns of R are the extremal rays.

### **EXAMPLES:**

class sage.geometry.polyhedron.double\_description.StandardDoubleDescriptionPair(problem,

 $A\_rows$ ,  $R\ cols$ )

 $Bases: sage.geometry.polyhedron.double\_description.DoubleDescriptionPair$ 

Double description pair for the "Standard Algorithm".

See StandardAlgorithm.

### add\_inequality(a)

Add the inequality  ${\bf a}$  to the matrix  ${\cal A}$  of the double description.

### INPUT:

• a – vector. An inequality.

### **EXAMPLES:**

```
sage: A = matrix([(-1, 1, 0), (-1, 2, 1), (1/2, -1/2, -1)])
sage: from sage.geometry.polyhedron.double_description import StandardAlgorithm
sage: DD, _ = StandardAlgorithm(A).initial_pair()
sage: DD.add_inequality(vector([1,0,0]))
sage: DD
```

```
Double description pair (A, R) defined by
                                                    0]
    [ -1 1
                   0]
                           [
                                 1
                                        1
A = \begin{bmatrix} -1 \end{bmatrix}
              2
                          R = [
                   1],
                                   1
                                        1
                                              1
                                                   1]
   [ 1/2 -1/2
                  -17
                              Γ
                                                   -27
                                       -1 - 1/2
       1
                   07
```

 $sage.geometry.polyhedron.double_description.random_inequalities(d, n)$ 

Random collections of inequalities for testing purposes.

### INPUT:

- d integer. The dimension.
- n integer. The number of random inequalities to generate.

### **OUTPUT**:

A random set of inequalities as a StandardAlgorithm instance.

#### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.double_description import random_inequalities
sage: P = random_inequalities(5, 10)
sage: P.run().verify()
```

# 2.7.8 Double Description for Arbitrary Polyhedra

This module is part of the python backend for polyhedra. It uses the double description method for cones  $double\_description$  to find minimal H/V-representations of polyhedra. The latter works with cones only. This is sufficient to treat general polyhedra by the following construction: Any polyhedron can be embedded in one dimension higher in the hyperplane (1, \*, ..., \*). The cone over the embedded polyhedron will be called the *homogenized cone* in the following. Conversely, intersecting the homogenized cone with the hyperplane  $x_0 = 1$  gives you back the original polyhedron.

While slower than specialized C/C++ implementations, the implementation is general and works with any field in Sage that allows you to define polyhedra.

**Note:** If you just want polyhedra over arbitrary fields then you should just use the *Polyhedron()* constructor.

# **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.double_description_inhomogeneous \
...: import Hrep2Vrep, Vrep2Hrep
sage: Hrep2Vrep(QQ, 2, [(1,2,3), (2,4,3)], [])
[-1/2|-1/2  1/2|]
[ 0| 2/3 -1/3|]
```

Note that the columns of the printed matrix are the vertices, rays, and lines of the minimal V-representation. Dually, the rows of the following are the inequalities and equations:

```
sage: Vrep2Hrep(QQ, 2, [(-1/2,0)], [(-1/2,2/3), (1/2,-1/3)], [])
[1 2 3]
[2 4 3]
[----]
```

Bases: sage.geometry.polyhedron.double\_description\_inhomogeneous.PivotedInequalities
Convert H-representation to a minimal V-representation.

### INPUT:

- base\_ring a field.
- dim integer. The ambient space dimension.
- inequalities list of inequalities. Each inequality is given as constant term, dim coefficients.
- equations list of equations. Same notation as for inequalities.

### **EXAMPLES:**

```
sage: from sage.geometry.polyhedron.double_description_inhomogeneous import_
→Hrep2Vrep
sage: Hrep2Vrep(QQ, 2, [(1,2,3), (2,4,3)], [])
[-1/2|-1/2  1/2|]
   0 | 2/3 -1/3|]
sage: Hrep2Vrep(QQ, 2, [(1,2,3), (2,-2,-3)], [])
   1 -1/2|| 1]
         0||-2/3|
sage: Hrep2Vrep(QQ, 2, [(1,2,3), (2,2,3)], [])
[-1/2| 1/2|
   0
         0[-2/3]
sage: Hrep2Vrep(QQ, 2, [(8,7,-2), (1,-4,3), (4,-3,-1)], [])
[1 \ 0 \ -2||]
[1 \ 4 \ -3||]
sage: Hrep2Vrep(QQ, 2, [(1,2,3), (2,4,3), (5,-1,-2)], [])
[-19/5 - 1/2| 2/33 1/11|]
[22/5]
           0|-1/33 - 2/33|
sage: Hrep2Vrep(QQ, 2, [(0,2,3), (0,4,3), (0,-1,-2)], [])
  0 | 1/2 1/3|]
    0|-1/3 - 1/6|
sage: Hrep2Vrep(QQ, 2, [], [(1,2,3), (7,8,9)])
[-2||]
[ 1||]
sage: Hrep2Vrep(QQ, 2, [(1,0,0)], [])
                                         # universe
[0||1|0]
[0||0 1]
sage: Hrep2Vrep(QQ, 2, [(-1,0,0)], [])
                                         # empty
sage: Hrep2Vrep(QQ, 2, [], [])
                                 # universe
[0||1 0]
[0||0|1]
```

### verify(inequalities, equations)

Compare result to PPL if the base ring is QQ.

This method is for debugging purposes and compares the computation with another backend if available.

# INPUT:

• inequalities, equations - see Hrep2Vrep.

### **EXAMPLES:**

Bases: sage.structure.sage\_object.SageObject

Base class for inequalities that may contain linear subspaces

### INPUT:

- base\_ring a field.
- dim integer. The ambient space dimension.

### **EXAMPLES:**

Bases: sage.geometry.polyhedron.double\_description\_inhomogeneous.PivotedInequalities

Convert V-representation to a minimal H-representation.

# INPUT:

- base\_ring a field.
- dim integer. The ambient space dimension.
- $\bullet$  vertices list of vertices. Each vertex is given as list of  $\dim$  coordinates.
- rays list of rays. Each ray is given as list of dim coordinates, not all zero.
- lines list of line generators. Each line is given as list of dim coordinates, not all zero.

# EXAMPLES:

```
[----]
sage: Vrep2Hrep(QQ, 2, [(1,0), (-1/2,0)], [], [(1,-2/3)])
[ 1/3 2/3
           17
[2/3 - 2/3 - 1]
[----]
sage: Vrep2Hrep(QQ, 2, [(-1/2,0)], [(1/2,0)], [(1,-2/3)])
[1 2 3]
[----]
sage: Vrep2Hrep(QQ, 2, [(1,1), (0,4), (-2,-3)], [], [])
[ 8/13 7/13 -2/13]
[ 1/13 -4/13 3/13]
[ 4/13 -3/13 -1/13]
[----]
sage: Vrep2Hrep(QQ, 2, [(-19/5,22/5), (-1/2,0)], [(2/33,-1/33), (1/11,-2/33)], [])
[10/11 - 2/11 - 4/11]
[ 66/5 132/5 99/5]
[ 2/11 4/11 6/11]
[----]
sage: Vrep2Hrep(QQ, 2, [(0,0)], [(1/2,-1/3), (1/3,-1/6)], [])
[0 -6 -12]
[ 0 12 18]
[-----]
sage: Vrep2Hrep(QQ, 2, [(-1/2, 0)], [], [(1, -2/3)])
[----]
[1 2 3]
sage: Vrep2Hrep(QQ, 2, [(-1/2,0)], [], [(1,-2/3), (1,0)])
```

# verify(vertices, rays, lines)

Compare result to PPL if the base ring is QQ.

This method is for debugging purposes and compares the computation with another backend if available.

# INPUT:

• vertices, rays, lines – see *Vrep2Hrep*.

Combinatorial and Discrete Geometry, Release 9.7	

**CHAPTER** 

THREE

# **TRIANGULATIONS**

# 3.1 Triangulations of a point configuration

A point configuration is a finite set of points in Euclidean space or, more generally, in projective space. A triangulation is a simplicial decomposition of the convex hull of a given point configuration such that all vertices of the simplices end up lying on points of the configuration. That is, there are no new vertices apart from the initial points.

Note that points that are not vertices of the convex hull need not be used in the triangulation. A triangulation that does make use of all points of the configuration is called fine, and you can restrict yourself to such triangulations if you want. See *PointConfiguration* and *restrict\_to\_fine\_triangulations()* for more details.

Finding a single triangulation and listing all connected triangulations is implemented natively in this package. However, for more advanced options [TOPCOM] needs to be installed. It is available as an optional package for Sage, and you can install it with the shell command

```
sage -i topcom
```

**Note:** TOPCOM and the internal algorithms tend to enumerate triangulations in a different order. This is why we always explicitly specify the engine as engine='topcom' or engine='internal' in the doctests. In your own applications, you do not need to specify the engine. By default, TOPCOM is used if it is available and the internal algorithms are used otherwise.

#### **EXAMPLES:**

First, we select the internal implementation for enumerating triangulations:

A 2-dimensional point configuration:

```
sage: p = PointConfiguration([[0,0],[0,1],[1,0],[1,1],[-1,-1]])
sage: p
A point configuration in affine 2-space over Integer Ring consisting
of 5 points. The triangulations of this point configuration are
assumed to be connected, not necessarily fine, not necessarily regular.
```

A triangulation of it:

```
sage: t = p.triangulate() # a single triangulation
sage: t
```

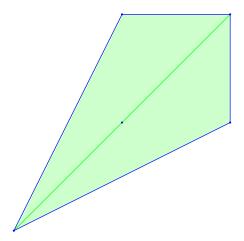
.

.

.

(continued from previous page)

```
(<1,3,4>, <2,3,4>)
sage: len(t)
2
sage: t[0]
(1, 3, 4)
sage: t[1]
(2, 3, 4)
sage: list(t)
[(1, 3, 4), (2, 3, 4)]
sage: t.plot(axes=False) # optional - sage.plot
Graphics object consisting of 12 graphics primitives
```



List triangulations of it:

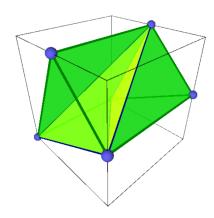
```
sage: list( p.triangulations() )
[(<1,3,4>, <2,3,4>),
  (<0,1,3>, <0,1,4>, <0,2,3>, <0,2,4>),
  (<1,2,3>, <1,2,4>),
  (<0,1,2>, <0,1,4>, <0,2,4>, <1,2,3>)]
sage: p_fine = p.restrict_to_fine_triangulations()
sage: p_fine
```

```
A point configuration in affine 2-space over Integer Ring consisting of 5 points. The triangulations of this point configuration are assumed to be connected, fine, not necessarily regular.

sage: list( p_fine.triangulations() )
[(<0,1,3>, <0,1,4>, <0,2,3>, <0,2,4>),
  (<0,1,2>, <0,1,4>, <0,2,4>, <1,2,3>)]
```

## A 3-dimensional point configuration:

```
sage: p = [[0,-1,-1],[0,0,1],[0,1,0], [1,-1,-1],[1,0,1],[1,1,0]]
sage: points = PointConfiguration(p)
sage: triang = points.triangulate()
sage: triang.plot(axes=False) # optional - sage.plot
Graphics3d Object
```



The standard example of a non-regular triangulation (requires TOPCOM):

```
sage: PointConfiguration.set_engine('topcom')
                                                # optional - topcom
sage: p = PointConfiguration([[-1, -5/9], [0, 10/9], [1, -5/9], [-2, -10/9], [0, 20/9], [2, -10/9]])
sage: regular = p.restrict_to_regular_triangulations(True).triangulations_list()
→optional - topcom
sage: nonregular = p.restrict_to_regular_triangulations(False).triangulations_list() #_
→optional - topcom
sage: len(regular)
                       # optional - topcom
sage: len(nonregular) # optional - topcom
sage: nonregular[0].plot(aspect_ratio=1, axes=False)
                                                       # optional - topcom # optional -_
⇒sage.plot
Graphics object consisting of 25 graphics primitives
sage: PointConfiguration.set_engine('internal') # to make doctests independent of_
→ TOPCOM
```

Note that the points need not be in general position. That is, the points may lie in a hyperplane and the linear dependencies will be removed before passing the data to TOPCOM which cannot handle it:

```
sage: points = [[0,0,0,1],[0,3,0,1],[3,0,0,1],[0,0,1,1],[0,3,1,1],[3,0,1,1],[1,1,2,1]]
sage: points = [ p+[1,2,3] for p in points ]
sage: pc = PointConfiguration(points)
sage: pc.ambient_dim()
7
sage: pc.dim()
3
sage: pc.triangulate()
(<0,1,2,6>, <0,1,3,6>, <0,2,3,6>, <1,2,4,6>, <1,3,4,6>, <2,3,5,6>, <2,4,5,6>)
sage: _ in pc.triangulations()
True
sage: len( pc.triangulations_list() )
26
```

### **AUTHORS:**

- Volker Braun: initial version, 2010
- Josh Whitney: added functionality for computing volumes and secondary polytopes of PointConfigurations
- Marshall Hampton: improved documentation and doctest coverage
- Volker Braun: rewrite using Parent/Element and categories. Added a Point class. More doctests. Less zombies.
- Volker Braun: Cythonized parts of it, added a C++ implementation of the bistellar flip algorithm to enumerate all connected triangulations.
- Volker Braun 2011: switched the triangulate() method to the placing triangulation (faster).

Bases: sage.structure.unique\_representation.UniqueRepresentation, sage.geometry.triangulation.base.PointConfiguration\_base

A collection of points in Euclidean (or projective) space.

This is the parent class for the triangulations of the point configuration. There are a few options to specifically select what kind of triangulations are admissible.

# INPUT:

The constructor accepts the following arguments:

- points the points. Technically, any iterable of iterables will do. In particular, a *PointConfiguration* can be passed.
- projective boolean (default: False). Whether the point coordinates should be interpreted as projective (True) or affine (False) coordinates. If necessary, points are projectivized by setting the last homogeneous coordinate to one and/or affine patches are chosen internally.
- connected boolean (default: True). Whether the triangulations should be connected to the regular triangulations via bistellar flips. These are much easier to compute than all triangulations.
- fine boolean (default: False). Whether the triangulations must be fine, that is, make use of all points of the configuration.
- regular boolean or None (default: None). Whether the triangulations must be regular. A regular triangulation is one that is induced by a piecewise-linear convex support function. In other words, the shadows of the faces of a polyhedron in one higher dimension.
  - True: Only regular triangulations.

- False: Only non-regular triangulations.
- None (default): Both kinds of triangulation.
- star either None or a point. Whether the triangulations must be star. A triangulation is star if all maximal simplices contain a common point. The central point can be specified by its index (an integer) in the given points or by its coordinates (anything iterable.)

#### **EXAMPLES:**

```
sage: p = PointConfiguration([[0,0],[0,1],[1,0],[1,1],[-1,-1]])
sage: p
A point configuration in affine 2-space over Integer Ring
consisting of 5 points. The triangulations of this point
configuration are assumed to be connected, not necessarily fine,
not necessarily regular.
sage: p.triangulate() # a single triangulation
(<1,3,4>, <2,3,4>)
```

#### **Element**

alias of sage.geometry.triangulation.element.Triangulation

### Gale\_transform(points=None)

Return the Gale transform of self.

### INPUT:

• points – a tuple of points or point indices or None (default). A subset of points for which to compute the Gale transform. By default, all points are used.

#### **OUTPUT**:

A matrix over base\_ring().

# **EXAMPLES:**

### an\_element()

Synonymous for triangulate().

### bistellar\_flips()

Return the bistellar flips.

## **OUTPUT**:

The bistellar flips as a tuple. Each flip is a pair  $(T_+, T_-)$  where  $T_+$  and  $T_-$  are partial triangulations of the point configuration.

```
sage: pc = PointConfiguration([(0,0),(1,0),(0,1),(1,1)])
sage: pc.bistellar_flips()
(((<0,1,3>, <0,2,3>), (<0,1,2>, <1,2,3>)),)
sage: Tpos, Tneg = pc.bistellar_flips()[0]
sage: Tpos.plot(axes=False) # optional - sage.plot
Graphics object consisting of 11 graphics primitives
sage: Tneg.plot(axes=False) # optional - sage.plot
Graphics object consisting of 11 graphics primitives
```

### The 3d analog:

```
sage: pc = PointConfiguration([(0,0,0),(0,2,0),(0,0,2),(-1,0,0),(1,1,1)])
sage: pc.bistellar_flips()
(((<0,1,2,3>, <0,1,2,4>), (<0,1,3,4>, <0,2,3,4>, <1,2,3,4>)),)
```

A 2d flip on the base of the pyramid over a square:

```
sage: pc = PointConfiguration([(0,0,0),(0,2,0),(0,0,2),(0,2,2),(1,1,1)])
sage: pc.bistellar_flips()
(((<0,1,3>, <0,2,3>), (<0,1,2>, <1,2,3>)),)
sage: Tpos, Tneg = pc.bistellar_flips()[0]
sage: Tpos.plot(axes=False) # optional - sage.plot
Graphics3d Object
```

### circuits()

Return the circuits of the point configuration.

Roughly, a circuit is a minimal linearly dependent subset of the points. That is, a circuit is a partition

$$\{0, 1, \dots, n-1\} = C_+ \cup C_0 \cup C_-$$

such that there is an (unique up to an overall normalization) affine relation

$$\sum_{i \in C_+} \alpha_i \vec{p}_i = \sum_{j \in C_-} \alpha_j \vec{p}_j$$

with all positive (or all negative) coefficients, where  $\vec{p_i} = (p_1, \dots, p_k, 1)$  are the projective coordinates of the *i*-th point.

# **OUTPUT**:

The list of (unsigned) circuits as triples  $(C_+, C_0, C_-)$ . The swapped circuit  $(C_-, C_0, C_+)$  is not returned separately.

### **EXAMPLES:**

```
sage: p = PointConfiguration([(0,0),(+1,0),(-1,0),(0,+1),(0,-1)])
sage: sorted(p.circuits())
[((0,), (1, 2), (3, 4)), ((0,), (3, 4), (1, 2)), ((1, 2), (0,), (3, 4))]
```

## circuits\_support()

A generator for the supports of the circuits of the point configuration.

See circuits() for details.

### **OUTPUT**:

A generator for the supports  $C_- \cup C_+$  (returned as a Python tuple) for all circuits of the point configuration.

```
sage: p = PointConfiguration([(0,0), (+1,0), (-1,0), (0,+1), (0,-1)])
sage: sorted(p.circuits_support())
[(0, 1, 2), (0, 3, 4), (1, 2, 3, 4)]
```

### contained\_simplex(large=True, initial\_point=None, point\_order=None)

Return a simplex contained in the point configuration.

#### INPUT:

- large boolean. Whether to attempt to return a large simplex.
- initial\_point a *Point* or None (default). A specific point to start with when picking the simplex vertices.
- point\_order a list or tuple of (some or all) *Point* s or None (default).

### **OUTPUT**:

A tuple of points that span a simplex of dimension dim(). If large==True, the simplex is constructed by successively picking the farthest point. This will ensure that the simplex is not unnecessarily small, but will in general not return a maximal simplex. If a point\_order is specified, the simplex is greedily constructed by considering the points in this order. The large option and initial\_point is ignored in this case. The point\_order may contain only a subset of the points; in this case, the dimension of the simplex will be the dimension of this subset.

### **EXAMPLES:**

```
sage: pc = PointConfiguration([(0,0),(1,0),(2,1),(1,1),(0,1)])
sage: pc.contained_simplex()
(P(0, 1), P(2, 1), P(1, 0))
sage: pc.contained_simplex(large=False)
(P(0, 1), P(1, 1), P(1, 0))
sage: pc.contained_simplex(initial_point=pc.point(2))
(P(2, 1), P(0, 0), P(1, 0))

sage: pc = PointConfiguration([[0,0],[0,1],[1,0],[1,1],[-1,-1]])
sage: pc.contained_simplex()
(P(-1, -1), P(1, 1), P(0, 1))
sage: pc.contained_simplex(point_order = [pc[1],pc[3],pc[4],pc[2],pc[0]])
(P(0, 1), P(1, 1), P(-1, -1))
```

Lower-dimensional example:

```
sage: pc.contained_simplex(point_order = [pc[0],pc[3],pc[4]])
(P(0, 0), P(1, 1))
```

### convex\_hull()

Return the convex hull of the point configuration.

# EXAMPLES:

```
sage: p = PointConfiguration([[0,0],[0,1],[1,0],[1,1],[-1,-1]])
sage: p.convex_hull()
A 2-dimensional polyhedron in ZZ^2 defined as the convex hull of 4 vertices
```

### distance(x, y)

Returns the distance between two points.

INPUT:

• x, y – two points of the point configuration.

#### **OUTPUT:**

The distance between x and y, measured either with distance\_affine() or distance\_FS() depending on whether the point configuration is defined by affine or projective points. These are related, but not equal to the usual flat and Fubini-Study distance.

### **EXAMPLES:**

### $distance_FS(x, y)$

Returns the distance between two points.

The distance function used in this method is  $1 - \cos d_{FS}(x, y)^2$ , where  $d_{FS}$  is the Fubini-Study distance of projective points. Recall the Fubini-Studi distance function

$$d_{FS}(x,y) = \arccos\sqrt{\frac{(x \cdot y)^2}{|x|^2|y|^2}}$$

### INPUT:

• x, y – two points of the point configuration.

### **OUTPUT**:

The distance  $1 - \cos d_{FS}(x, y)^2$ . Note that this distance lies in the same field as the entries of x, y. That is, the distance of rational points will be rational and so on.

### **EXAMPLES:**

```
sage: pc = PointConfiguration([(0,0),(1,0),(2,1),(1,2),(0,1)])
sage: [ pc.distance_FS(pc.point(0), p) for p in pc.points() ]
[0, 1/2, 5/6, 5/6, 1/2]
```

### $distance\_affine(x, y)$

Returns the distance between two points.

The distance function used in this method is  $d_{aff}(x,y)^2$ , the square of the usual affine distance function

$$d_{aff}(x,y) = |x - y|$$

### INPUT:

• x, y – two points of the point configuration.

## **OUTPUT**:

The metric distance-square  $d_{aff}(x,y)^2$ . Note that this distance lies in the same field as the entries of x, y. That is, the distance of rational points will be rational and so on.

```
sage: pc = PointConfiguration([(0,0),(1,0),(2,1),(1,2),(0,1)])
sage: [ pc.distance_affine(pc.point(0), p) for p in pc.points() ]
[0, 1, 5, 5, 1]
```

### exclude\_points(point idx list)

Return a new point configuration with the given points removed.

#### INPUT:

• point\_idx\_list – a list of integers. The indices of points to exclude.

### **OUTPUT**:

A new *PointConfiguration* with the given points removed.

#### **EXAMPLES:**

```
sage: p = PointConfiguration([[-1,0], [0,0], [1,-1], [1,0], [1,1]])
sage: list(p)
[P(-1, 0), P(0, 0), P(1, -1), P(1, 0), P(1, 1)]
sage: q = p.exclude_points([3])
sage: list(q)
[P(-1, 0), P(0, 0), P(1, -1), P(1, 1)]
sage: p.exclude_points( p.face_interior(codim=1) ).points()
(P(-1, 0), P(0, 0), P(1, -1), P(1, 1))
```

### face\_codimension(point)

Return the smallest  $d \in \mathbf{Z}$  such that point is contained in the interior of a codimension-d face.

#### **EXAMPLES:**

```
sage: triangle = PointConfiguration([[0,0], [1,-1], [1,0], [1,1]])
sage: triangle.point(2)
P(1, 0)
sage: triangle.face_codimension(2)
1
sage: triangle.face_codimension( [1,0] )
1
```

This also works for degenerate cases like the tip of the pyramid over a square (which saturates four inequalities):

### face\_interior(dim=None, codim=None)

Return points by the codimension of the containing face in the convex hull.

## **EXAMPLES:**

```
sage: triangle = PointConfiguration([[-1,0], [0,0], [1,-1], [1,0], [1,1]])
sage: triangle.face_interior()
((1,), (3,), (0, 2, 4))
sage: triangle.face_interior(dim=0) # the vertices of the convex hull
(0, 2, 4)
```

```
sage: triangle.face_interior(codim=1) # interior of facets
(3,)
```

### farthest\_point(points, among=None)

Return the point with the most distance from points.

### INPUT:

- points a list of points.
- among a list of points or None (default). The set of points from which to pick the farthest one. By default, all points of the configuration are considered.

### **OUTPUT**:

A *Point* with largest minimal distance from all given points.

# **EXAMPLES**:

```
sage: pc = PointConfiguration([(0,0),(1,0),(1,1),(0,1)])
sage: pc.farthest_point([ pc.point(0) ])
P(1, 1)
```

# lexicographic\_triangulation()

Return the lexicographic triangulation.

The algorithm was taken from [PUNTOS].

### **EXAMPLES:**

```
sage: p = PointConfiguration([(0,0),(+1,0),(-1,0),(0,+1),(0,-1)])
sage: p.lexicographic_triangulation()
(<1,3,4>, <2,3,4>)
```

### placing\_triangulation(point\_order=None)

Construct the placing (pushing) triangulation.

### INPUT:

• point\_order – list of points or integers. The order in which the points are to be placed. If not given, the points will be placed in some arbitrary order that attempts to produce a small number of simplices.

### **OUTPUT**:

A Triangulation.

### **EXAMPLES:**

```
[0, 1, 1, 0, 0, 1, 0, -2, 1, 0, 0, -1, 1, 1],
         [0, 0, 0, 0, 1, 0, -1, 0, 0, 0, 0, 0, 0, 0]
. . . . :
....: ])
sage: p = PointConfiguration(U.columns())
sage: triangulation = p.placing_triangulation(); triangulation
(<0,2,3,4,6,7>, <0,2,3,4,6,12>, <0,2,3,4,7,13>, <0,2,3,4,12,13>,
<0,2,3,6,7,13>, <0,2,3,6,12,13>, <0,2,4,6,7,13>, <0,2,4,6,12,13>,
<0,3,4,6,7,12>,<0,3,4,7,12,13>,<0,3,6,7,12,13>,<0,4,6,7,12,13>,
<1,3,4,5,6,12>, <1,3,4,6,11,12>, <1,3,4,7,11,13>, <1,3,4,11,12,13>,
<1,3,6,7,11,13>, <1,3,6,11,12,13>, <1,4,6,7,11,13>, <1,4,6,11,12,13>,
<3,4,6,7,11,12>, <3,4,7,11,12,13>, <3,6,7,11,12,13>, <4,6,7,11,12,13>)
sage: sum(p.volume(t) for t in triangulation)
42
sage: p0 = PointConfiguration([(0,0),(+1,0),(-1,0),(0,+1),(0,-1)])
sage: p0.pushing_triangulation(point_order=[1,2,0,3,4])
(<1,2,3>,<1,2,4>)
sage: p0.pushing_triangulation(point_order=[0,1,2,3,4])
(<0,1,3>,<0,1,4>,<0,2,3>,<0,2,4>)
```

The same triangulation with renumbered points 0->4, 1->0, etc:

```
sage: p1 = PointConfiguration([(+1,0),(-1,0),(0,+1),(0,-1),(0,0)])
sage: p1.pushing_triangulation(point_order=[4,0,1,2,3])
(<0,2,4>, <0,3,4>, <1,2,4>, <1,3,4>)
```

### plot(\*\*kwds)

Produce a graphical representation of the point configuration.

# **EXAMPLES:**

```
sage: p = PointConfiguration([[0,0],[0,1],[1,0],[1,1],[-1,-1]])
sage: p.plot(axes=False) # optional - sage.plot
Graphics object consisting of 5 graphics primitives
```

positive\_circuits(\*negative)

Returns the positive part of circuits with fixed negative part.

A circuit is a pair  $(C_+, C_-)$ , each consisting of a subset (actually, an ordered tuple) of point indices.

### INPUT:

• \*negative – integer. The indices of points.

### **OUTPUT**:

A tuple of all circuits with  $C_{-}$  = negative.

#### **EXAMPLES:**

### pushing\_triangulation(point\_order=None)

Construct the placing (pushing) triangulation.

### INPUT:

• point\_order – list of points or integers. The order in which the points are to be placed. If not given, the points will be placed in some arbitrary order that attempts to produce a small number of simplices.

#### OUTPUT:

A Triangulation.

### **EXAMPLES:**

```
sage: pc = PointConfiguration([(0,0),(1,0),(2,1),(1,2),(0,1)])
sage: pc.placing_triangulation()
(<0,1,2>,<0,2,4>,<2,3,4>)
sage: pc.placing_triangulation(point_order=(3,2,1,4,0))
(<0,1,4>, <1,2,3>, <1,3,4>)
sage: pc.placing_triangulation(point_order=[pc[1],pc[3],pc[4],pc[0]])
(<0,1,4>,<1,3,4>)
sage: U=matrix([
        [0, 0, 0, 0, 0, 2, 4, -1, 1, 1, 0, 0, 1, 0],
        [0, 0, 0, 1, 0, 0, -1, 0, 0, 0, 0, 0, 0, 0],
        [0, 2, 0, 0, 0, 0, -1, 0, 1, 0, 1, 0, 0, 1],
. . . . .
        [0, 1, 1, 0, 0, 1, 0, -2, 1, 0, 0, -1, 1, 1],
         [0, 0, 0, 0, 1, 0, -1, 0, 0, 0, 0, 0, 0, 0]
. . . . . .
....: ])
sage: p = PointConfiguration(U.columns())
sage: triangulation = p.placing_triangulation(); triangulation
(<0,2,3,4,6,7>, <0,2,3,4,6,12>, <0,2,3,4,7,13>, <0,2,3,4,12,13>,
<0,2,3,6,7,13>, <0,2,3,6,12,13>, <0,2,4,6,7,13>, <0,2,4,6,12,13>,
<0,3,4,6,7,12>, <0,3,4,7,12,13>, <0,3,6,7,12,13>, <0,4,6,7,12,13>,
<1,3,4,5,6,12>, <1,3,4,6,11,12>, <1,3,4,7,11,13>, <1,3,4,11,12,13>,
<1,3,6,7,11,13>, <1,3,6,11,12,13>, <1,4,6,7,11,13>, <1,4,6,11,12,13>,
<3,4,6,7,11,12>, <3,4,7,11,12,13>, <3,6,7,11,12,13>, <4,6,7,11,12,13>)
sage: sum(p.volume(t) for t in triangulation)
sage: p0 = PointConfiguration([(0,0),(+1,0),(-1,0),(0,+1),(0,-1)])
sage: p0.pushing_triangulation(point_order=[1,2,0,3,4])
(<1,2,3>,<1,2,4>)
```

```
sage: p0.pushing_triangulation(point_order=[0,1,2,3,4])
(<0,1,3>, <0,1,4>, <0,2,3>, <0,2,4>)
```

The same triangulation with renumbered points 0->4, 1->0, etc:

```
sage: p1 = PointConfiguration([(+1,0),(-1,0),(0,+1),(0,-1),(0,0)])
sage: p1.pushing_triangulation(point_order=[4,0,1,2,3])
(<0,2,4>, <0,3,4>, <1,2,4>, <1,3,4>)
```

### restrict\_to\_connected\_triangulations(connected=True)

Restrict to connected triangulations.

#### NOTE:

Finding non-connected triangulations requires the optional TOPCOM package.

### INPUT:

• connected – boolean. Whether to restrict to triangulations that are connected by bistellar flips to the regular triangulations.

#### OUTPUT:

A new *PointConfiguration* with the same points, but whose triangulations will all be in the connected component. See *PointConfiguration* for details.

#### **EXAMPLES:**

```
sage: p = PointConfiguration([[0,0],[0,1],[1,0],[1,1],[-1,-1]])
A point configuration in affine 2-space over Integer Ring
consisting of 5 points. The triangulations of this point
configuration are assumed to be connected, not necessarily
fine, not necessarily regular.
sage: len(p.triangulations_list())
sage: PointConfiguration.set_engine('topcom')
                                                                        #_
→optional - topcom
sage: p_all = p.restrict_to_connected_triangulations(connected=False)
→optional - topcom
sage: len(p_all.triangulations_list())
                                                                        #_
→optional - topcom
sage: p == p_all.restrict_to_connected_triangulations(connected=True)
→optional - topcom
sage: PointConfiguration.set_engine('internal')
```

# restrict\_to\_fine\_triangulations(fine=True)

Restrict to fine triangulations.

#### INPUT:

• fine – boolean. Whether to restrict to fine triangulations.

#### OUTPUT:

A new *PointConfiguration* with the same points, but whose triangulations will all be fine. See *PointConfiguration* for details.

### **EXAMPLES:**

```
sage: p = PointConfiguration([[0,0],[0,1],[1,0],[1,1],[-1,-1]])
sage: p
A point configuration in affine 2-space over Integer Ring
consisting of 5 points. The triangulations of this point
configuration are assumed to be connected, not necessarily
fine, not necessarily regular.

sage: len(p.triangulations_list())
4
sage: p_fine = p.restrict_to_fine_triangulations()
sage: len(p.triangulations_list())
4
sage: p == p_fine.restrict_to_fine_triangulations(fine=False)
True
```

### restrict\_to\_regular\_triangulations(regular=True)

Restrict to regular triangulations.

#### NOTE:

Regularity testing requires the optional TOPCOM package.

### INPUT:

• regular – True, False, or None. Whether to restrict to regular triangulations, irregular triangulations, or lift any restrictions on regularity.

#### **OUTPUT**:

A new *PointConfiguration* with the same points, but whose triangulations will all be regular as specified. See *PointConfiguration* for details.

### **EXAMPLES:**

# restrict\_to\_star\_triangulations(star)

Restrict to star triangulations with the given point as the center.

INPUT:

• origin – None or an integer or the coordinates of a point. An integer denotes the index of the central point. If None is passed, any restriction on the starshape will be removed.

#### **OUTPUT:**

A new *PointConfiguration* with the same points, but whose triangulations will all be star. See *PointConfiguration* for details.

### **EXAMPLES:**

### restricted\_automorphism\_group()

Return the restricted automorphism group.

First, let the linear automorphism group be the subgroup of the affine group  $AGL(d, \mathbf{R}) = GL(d, \mathbf{R}) \ltimes \mathbf{R}^d$  preserving the d-dimensional point configuration. The affine group acts in the usual way  $\vec{x} \mapsto A\vec{x} + b$  on the ambient space.

The restricted automorphism group is the subgroup of the linear automorphism group generated by permutations of points. See [BSS2009] for more details and a description of the algorithm.

#### **OUTPUT**:

A PermutationGroup that is isomorphic to the restricted automorphism group is returned.

Note that in Sage, permutation groups always act on positive integers while lists etc. are indexed by nonnegative integers. The indexing of the permutation group is chosen to be shifted by +1. That is, the transposition (i,j) in the permutation group corresponds to exchange of self[i-1] and self[j-1].

#### **EXAMPLES:**

The square with an off-center point in the middle. Note that the middle point breaks the restricted automorphism group  $D_4$  of the convex hull:

```
sage: square = PointConfiguration([(3/4,3/4),(1,1),(1,-1),(-1,-1),(-1,1)])
sage: square.restricted_automorphism_group()
```

```
Permutation Group with generators [(3,5)]
sage: DihedralGroup(1).is_isomorphic(_)
True
```

### secondary\_polytope()

Calculate the secondary polytope of the point configuration.

For a definition of the secondary polytope, see [GKZ1994] page 220 Definition 1.6.

Note that if you restricted the admissible triangulations of the point configuration then the output will be the corresponding face of the whole secondary polytope.

### **OUTPUT**:

The secondary polytope of the point configuration as an instance of *Polyhedron\_base*.

### **EXAMPLES:**

```
sage: p = PointConfiguration([[0,0],[1,0],[2,1],[1,2],[0,1]])
sage: poly = p.secondary_polytope()
sage: poly.vertices_matrix()
[1 1 3 3 5]
[3 5 1 4 1]
[4 2 5 2 4]
[2 4 2 5 4]
[5 3 4 1 1]
sage: poly.Vrepresentation()
(A vertex at (1, 3, 4, 2, 5),
A vertex at (1, 5, 2, 4, 3),
A vertex at (3, 1, 5, 2, 4),
A vertex at (3, 4, 2, 5, 1),
A vertex at (5, 1, 4, 4, 1)
sage: poly.Hrepresentation()
(An equation (0, 0, 1, 2, 1) \times -13 == 0,
An equation (1, 0, 0, 2, 2) \times -15 == 0,
An equation (0, 1, 0, -3, -2) x + 13 == 0,
An inequality (0, 0, 0, -1, -1) x + 7 >= 0,
An inequality (0, 0, 0, 1, 0) \times -2 >= 0,
An inequality (0, 0, 0, -2, -1) x + 11 >= 0,
An inequality (0, 0, 0, 0, 1) x - 1 >= 0,
An inequality (0, 0, 0, 3, 2) \times -14 >= 0
```

### classmethod set\_engine(engine='auto')

Set the engine used to compute triangulations.

# INPUT:

• engine – either 'auto' (default), 'internal', or 'topcom'. The latter two instruct this package to always use its own triangulation algorithms or TOPCOM's algorithms, respectively. By default ('auto'), internal routines are used.

### **EXAMPLES:**

```
sage: p = PointConfiguration([[0,0],[0,1],[1,0],[1,1],[-1,-1]])
sage: p.set_engine('internal') # to make doctests independent of TOPCOM
sage: p.triangulate()
```

```
(<1,3,4>, <2,3,4>)
sage: p.set_engine('topcom') # optional - topcom
sage: p.triangulate() # optional - topcom
(<0,1,2>, <0,1,4>, <0,2,4>, <1,2,3>)
sage: p.set_engine('internal') # optional - topcom
```

#### star\_center()

Return the center used for star triangulations.

#### See also:

```
restrict_to_star_triangulations().
```

#### **OUTPUT**:

A *Point* if a distinguished star central point has been fixed. ValueError exception is raised otherwise.

#### **EXAMPLES:**

```
sage: pc = PointConfiguration([(1,0),(-1,0),(0,1),(0,2)], star=(0,1)); pc
A point configuration in affine 2-space over Integer Ring
consisting of 4 points. The triangulations of this point
configuration are assumed to be connected, not necessarily
fine, not necessarily regular, and star with center P(0, 1).
sage: pc.star_center()
P(0, 1)
sage: pc_nostar = pc.restrict_to_star_triangulations(None)
sage: pc_nostar
A point configuration in affine 2-space over Integer Ring
consisting of 4 points. The triangulations of this point
configuration are assumed to be connected, not necessarily
fine, not necessarily regular.
sage: pc_nostar.star_center()
Traceback (most recent call last):
ValueError: The point configuration has no star center defined.
```

# triangulate(verbose=False)

Return one (in no particular order) triangulation.

### INPUT:

• verbose – boolean. Whether to print out the TOPCOM interaction, if any.

#### **OUTPUT**:

A *Triangulation* satisfying all restrictions imposed. Raises a ValueError if no such triangulation exists.

```
sage: p = PointConfiguration([[0,0],[0,1],[1,0],[1,1],[-1,-1]])
sage: p.triangulate()
(<1,3,4>, <2,3,4>)
sage: list( p.triangulate() )
[(1, 3, 4), (2, 3, 4)]
```

Using TOPCOM yields a different, but equally good, triangulation:

```
sage: p.set_engine('topcom')  # optional - topcom
sage: p.triangulate()  # optional - topcom
(<0,1,2>, <0,1,4>, <0,2,4>, <1,2,3>)
sage: list( p.triangulate() )  # optional - topcom
[(0, 1, 2), (0, 1, 4), (0, 2, 4), (1, 2, 3)]
sage: p.set_engine('internal')  # optional - topcom
```

# triangulations(verbose=False)

Returns all triangulations.

• verbose – boolean (default: False). Whether to print out the TOPCOM interaction, if any.

#### **OUTPUT**:

A generator for the triangulations satisfying all the restrictions imposed. Each triangulation is returned as a *Triangulation* object.

#### **EXAMPLES:**

```
sage: p = PointConfiguration([[0,0],[0,1],[1,0],[1,1],[-1,-1]])
   sage: iter = p.triangulations()
   sage: next(iter)
   (<1,3,4>, <2,3,4>)
   sage: next(iter)
   (<0,1,3>, <0,1,4>, <0,2,3>, <0,2,4>)
   sage: next(iter)
   (<1,2,3>,<1,2,4>)
   sage: next(iter)
   (<0,1,2>, <0,1,4>, <0,2,4>, <1,2,3>)
   sage: p.triangulations_list()
   [(<1,3,4>,<2,3,4>),
   (<0,1,3>, <0,1,4>, <0,2,3>, <0,2,4>),
   (<1,2,3>,<1,2,4>),
   (<0,1,2>, <0,1,4>, <0,2,4>, <1,2,3>)
   sage: p_fine = p.restrict_to_fine_triangulations()
   sage: p_fine.triangulations_list()
   [(<0,1,3>,<0,1,4>,<0,2,3>,<0,2,4>),
    (<0,1,2>, <0,1,4>, <0,2,4>, <1,2,3>)
Note that we explicitly asked the internal algorithm to
compute the triangulations. Using TOPCOM, we obtain the same
triangulations but in a different order::
   sage: p.set_engine('topcom')
                                                      # optional - topcom
                                                      # optional - topcom
  sage: iter = p.triangulations()
                                                      # optional - topcom
   sage: next(iter)
   (<0,1,2>, <0,1,4>, <0,2,4>, <1,2,3>)
   sage: next(iter)
                                                      # optional - topcom
   (<0,1,3>,<0,1,4>,<0,2,3>,<0,2,4>)
                                                      # optional - topcom
   sage: next(iter)
   (<1,2,3>, <1,2,4>)
   sage: next(iter)
                                                      # optional - topcom
   (<1,3,4>, <2,3,4>)
   sage: p.triangulations_list()
                                                      # optional - topcom
```

```
[(<0,1,2>, <0,1,4>, <0,2,4>, <1,2,3>),
  (<0,1,3>, <0,1,4>, <0,2,3>, <0,2,4>),
  (<1,2,3>, <1,2,4>),
  (<1,3,4>, <2,3,4>)]

sage: p_fine = p.restrict_to_fine_triangulations() # optional - topcom

sage: p_fine.set_engine('topcom') # optional - topcom

sage: p_fine.triangulations_list() # optional - topcom

[(<0,1,2>, <0,1,4>, <0,2,4>, <1,2,3>),
  (<0,1,3>, <0,1,4>, <0,2,3>, <0,2,4>)]

sage: p.set_engine('internal') # optional - topcom
```

# triangulations\_list(verbose=False)

Return all triangulations.

#### INPUT:

• verbose – boolean. Whether to print out the TOPCOM interaction, if any.

#### OUTPUT

A list of triangulations (see Triangulation) satisfying all restrictions imposed previously.

#### **EXAMPLES:**

```
sage: p = PointConfiguration([[0,0],[0,1],[1,0],[1,1]])
sage: p.triangulations_list()
[(<0,1,2>, <1,2,3>), (<0,1,3>, <0,2,3>)]
sage: list(map(list, p.triangulations_list()))
[[(0, 1, 2), (1, 2, 3)], [(0, 1, 3), (0, 2, 3)]]
sage: p.set_engine('topcom')  # optional - topcom
sage: p.triangulations_list()  # optional - topcom
[(<0,1,2>, <1,2,3>), (<0,1,3>, <0,2,3>)]
sage: p.set_engine('internal')  # optional - topcom
```

# volume(simplex=None)

Find n! times the n-volume of a simplex of dimension n.

# INPUT:

• simplex (optional argument) – a simplex from a triangulation T specified as a list of point indices.

#### **OUTPUT**:

- If a simplex was passed as an argument: n!\*(volume of simplex).
- Without argument: n!\*(the total volume of the convex hull).

# **EXAMPLES:**

The volume of the standard simplex should always be 1:

```
sage: p = PointConfiguration([[0,0],[1,0],[0,1],[1,1]])
sage: p.volume( [0,1,2] )
1
sage: simplex = p.triangulate()[0] # first simplex of triangulation
sage: p.volume(simplex)
1
```

The square can be triangulated into two minimal simplices, so in the "integral" normalization its volume equals two:

```
sage: p.volume()
2
```

**Note:** We return n!\*(metric volume of the simplex) to ensure that the volume is an integer. Essentially, this normalizes things so that the volume of the standard n-simplex is 1. See [GKZ1994] page 182.

# 3.2 Base classes for triangulations

We provide (fast) cython implementations here.

#### **AUTHORS:**

• Volker Braun (2010-09-14): initial version.

# class sage.geometry.triangulation.base.ConnectedTriangulationsIterator

Bases: sage.structure.sage\_object.SageObject

A Python shim for the C++-class 'triangulations'

#### INPUT:

- point\_configuration a PointConfiguration.
- seed a regular triangulation or None (default). In the latter case, a suitable triangulation is generated automatically. Otherwise, you can explicitly specify the seed triangulation as
  - A *Triangulation* object, or
  - an iterable of iterables specifying the vertices of the simplices, or
  - an iterable of integers, which are then considered the enumerated simplices (see simplex\_to\_int().
- star either None (default) or an integer. If an integer is passed, all returned triangulations will be star with respect to the
- fine boolean (default: False). Whether to return only fine triangulations, that is, simplicial decompositions that make use of all the points of the configuration.

# **OUTPUT:**

An iterator. The generated values are tuples of integers, which encode simplices of the triangulation. The output is a suitable input to *Triangulation*.

# EXAMPLES:

```
sage: p = PointConfiguration([[0,0],[0,1],[1,0],[1,1],[-1,-1]])
sage: from sage.geometry.triangulation.base import ConnectedTriangulationsIterator
sage: ci = ConnectedTriangulationsIterator(p)
sage: next(ci)
(9, 10)
sage: next(ci)
(2, 3, 4, 5)
sage: next(ci)
(7, 8)
```

```
sage: next(ci)
(1, 3, 5, 7)
sage: next(ci)
Traceback (most recent call last):
...
StopIteration
```

You can reconstruct the triangulation from the compressed output via:

```
sage: from sage.geometry.triangulation.element import Triangulation
sage: Triangulation((2, 3, 4, 5), p)
(<0,1,3>, <0,1,4>, <0,2,3>, <0,2,4>)
```

How to use the restrictions:

```
sage: ci = ConnectedTriangulationsIterator(p, fine=True)
sage: list(ci)
[(2, 3, 4, 5), (1, 3, 5, 7)]
sage: ci = ConnectedTriangulationsIterator(p, star=1)
sage: list(ci)
[(7, 8)]
sage: ci = ConnectedTriangulationsIterator(p, star=1, fine=True)
sage: list(ci)
[]
```

# class sage.geometry.triangulation.base.Point

Bases: sage.structure.sage\_object.SageObject

A point of a point configuration.

Note that the coordinates of the points of a point configuration are somewhat arbitrary. What counts are the abstract linear relations between the points, for example encoded by the *circuits()*.

**Warning:** You should not create *Point* objects manually. The constructor of *PointConfiguration\_base* takes care of this for you.

#### INPUT:

- point\_configuration *PointConfiguration\_base*. The point configuration to which the point belongs.
- i integer. The index of the point in the point configuration.
- projective the projective coordinates of the point.
- affine the affine coordinates of the point.
- reduced the reduced (with linearities removed) coordinates of the point.

```
sage: pc = PointConfiguration([(0,0)])
sage: from sage.geometry.triangulation.base import Point
sage: Point(pc, 123, (0,0,1), (0,0), ())
P(0, 0)
```

#### affine()

Return the affine coordinates of the point in the ambient space.

#### **OUTPUT**:

A tuple containing the coordinates.

# **EXAMPLES**:

```
sage: pc = PointConfiguration([[10, 0, 1], [10, 0, 0], [10, 2, 3]])
sage: p = pc.point(2); p
P(10, 2, 3)
sage: p.affine()
(10, 2, 3)
sage: p.projective()
(10, 2, 3, 1)
sage: p.reduced_affine()
(2, 2)
sage: p.reduced_projective()
(2, 2, 1)
sage: p.reduced_affine_vector()
(2, 2)
```

#### index()

Return the index of the point in the point configuration.

# **EXAMPLES:**

```
sage: pc = PointConfiguration([[0, 1], [0, 0], [1, 0]])
sage: p = pc.point(2); p
P(1, 0)
sage: p.index()
2
```

# point\_configuration()

Return the point configuration to which the point belongs.

#### **OUTPUT**:

A PointConfiguration.

### **EXAMPLES:**

```
sage: pc = PointConfiguration([ (0,0), (1,0), (0,1) ])
sage: p = pc.point(0)
sage: p is pc.point(0)
True
sage: p.point_configuration() is pc
True
```

#### projective()

Return the projective coordinates of the point in the ambient space.

#### **OUTPUT**:

A tuple containing the coordinates.

```
sage: pc = PointConfiguration([[10, 0, 1], [10, 0, 0], [10, 2, 3]])
sage: p = pc.point(2); p
P(10, 2, 3)
sage: p.affine()
(10, 2, 3)
sage: p.projective()
(10, 2, 3, 1)
sage: p.reduced_affine()
(2, 2)
sage: p.reduced_projective()
(2, 2, 1)
sage: p.reduced_affine_vector()
(2, 2)
```

# reduced\_affine()

Return the affine coordinates of the point on the hyperplane spanned by the point configuration.

#### **OUTPUT:**

A tuple containing the coordinates.

# **EXAMPLES:**

```
sage: pc = PointConfiguration([[10, 0, 1], [10, 0, 0], [10, 2, 3]])
sage: p = pc.point(2); p
P(10, 2, 3)
sage: p.affine()
(10, 2, 3)
sage: p.projective()
(10, 2, 3, 1)
sage: p.reduced_affine()
(2, 2)
sage: p.reduced_projective()
(2, 2, 1)
sage: p.reduced_affine_vector()
(2, 2)
```

# reduced\_affine\_vector()

Return the affine coordinates of the point on the hyperplane spanned by the point configuration.

# **OUTPUT**:

A tuple containing the coordinates.

#### **EXAMPLES:**

```
sage: pc = PointConfiguration([[10, 0, 1], [10, 0, 0], [10, 2, 3]])
sage: p = pc.point(2); p
P(10, 2, 3)
sage: p.affine()
(10, 2, 3)
sage: p.projective()
(10, 2, 3, 1)
sage: p.reduced_affine()
(2, 2)
sage: p.reduced_projective()
```

```
(2, 2, 1)
sage: p.reduced_affine_vector()
(2, 2)
```

# reduced\_projective()

Return the projective coordinates of the point on the hyperplane spanned by the point configuration.

#### **OUTPUT**:

A tuple containing the coordinates.

#### **EXAMPLES**:

```
sage: pc = PointConfiguration([[10, 0, 1], [10, 0, 0], [10, 2, 3]])
sage: p = pc.point(2); p
P(10, 2, 3)
sage: p.affine()
(10, 2, 3)
sage: p.projective()
(10, 2, 3, 1)
sage: p.reduced_affine()
(2, 2)
sage: p.reduced_projective()
(2, 2, 1)
sage: p.reduced_affine_vector()
(2, 2)
```

# reduced\_projective\_vector()

Return the affine coordinates of the point on the hyperplane spanned by the point configuration.

### OUTPUT:

A tuple containing the coordinates.

#### **EXAMPLES**:

```
sage: pc = PointConfiguration([[10, 0, 1], [10, 0, 0], [10, 2, 3]])
sage: p = pc.point(2); p
P(10, 2, 3)
sage: p.affine()
(10, 2, 3)
sage: p.projective()
(10, 2, 3, 1)
sage: p.reduced_affine()
(2, 2)
sage: p.reduced_projective()
(2, 2, 1)
sage: p.reduced_affine_vector()
(2, 2)
sage: type(p.reduced_affine_vector())
<class 'sage.modules.vector_rational_dense.Vector_rational_dense'>
```

# class sage.geometry.triangulation.base.PointConfiguration\_base

Bases: sage.structure.parent.Parent

The cython abstract base class for PointConfiguration.

Warning: You should not instantiate this base class, but only its derived class PointConfiguration.

#### ambient\_dim()

Return the dimension of the ambient space of the point configuration.

See also dimension()

**EXAMPLES:** 

```
sage: p = PointConfiguration([[0,0,0]])
sage: p.ambient_dim()
3
sage: p.dim()
0
```

#### base\_ring()

Return the base ring, that is, the ring containing the coordinates of the points.

**OUTPUT**:

A ring.

**EXAMPLES:** 

```
sage: p = PointConfiguration([(0,0)])
sage: p.base_ring()
Integer Ring

sage: p = PointConfiguration([(1/2,3)])
sage: p.base_ring()
Rational Field

sage: p = PointConfiguration([(0.2, 5)])
sage: p.base_ring()
Real Field with 53 bits of precision
```

# dim()

Return the actual dimension of the point configuration.

See also ambient\_dim()

**EXAMPLES:** 

```
sage: p = PointConfiguration([[0,0,0]])
sage: p.ambient_dim()
3
sage: p.dim()
0
```

# int\_to\_simplex(s)

Reverses the enumeration of possible simplices in simplex\_to\_int().

The enumeration is compatible with [PUNTOS].

INPUT:

• s - int. An integer that uniquely specifies a simplex.

#### **OUTPUT**:

An ordered tuple consisting of the indices of the vertices of the simplex.

### **EXAMPLES:**

# is\_affine()

Whether the configuration is defined by affine points.

#### **OUTPUT:**

Boolean. If true, the homogeneous coordinates all have 1 as their last entry.

#### **EXAMPLES:**

```
sage: p = PointConfiguration([(0.2, 5), (3, 0.1)])
sage: p.is_affine()
True

sage: p = PointConfiguration([(0.2, 5, 1), (3, 0.1, 1)], projective=True)
sage: p.is_affine()
False
```

### n\_points()

Return the number of points.

Same as len(self).

### **EXAMPLES:**

```
sage: p = PointConfiguration([[0,0],[0,1],[1,0],[1,1],[-1,-1]])
sage: p
A point configuration in affine 2-space over Integer Ring
consisting of 5 points. The triangulations of this point
configuration are assumed to be connected, not necessarily
fine, not necessarily regular.
sage: len(p)
5
sage: p.n_points()
```

# point(i)

Return the i-th point of the configuration.

```
Same as __getitem__()
```

# INPUT:

• i – integer.

#### **OUTPUT**:

A point of the point configuration.

#### **EXAMPLES:**

```
sage: pconfig = PointConfiguration([[0,0],[0,1],[1,0],[1,1],[-1,-1]])
sage: list(pconfig)
[P(0, 0), P(0, 1), P(1, 0), P(1, 1), P(-1, -1)]
sage: [ p for p in pconfig.points() ]
[P(0, 0), P(0, 1), P(1, 0), P(1, 1), P(-1, -1)]
sage: pconfig.point(0)
P(0, 0)
sage: pconfig[0]
P(0, 0)
sage: pconfig.point(1)
P(0, 1)
sage: pconfig.point( pconfig.n_points()-1 )
P(-1, -1)
```

#### points()

Return a list of the points.

# **OUTPUT**:

Returns a list of the points. See also the \_\_iter\_\_() method, which returns the corresponding generator.

### EXAMPLES:

```
sage: pconfig = PointConfiguration([[0,0],[0,1],[1,0],[1,1],[-1,-1]])
sage: list(pconfig)
[P(0, 0), P(0, 1), P(1, 0), P(1, 1), P(-1, -1)]
sage: [ p for p in pconfig.points() ]
[P(0, 0), P(0, 1), P(1, 0), P(1, 1), P(-1, -1)]
sage: pconfig.point(0)
P(0, 0)
sage: pconfig.point(1)
P(0, 1)
sage: pconfig.point( pconfig.n_points()-1 )
P(-1, -1)
```

# reduced\_affine\_vector\_space()

Return the vector space that contains the affine points.

### **OUTPUT**:

A vector space over the fraction field of base\_ring().

#### **EXAMPLES:**

```
sage: p = PointConfiguration([[0,0,0], [1,2,3]])
sage: p.base_ring()
Integer Ring
sage: p.reduced_affine_vector_space()
Vector space of dimension 1 over Rational Field
```

```
sage: p.reduced_projective_vector_space()
Vector space of dimension 2 over Rational Field
```

# reduced\_projective\_vector\_space()

Return the vector space that is spanned by the homogeneous coordinates.

#### **OUTPUT**:

A vector space over the fraction field of base\_ring().

#### **EXAMPLES:**

```
sage: p = PointConfiguration([[0,0,0], [1,2,3]])
sage: p.base_ring()
Integer Ring
sage: p.reduced_affine_vector_space()
Vector space of dimension 1 over Rational Field
sage: p.reduced_projective_vector_space()
Vector space of dimension 2 over Rational Field
```

# simplex\_to\_int(simplex)

Returns an integer that uniquely identifies the given simplex.

See also the inverse method  $int_to_simplex()$ .

The enumeration is compatible with [PUNTOS].

#### INPUT:

• simplex – iterable, for example a list. The elements are the vertex indices of the simplex.

### **OUTPUT**:

An integer that uniquely specifies the simplex.

# 3.3 A triangulation

In Sage, the *PointConfiguration* and *Triangulation* satisfy a parent/element relationship. In particular, each triangulation refers back to its point configuration. If you want to triangulate a point configuration, you should construct a point configuration first and then use one of its methods to triangulate it according to your requirements. You should never have to construct a *Triangulation* object directly.

#### **EXAMPLES:**

First, we select the internal implementation for enumerating triangulations:

```
sage: PointConfiguration.set_engine('internal') # to make doctests independent of

¬TOPCOM
```

Here is a simple example of how to triangulate a point configuration:

```
sage: p = [[0,-1,-1],[0,0,1],[0,1,0], [1,-1,-1],[1,0,1],[1,1,0]]
sage: points = PointConfiguration(p)
sage: triang = points.triangulate(); triang
(<0,1,2,5>, <0,1,3,5>, <1,3,4,5>)
sage: triang.plot(axes=False) # optional - sage.plot
Graphics3d Object
```

See sage.geometry.triangulation.point\_configuration for more details.

```
class sage.geometry.triangulation.element.Triangulation(triangulation, parent, check=True)
    Bases: sage.structure.element.Element
```

A triangulation of a *PointConfiguration*.

**Warning:** You should never create *Triangulation* objects manually. See *triangulate()* and *triangulations()* to triangulate point configurations.

### adjacency\_graph()

Return a graph showing which simplices are adjacent in the triangulation.

#### **OUTPUT**:

A graph consisting of vertices referring to the simplices in the triangulation, and edges showing which simplices are adjacent to each other.

### See also:

• To obtain the triangulation's 1-skeleton, use SimplicialComplex.graph() through MyTriangulation.simplicial\_complex().graph().

# **AUTHORS:**

• Stephen Farley (2013-08-10): initial version

#### **EXAMPLES:**

693

3.3. A triangulation

#### boundary()

Return the boundary of the triangulation.

#### **OUTPUT:**

The outward-facing boundary simplices (of dimension d-1) of the d-dimensional triangulation as a set. Each boundary is returned by a tuple of point indices.

### **EXAMPLES:**

```
sage: triangulation = polytopes.cube().triangulate(engine='internal')
sage: triangulation
(<0,1,2,7>, <0,1,5,7>, <0,2,3,7>, <0,3,4,7>, <0,4,5,7>, <1,5,6,7>)
sage: triangulation.boundary()
frozenset({(0, 1, 2),}
           (0, 1, 5),
           (0, 2, 3),
           (0, 3, 4),
           (0, 4, 5),
           (1, 2, 7),
           (1, 5, 6),
           (1, 6, 7),
           (2, 3, 7),
           (3, 4, 7),
           (4, 5, 7),
           (5, 6, 7)
sage: triangulation.interior_facets()
frozenset({(0, 1, 7), (0, 2, 7), (0, 3, 7), (0, 4, 7), (0, 5, 7), (1, 5, 7)})
```

# boundary\_polyhedral\_complex(\*\*kwds)

Return the boundary of self as a PolyhedralComplex.

# **OUTPUT**:

A PolyhedralComplex whose maximal cells are the simplices of the boundary of self.

```
sage: P = polytopes.cube()
sage: pc = PointConfiguration(P.vertices())
sage: T = pc.placing_triangulation(); T
(<0,1,2,7>, <0,1,5,7>, <0,2,3,7>, <0,3,4,7>, <0,4,5,7>, <1,5,6,7>)
sage: bd_C = T.boundary_polyhedral_complex(); bd_C
Polyhedral complex with 12 maximal cells
sage: [P.vertices_list() for P in bd_C.maximal_cells_sorted()]
[[[-1, -1, -1], [-1, -1, 1], [-1, 1, 1]],
[[-1, -1, -1], [-1, -1, 1], [1, -1, -1]],
[[-1, -1, -1], [-1, 1, -1], [-1, 1, 1]],
[[-1, -1, -1], [-1, 1, -1], [1, 1, -1]],
[[-1, -1, -1], [1, -1, -1], [1, 1, -1]],
[[-1, -1, 1], [-1, 1, 1], [1, -1, 1]],
[[-1, -1, 1], [1, -1, -1], [1, -1, 1]],
[[-1, 1, -1], [-1, 1, 1], [1, 1, -1]],
[[-1, 1, 1], [1, -1, 1], [1, 1, 1]],
[[-1, 1, 1], [1, 1, -1], [1, 1, 1]],
[[1, -1, -1], [1, -1, 1], [1, 1, 1]],
[[1, -1, -1], [1, 1, -1], [1, 1, 1]]]
```

It is a subcomplex of self as a polyhedral\_complex():

```
sage: C = T.polyhedral_complex()
sage: bd_C.is_subcomplex(C)
True
```

# boundary\_simplicial\_complex()

Return the boundary of self as an (abstract) simplicial complex.

**OUTPUT**:

A SimplicialComplex.

**EXAMPLES:** 

```
sage: p = polytopes.cuboctahedron()
sage: triangulation = p.triangulate(engine='internal')
sage: bd_sc = triangulation.boundary_simplicial_complex()
sage: bd_sc
Simplicial complex with 12 vertices and 20 facets
```

The boundary of every convex set is a topological sphere, so it has spherical homology:

```
sage: bd_sc.homology()
{0: 0, 1: 0, 2: Z}
```

It is a subcomplex of self as a simplicial\_complex():

```
sage: sc = triangulation.simplicial_complex()
sage: all(f in sc for f in bd_sc.maximal_faces())
True
```

# enumerate\_simplices()

Return the enumerated simplices.

**OUTPUT**:

A tuple of integers that uniquely specifies the triangulation.

**EXAMPLES:** 

You can recreate the triangulation from this list by passing it to the constructor:

3.3. A triangulation 695

```
sage: from sage.geometry.triangulation.point_configuration import Triangulation
sage: Triangulation([1678, 1688, 1769, 1779, 1895, 1905, 2112, 2143,
...: 2234, 2360, 2555, 2580, 2610, 2626, 2650, 2652, 2654, 2661, 2663,
...: 2667, 2685, 2755, 2757, 2759, 2766, 2768, 2772, 2811, 2881, 2883,
...: 2885, 2892, 2894, 2898], pc)
(<1,3,4,7,10,13>, <1,3,4,8,10,13>, <1,3,6,7,10,13>, <1,3,6,8,10,13>,
<1,4,6,7,10,13>, <1,4,6,8,10,13>, <2,3,4,6,7,12>, <2,3,4,7,12,13>,
<2,3,6,7,12,13>, <2,4,6,7,12,13>, <3,4,5,6,9,12>, <3,4,5,8,9,12>,
<3,4,6,7,11,12>, <3,4,6,9,11,12>, <3,4,7,10,11,13>, <3,4,7,11,12,13>,
<3,4,8,9,10,12>, <3,4,8,10,12,13>, <3,4,9,10,11,12>, <3,4,10,11,12,13>,
<3,5,6,8,9,12>, <3,6,7,10,11,13>, <3,6,7,11,12,13>, <4,5,6,8,9,12>,
<4,6,7,10,11,13>, <4,6,7,11,12,13>, <4,6,8,9,10,12>, <4,6,8,9,10,12>, <4,6,8,9,10,12>, <4,6,8,9,10,12>, <4,6,8,9,10,12>, <4,6,8,9,10,12>, <4,6,8,9,10,12>, <4,6,8,9,10,12>, <4,6,8,9,10,12>, <4,6,8,9,10,12>, <4,6,8,9,10,11,12>, <4,6,8,10,12,13>)
```

# fan(origin=None)

Construct the fan of cones over the simplices of the triangulation.

#### INPUT:

• origin – None (default) or coordinates of a point. The common apex of all cones of the fan. If None, the triangulation must be a star triangulation and the distinguished central point is used as the origin.

#### **OUTPUT**:

A *RationalPolyhedralFan*. The coordinates of the points are shifted so that the apex of the fan is the origin of the coordinate system.

**Note:** If the set of cones over the simplices is not a fan, a suitable exception is raised.

# **EXAMPLES:**

Toric diagrams (the  $\mathbb{Z}_5$  hyperconifold):

```
sage: vertices=[(0, 1, 0), (0, 3, 1), (0, 2, 3), (0, 0, 2)]
sage: interior=[(0, 1, 1), (0, 1, 2), (0, 2, 1), (0, 2, 2)]
sage: points = vertices+interior
sage: pc = PointConfiguration(points, fine=True)
sage: triangulation = pc.triangulate()
sage: fan = triangulation.fan( (-1,0,0) )
sage: fan
Rational polyhedral fan in 3-d lattice N
sage: fan.rays()
N(1, 1, 0),
N(1, 3, 1),
N(1, 2, 3),
```

```
N(1, 0, 2),
N(1, 1, 1),
N(1, 1, 2),
N(1, 2, 1),
N(1, 2, 2)
in 3-d lattice N
```

# gkz\_phi()

Calculate the GKZ phi vector of the triangulation.

The phi vector is a vector of length equals to the number of points in the point configuration. For a fixed triangulation T, the entry corresponding to the i-th point  $p_i$  is

$$\phi_T(p_i) = \sum_{t \in T, t \ni p_i} Vol(t)$$

that is, the total volume of all simplices containing  $p_i$ . See also [GKZ1994] page 220 equation 1.4.

#### **OUTPUT**:

The phi vector of self.

# **EXAMPLES:**

```
sage: p = PointConfiguration([[0,0],[1,0],[2,1],[1,2],[0,1]])
sage: p.triangulate().gkz_phi()
(3, 1, 5, 2, 4)
sage: p.lexicographic_triangulation().gkz_phi()
(1, 3, 4, 2, 5)
```

### interior\_facets()

Return the interior facets of the triangulation.

# **OUTPUT**:

The inward-facing boundary simplices (of dimension d-1) of the d-dimensional triangulation as a set. Each boundary is returned by a tuple of point indices.

### **EXAMPLES:**

```
sage: triangulation = polytopes.cube().triangulate(engine='internal')
sage: triangulation
(<0,1,2,7>, <0,1,5,7>, <0,2,3,7>, <0,3,4,7>, <0,4,5,7>, <1,5,6,7>)
sage: triangulation.boundary()
frozenset({(0, 1, 2),}
           (0, 1, 5),
           (0, 2, 3),
           (0, 3, 4),
           (0, 4, 5),
           (1, 2, 7),
           (1, 5, 6),
           (1, 6, 7),
           (2, 3, 7),
           (3, 4, 7),
           (4, 5, 7),
           (5, 6, 7)
```

```
sage: triangulation.interior_facets()
frozenset({(0, 1, 7), (0, 2, 7), (0, 3, 7), (0, 4, 7), (0, 5, 7), (1, 5, 7)})
```

#### normal\_cone()

Return the (closure of the) normal cone of the triangulation.

Recall that a regular triangulation is one that equals the "crease lines" of a convex piecewise-linear function. This support function is not unique, for example, you can scale it by a positive constant. The set of all piecewise-linear functions with fixed creases forms an open cone. This cone can be interpreted as the cone of normal vectors at a point of the secondary polytope, which is why we call it normal cone. See [GKZ1994] Section 7.1 for details.

#### OUTPUT:

The closure of the normal cone. The i-th entry equals the value of the piecewise-linear function at the i-th point of the configuration.

For an irregular triangulation, the normal cone is empty. In this case, a single point (the origin) is returned.

#### **EXAMPLES:**

```
sage: triangulation = polytopes.hypercube(2).triangulate(engine='internal')
sage: triangulation
(<0,1,3>,<1,2,3>)
sage: N = triangulation.normal_cone(); N
4-d cone in 4-d lattice
sage: N.rays()
(0, 0, 0, -1),
(0, 0, 1, 1),
(0, 0, -1, -1),
(1, 0, 0, 1),
(-1, 0, 0, -1),
(0, 1, 0, -1),
(0, -1, 0, 1)
in Ambient free module of rank 4
over the principal ideal domain Integer Ring
sage: N.dual().rays()
(1, -1, 1, -1)
in Ambient free module of rank 4
over the principal ideal domain Integer Ring
```

### plot(\*\*kwds)

Produce a graphical representation of the triangulation.

#### **EXAMPLES:**

```
sage: p = PointConfiguration([[0,0],[0,1],[1,0],[1,1],[-1,-1]])
sage: triangulation = p.triangulate()
sage: triangulation
(<1,3,4>, <2,3,4>)
sage: triangulation.plot(axes=False) # optional - sage.plot
Graphics object consisting of 12 graphics primitives
```

# point\_configuration()

Returns the point configuration underlying the triangulation.

```
sage: pconfig = PointConfiguration([[0,0],[0,1],[1,0]])
sage: pconfig
A point configuration in affine 2-space over Integer Ring
consisting of 3 points. The triangulations of this point
configuration are assumed to be connected, not necessarily
fine, not necessarily regular.
sage: triangulation = pconfig.triangulate()
sage: triangulation
(<0,1,2>)
sage: triangulation.point_configuration()
A point configuration in affine 2-space over Integer Ring
consisting of 3 points. The triangulations of this point
configuration are assumed to be connected, not necessarily
fine, not necessarily regular.
sage: pconfig == triangulation.point_configuration()
True
```

# polyhedral\_complex(\*\*kwds)

Return self as a PolyhedralComplex.

**OUTPUT:** 

A PolyhedralComplex whose maximal cells are the simplices of the triangulation.

#### **EXAMPLES:**

```
sage: P = polytopes.cube()
sage: pc = PointConfiguration(P.vertices())
sage: T = pc.placing_triangulation(); T
(<0,1,2,7>, <0,1,5,7>, <0,2,3,7>, <0,3,4,7>, <0,4,5,7>, <1,5,6,7>)
sage: C = T.polyhedral_complex(); C
Polyhedral complex with 6 maximal cells
sage: [P.vertices_list() for P in C.maximal_cells_sorted()]
[[[-1, -1, -1], [-1, -1, 1], [-1, 1, 1], [1, -1, -1]],
        [[-1, -1, -1], [-1, 1, 1], [1, -1, -1], [1, 1, -1]],
        [[-1, -1, 1], [-1, 1, 1], [1, -1, -1], [1, 1, 1]],
        [[-1, 1, 1], [1, -1, -1], [1, -1, 1]],
        [[-1, 1, 1], [1, -1, -1], [1, 1, 1]]]
```

# simplicial\_complex()

Return self as an (abstract) simplicial complex.

**OUTPUT**:

A SimplicialComplex.

#### **EXAMPLES:**

```
sage: p = polytopes.cuboctahedron()
sage: sc = p.triangulate(engine='internal').simplicial_complex()
sage: sc
Simplicial complex with 12 vertices and 16 facets
```

Any convex set is contractable, so its reduced homology groups vanish:

3.3. A triangulation 699

```
sage: sc.homology()
{0: 0, 1: 0, 2: 0, 3: 0}
```

sage.geometry.triangulation.element.triangulation\_render\_2d(triangulation, \*\*kwds)
Return a graphical representation of a 2-d triangulation.

#### INPUT:

- triangulation a Triangulation.
- \*\*kwds keywords that are passed on to the graphics primitives.

#### **OUTPUT**:

A 2-d graphics object.

#### **EXAMPLES:**

sage.geometry.triangulation.element.triangulation\_render\_3d(triangulation, \*\*kwds)
Return a graphical representation of a 3-d triangulation.

# INPUT:

- triangulation a Triangulation.
- \*\*kwds keywords that are passed on to the graphics primitives.

# OUTPUT:

A 3-d graphics object.

```
sage: p = [[0,-1,-1],[0,0,1],[0,1,0], [1,-1,-1],[1,0,1],[1,1,0]]
sage: points = PointConfiguration(p)
sage: triang = points.triangulate()
sage: triang.plot(axes=False)  # indirect doctest # optional - sage.plot
Graphics3d Object
```

**CHAPTER** 

**FOUR** 

# **MISCELLANEOUS**

# 4.1 Abstract base classes for classes in geometry

# class sage.geometry.abc.ConvexRationalPolyhedralCone

Bases: object

Abstract base class for ConvexRationalPolyhedralCone

This class is defined for the purpose of isinstance tests. It should not be instantiated.

#### **EXAMPLES**:

By design, there is a unique direct subclass:

### class sage.geometry.abc.LatticePolytope

Bases: object

Abstract base class for LatticePolytopeClass

This class is defined for the purpose of isinstance tests. It should not be instantiated.

# EXAMPLES:

By design, there is a unique direct subclass:

#### class sage.geometry.abc.Polyhedron

Bases: object

Abstract base class for Polyhedron\_base

This class is defined for the purpose of isinstance tests. It should not be instantiated.

**EXAMPLES:** 

By design, there is a unique direct subclass:

# 4.2 Convex Sets

EXAMPLES:

Return the affine hull of self as a polyhedron.

```
sage: from sage.geometry.convex_set import ConvexSet_compact
sage: class EmbeddedDisk(ConvexSet_compact):
....: def an_affine_basis(self):
```

```
affine_hull_projection(as_convex_set=None, as_affine_map=False, orthogonal=False, orthonormal=False, extend=False, minimal=False, return_all_data=False, **kwds)
```

Return self projected into its affine hull.

Each convex set is contained in some smallest affine subspace (possibly the entire ambient space) – its affine hull. We provide an affine linear map that projects the ambient space of the convex set to the standard Euclidean space of dimension of the convex set, which restricts to a bijection from the affine hull.

The projection map is not unique; some parameters control the choice of the map. Other parameters control the output of the function.

#### **EXAMPLES:**

```
sage: P = Polyhedron(vertices=[[1, 0], [0, 1]])
sage: ri_P = P.relative_interior(); ri_P
Relative interior of a 1-dimensional polyhedron in ZZ^2 defined as the convex_
→hull of 2 vertices
sage: ri_P.affine_hull_projection(as_affine_map=True)
(Vector space morphism represented by the matrix:
[1]
Domain: Vector space of dimension 2 over Rational Field
Codomain: Vector space of dimension 1 over Rational Field,
(0)
sage: P_aff = P.affine_hull_projection(); P_aff
A 1-dimensional polyhedron in ZZ^1 defined as the convex hull of 2 vertices
sage: ri_P_aff = ri_P.affine_hull_projection(); ri_P_aff
Relative interior of a 1-dimensional polyhedron in QQ^1 defined as the convex_
⊸hull of 2 vertices
sage: ri_P_aff.closure() == P_aff
True
```

#### ambient()

Return the ambient convex set or space.

The default implementation delegates to ambient\_vector\_space().

# EXAMPLES:

```
sage: from sage.geometry.convex_set import ConvexSet_base
sage: class ExampleSet(ConvexSet_base):
...:     def ambient_vector_space(self, base_field=None):
...:         return (base_field or QQ)^2001
sage: ExampleSet().ambient()
Vector space of dimension 2001 over Rational Field
```

4.2. Convex Sets 703

#### ambient\_dim()

Return the dimension of the ambient convex set or space.

The default implementation obtains it from ambient().

#### **EXAMPLES:**

```
sage: from sage.geometry.convex_set import ConvexSet_base
sage: class ExampleSet(ConvexSet_base):
....:     def ambient(self):
....:     return QQ^7
sage: ExampleSet().ambient_dim()
7
```

# ambient\_dimension()

Return the dimension of the ambient convex set or space.

This is the same as ambient\_dim().

#### **EXAMPLES:**

```
sage: from sage.geometry.convex_set import ConvexSet_base
sage: class ExampleSet(ConvexSet_base):
....:     def ambient_dim(self):
....:     return 91
sage: ExampleSet().ambient_dimension()
91
```

# ambient\_vector\_space(base\_field=None)

Return the ambient vector space.

Subclasses must provide an implementation of this method.

The default implementations of ambient(), ambient\_dim(), ambient\_dimension() use this method.

# **EXAMPLES:**

```
sage: from sage.geometry.convex_set import ConvexSet_base
sage: C = ConvexSet_base()
sage: C.ambient_vector_space()
Traceback (most recent call last):
...
NotImplementedError: <abstract method ambient_vector_space at ...>
```

# an\_affine\_basis()

Return points that form an affine basis for the affine hull.

The points are guaranteed to lie in the topological closure of self.

```
sage: from sage.geometry.convex_set import ConvexSet_base
sage: C = ConvexSet_base()
sage: C.an_affine_basis()
Traceback (most recent call last):
...
TypeError: 'NotImplementedType' object is not callable
```

#### an\_element()

Return a point of self.

If self is empty, an EmptySetError will be raised.

The default implementation delegates to \_some\_elements\_().

**EXAMPLES**:

```
sage: from sage.geometry.convex_set import ConvexSet_compact
sage: class BlueBox(ConvexSet_compact):
...:     def _some_elements_(self):
...:         yield 'blue'
...:         yield 'cyan'
sage: BlueBox().an_element()
'blue'
```

# cardinality()

Return the cardinality of this set.

OUTPUT:

Either an integer or Infinity.

**EXAMPLES:** 

# cartesian\_product(other)

Return the Cartesian product.

INPUT:

• other – another convex set

OUTPUT:

The Cartesian product of self and other.

# closure()

Return the topological closure of self.

**EXAMPLES:** 

```
sage: from sage.geometry.convex_set import ConvexSet_closed
sage: C = ConvexSet_closed()
sage: C.closure() is C
True
```

4.2. Convex Sets 705

#### codim()

Return the codimension of self in self.ambient().

**EXAMPLES:** 

```
sage: P = Polyhedron(vertices=[(1,2,3)], rays=[(1,0,0)])
sage: P.codimension()
2
```

An alias is *codim()*:

```
sage: P.codim()
2
```

#### codimension()

Return the codimension of self in self.ambient().

**EXAMPLES:** 

```
sage: P = Polyhedron(vertices=[(1,2,3)], rays=[(1,0,0)])
sage: P.codimension()
2
```

An alias is *codim()*:

```
sage: P.codim()
2
```

# contains(point)

Test whether self contains the given point.

INPUT:

• point – a point or its coordinates

# dilation(scalar)

Return the dilated (uniformly stretched) set.

INPUT:

• scalar – A scalar, not necessarily in base\_ring()

**EXAMPLES:** 

# dim()

Return the dimension of self.

Subclasses must provide an implementation of this method or of the method an\_affine\_basis().

### dimension()

Return the dimension of self.

This is the same as dim().

**EXAMPLES**:

# interior()

Return the topological interior of self.

**EXAMPLES:** 

```
sage: from sage.geometry.convex_set import ConvexSet_open
sage: C = ConvexSet_open()
sage: C.interior() is C
True
```

### intersection(other)

Return the intersection of self and other.

INPUT:

• other – another convex set

**OUTPUT:** 

The intersection.

# is\_closed()

Return whether self is closed.

The default implementation of this method only knows that the empty set, a singleton set, and the ambient space are closed.

**OUTPUT**:

Boolean.

**EXAMPLES:** 

```
sage: from sage.geometry.convex_set import ConvexSet_base
sage: class ExampleSet(ConvexSet_base):
....:     def dim(self):
....:     return 0
sage: ExampleSet().is_closed()
True
```

### is\_compact()

Return whether self is compact.

The default implementation of this method only knows that a non-closed set cannot be compact, and that the empty set and a singleton set are compact.

**OUTPUT**:

4.2. Convex Sets 707

Boolean.

```
sage: from sage.geometry.convex_set import ConvexSet_base sage: class Example-Set(ConvexSet_base): ....: def dim(self): ....: return 0 sage: ExampleSet().is_compact() True
```

# is\_empty()

Test whether self is the empty set.

**OUTPUT**:

Boolean.

**EXAMPLES:** 

```
sage: p = LatticePolytope([], lattice=ToricLattice(3).dual()); p
-1-d lattice polytope in 3-d lattice M
sage: p.is_empty()
True
```

#### is finite()

Test whether self is a finite set.

**OUTPUT:** 

Boolean.

**EXAMPLES:** 

# is\_full\_dimensional()

Return whether self is full dimensional.

**OUTPUT**:

Boolean. Whether the polyhedron is not contained in any strict affine subspace.

```
sage: c = Cone([(1,0)])
sage: c.is_full_dimensional()
False

sage: polytopes.hypercube(3).is_full_dimensional()
True
sage: Polyhedron(vertices=[(1,2,3)], rays=[(1,0,0)]).is_full_dimensional()
False
```

# is\_open()

Return whether self is open.

The default implementation of this method only knows that the empty set and the ambient space are open.

**OUTPUT:** 

Boolean.

**EXAMPLES:** 

```
sage: from sage.geometry.convex_set import ConvexSet_base
sage: class ExampleSet(ConvexSet_base):
...:     def is_empty(self):
...:     return False
...:     def is_universe(self):
...:     return True
sage: ExampleSet().is_open()
True
```

# is\_relatively\_open()

Return whether self is relatively open.

The default implementation of this method only knows that open sets are also relatively open, and in addition singletons are relatively open.

**OUTPUT**:

Boolean.

**EXAMPLES:** 

```
sage: from sage.geometry.convex_set import ConvexSet_base
sage: class ExampleSet(ConvexSet_base):
...:     def is_open(self):
...:     return True
sage: ExampleSet().is_relatively_open()
True
```

# is\_universe()

Test whether self is the whole ambient space.

**OUTPUT**:

Boolean.

# linear\_transformation(linear transf)

Return the linear transformation of self.

INPUT:

• linear\_transf - a matrix

# relative\_interior()

Return the relative interior of self.

**EXAMPLES:** 

```
sage: from sage.geometry.convex_set import ConvexSet_relatively_open
sage: C = ConvexSet_relatively_open()
sage: C.relative_interior() is C
True
```

4.2. Convex Sets 709

### representative\_point()

Return a "generic" point of self.

**OUTPUT:** 

A point in the relative interior of self as a coordinate vector.

**EXAMPLES**:

```
sage: C = Cone([[1, 2, 0], [2, 1, 0]])
sage: C.representative_point()
(1, 1, 0)
```

# some\_elements()

Return a list of some points of self.

If self is empty, an empty list is returned; no exception will be raised.

The default implementation delegates to \_some\_elements\_().

**EXAMPLES:** 

```
sage: from sage.geometry.convex_set import ConvexSet_compact
sage: class BlueBox(ConvexSet_compact):
...:     def _some_elements_(self):
...:         yield 'blue'
...:         yield 'cyan'
sage: BlueBox().some_elements()
['blue', 'cyan']
```

# translation(displacement)

Return the translation of self by a displacement vector.

INPUT:

• displacement – a displacement vector or a list/tuple of coordinates that determines a displacement vector

# class sage.geometry.convex\_set.ConvexSet\_closed

```
Bases: sage.geometry.convex_set.ConvexSet_base
```

Abstract base class for closed convex sets.

### is\_closed()

Return whether self is closed.

OUTPUT:

Boolean.

**EXAMPLES:** 

```
sage: hcube = polytopes.hypercube(5)
sage: hcube.is_closed()
True
```

# is\_open()

Return whether self is open.

OUTPUT:

Boolean.

# **EXAMPLES:**

```
sage: hcube = polytopes.hypercube(5)
sage: hcube.is_open()
False

sage: zerocube = polytopes.hypercube(0)
sage: zerocube.is_open()
True
```

# class sage.geometry.convex\_set.ConvexSet\_compact

```
Bases: sage.geometry.convex_set.ConvexSet_closed
```

Abstract base class for compact convex sets.

# is\_compact()

Return whether self is compact.

**OUTPUT**:

Boolean.

**EXAMPLES:** 

```
sage: cross3 = lattice_polytope.cross_polytope(3)
sage: cross3.is_compact()
True
```

# is\_relatively\_open()

Return whether self is open.

**OUTPUT**:

Boolean.

**EXAMPLES:** 

```
sage: hcube = polytopes.hypercube(5)
sage: hcube.is_open()
False

sage: zerocube = polytopes.hypercube(0)
sage: zerocube.is_open()
True
```

# is\_universe()

Return whether self is the whole ambient space

**OUTPUT:** 

Boolean.

**EXAMPLES:** 

```
sage: cross3 = lattice_polytope.cross_polytope(3)
sage: cross3.is_universe()
False
sage: point0 = LatticePolytope([[]]); point0
0-d reflexive polytope in 0-d lattice M
```

(continues on next page)

4.2. Convex Sets 711

```
sage: point0.is_universe()
True
```

# class sage.geometry.convex\_set.ConvexSet\_open

Bases: sage.geometry.convex\_set.ConvexSet\_relatively\_open

Abstract base class for open convex sets.

#### is\_closed()

Return whether self is closed.

**OUTPUT:** 

Boolean.

**EXAMPLES:** 

```
sage: from sage.geometry.convex_set import ConvexSet_open
sage: class OpenBall(ConvexSet_open):
...:     def dim(self):
...:     return 3
...:     def is_universe(self):
...:     return False
sage: OpenBall().is_closed()
False
```

#### is\_open()

Return whether self is open.

**OUTPUT**:

Boolean.

**EXAMPLES:** 

```
sage: from sage.geometry.convex_set import ConvexSet_open
sage: b = ConvexSet_open()
sage: b.is_open()
True
```

# class sage.geometry.convex\_set.ConvexSet\_relatively\_open

```
Bases: sage.geometry.convex_set.ConvexSet_base
```

Abstract base class for relatively open convex sets.

# is\_open()

Return whether self is open.

**OUTPUT**:

Boolean.

```
sage: segment = Polyhedron([[1, 2], [3, 4]])
sage: ri_segment = segment.relative_interior()
sage: ri_segment.is_open()
False
```

### is\_relatively\_open()

Return whether self is relatively open.

**OUTPUT:** 

Boolean.

**EXAMPLES:** 

```
sage: segment = Polyhedron([[1, 2], [3, 4]])
sage: ri_segment = segment.relative_interior()
sage: ri_segment.is_relatively_open()
True
```

# 4.3 Linear Expressions

A linear expression is just a linear polynomial in some (fixed) variables (allowing a nonzero constant term). This class only implements linear expressions for others to use.

**EXAMPLES:** 

```
sage: from sage.geometry.linear_expression import LinearExpressionModule
sage: L.<x,y,z> = LinearExpressionModule(QQ); L
Module of linear expressions in variables x, y, z over Rational Field
sage: x + 2*y + 3*z + 4
x + 2*y + 3*z + 4
sage: L(4)
0*x + 0*y + 0*z + 4
```

You can also pass coefficients and a constant term to construct linear expressions:

```
sage: L([1, 2, 3], 4)
x + 2*y + 3*z + 4
sage: L([(1, 2, 3), 4])
x + 2*y + 3*z + 4
sage: L([4, 1, 2, 3]) # note: constant is first in single-tuple notation
x + 2*y + 3*z + 4
```

The linear expressions are a module over the base ring, so you can add them and multiply them with scalars:

```
sage: m = x + 2*y + 3*z + 4
sage: 2*m
2*x + 4*y + 6*z + 8
sage: m+m
2*x + 4*y + 6*z + 8
sage: m-m
0*x + 0*y + 0*z + 0
```

class sage.geometry.linear\_expression.LinearExpression(parent, coefficients, constant, check=True)
 Bases: sage.structure.element.ModuleElement

A linear expression.

A linear expression is just a linear polynomial in some (fixed) variables.

```
sage: from sage.geometry.linear_expression import LinearExpressionModule
sage: L.<x,y,z> = LinearExpressionModule(QQ)
sage: m = L([1, 2, 3], 4); m
x + 2*y + 3*z + 4
sage: m2 = L([(1, 2, 3), 4]); m2
x + 2*y + 3*z + 4
sage: m3 = L([4, 1, 2, 3]); m3 # note: constant is first in single-tuple notation
x + 2*y + 3*z + 4
sage: m == m2
True
sage: m2 == m3
True
sage: L.zero()
0*x + 0*y + 0*z + 0
sage: a = L([12, 2/3, -1], -2)
sage: a - m
11*x - 4/3*y - 4*z - 6
sage: LZ.<x,y,z> = LinearExpressionModule(ZZ)
sage: a - LZ([2, -1, 3], 1)
10*x + 5/3*y - 4*z - 3
```

**A**()

Return the coefficient vector.

**OUTPUT**:

The coefficient vector of the linear expression.

**EXAMPLES:** 

```
sage: from sage.geometry.linear_expression import LinearExpressionModule
sage: L.<x,y,z> = LinearExpressionModule(QQ)
sage: linear = L([1, 2, 3], 4); linear
x + 2*y + 3*z + 4
sage: linear.A()
(1, 2, 3)
sage: linear.b()
```

**b**()

Return the constant term.

**OUTPUT**:

The constant term of the linear expression.

```
sage: from sage.geometry.linear_expression import LinearExpressionModule
sage: L.<x,y,z> = LinearExpressionModule(QQ)
sage: linear = L([1, 2, 3], 4); linear
x + 2*y + 3*z + 4
sage: linear.A()
(1, 2, 3)
sage: linear.b()
```

### change\_ring(base ring)

Change the base ring of this linear expression.

#### INPUT:

• base\_ring - a ring; the new base ring

#### OUTPUT:

A new linear expression over the new base ring.

#### **EXAMPLES:**

#### coefficients()

Return all coefficients.

#### **OUTPUT**:

The constant (as first entry) and coefficients of the linear terms (as subsequent entries) in a list.

#### **EXAMPLES:**

```
sage: from sage.geometry.linear_expression import LinearExpressionModule
sage: L.<x,y,z> = LinearExpressionModule(QQ)
sage: linear = L([1, 2, 3], 4); linear
x + 2*y + 3*z + 4
sage: linear.coefficients()
[4, 1, 2, 3]
```

# constant\_term()

Return the constant term.

#### **OUTPUT**:

The constant term of the linear expression.

# **EXAMPLES:**

```
sage: from sage.geometry.linear_expression import LinearExpressionModule
sage: L.<x,y,z> = LinearExpressionModule(QQ)
sage: linear = L([1, 2, 3], 4); linear
x + 2*y + 3*z + 4
sage: linear.A()
(1, 2, 3)
sage: linear.b()
4
```

### dense\_coefficient\_list()

Return all coefficients.

#### **OUTPUT**:

The constant (as first entry) and coefficients of the linear terms (as subsequent entries) in a list.

```
sage: from sage.geometry.linear_expression import LinearExpressionModule
sage: L.<x,y,z> = LinearExpressionModule(QQ)
sage: linear = L([1, 2, 3], 4); linear
x + 2*y + 3*z + 4
sage: linear.coefficients()
[4, 1, 2, 3]
```

#### evaluate(point)

Evaluate the linear expression.

#### INPUT:

• point – list/tuple/iterable of coordinates; the coordinates of a point

#### **OUTPUT**:

The linear expression Ax + b evaluated at the point x.

#### **EXAMPLES:**

```
sage: from sage.geometry.linear_expression import LinearExpressionModule
sage: L.<x,y> = LinearExpressionModule(QQ)
sage: ex = 2*x + 3* y + 4
sage: ex.evaluate([1,1])
9
sage: ex([1,1])  # syntactic sugar
9
sage: ex([pi, e])
2*pi + 3*e + 4
```

# monomial\_coefficients(copy=True)

Return a dictionary whose keys are indices of basis elements in the support of self and whose values are the corresponding coefficients.

# INPUT:

• copy - ignored

# **EXAMPLES:**

```
sage: from sage.geometry.linear_expression import LinearExpressionModule
sage: L.<x,y,z> = LinearExpressionModule(QQ)
sage: linear = L([1, 2, 3], 4)
sage: sorted(linear.monomial_coefficients().items(), key=lambda x: str(x[0]))
[(0, 1), (1, 2), (2, 3), ('b', 4)]
```

# class sage.geometry.linear\_expression.LinearExpressionModule(base\_ring, names=())

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

The module of linear expressions.

This is the module of linear polynomials which is the parent for linear expressions.

# **EXAMPLES:**

```
sage: from sage.geometry.linear_expression import LinearExpressionModule
sage: L = LinearExpressionModule(QQ, ('x', 'y', 'z'))
sage: L
```

```
Module of linear expressions in variables x, y, z over Rational Field sage: L.an_element() x + 0*y + 0*z + 0
```

#### **Element**

alias of LinearExpression

#### ambient\_module()

Return the ambient module.

#### See also:

```
ambient_vector_space()
```

#### **OUTPUT**:

The domain of the linear expressions as a free module over the base ring.

#### **EXAMPLES:**

```
sage: from sage.geometry.linear_expression import LinearExpressionModule
sage: L = LinearExpressionModule(QQ, ('x', 'y', 'z'))
sage: L.ambient_module()
Vector space of dimension 3 over Rational Field
sage: M = LinearExpressionModule(ZZ, ('r', 's'))
sage: M.ambient_module()
Ambient free module of rank 2 over the principal ideal domain Integer Ring
sage: M.ambient_vector_space()
Vector space of dimension 2 over Rational Field
```

### ambient\_vector\_space()

Return the ambient vector space.

#### See also:

```
ambient_module()
```

#### **OUTPUT**:

The vector space (over the fraction field of the base ring) where the linear expressions live.

## **EXAMPLES:**

```
sage: from sage.geometry.linear_expression import LinearExpressionModule
sage: L = LinearExpressionModule(QQ, ('x', 'y', 'z'))
sage: L.ambient_vector_space()
Vector space of dimension 3 over Rational Field
sage: M = LinearExpressionModule(ZZ, ('r', 's'))
sage: M.ambient_module()
Ambient free module of rank 2 over the principal ideal domain Integer Ring
sage: M.ambient_vector_space()
Vector space of dimension 2 over Rational Field
```

#### basis()

Return a basis of self.

```
sage: from sage.geometry.linear_expression import LinearExpressionModule
sage: L = LinearExpressionModule(QQ, ('x', 'y', 'z'))
sage: list(L.basis())
[x + 0*y + 0*z + 0,
0*x + y + 0*z + 0,
0*x + 0*y + z + 0,
0*x + 0*y + z + 1]
```

## change\_ring(base\_ring)

Return a new module with a changed base ring.

INPUT:

• base\_ring – a ring; the new base ring

**OUTPUT**:

A new linear expression over the new base ring.

**EXAMPLES:** 

```
sage: from sage.geometry.linear_expression import LinearExpressionModule
sage: M.<y> = LinearExpressionModule(ZZ)
sage: L = M.change_ring(QQ); L
Module of linear expressions in variable y over Rational Field
```

#### gen(i)

Return the i-th generator.

INPUT:

• i – integer

OUTPUT:

A linear expression.

**EXAMPLES:** 

```
sage: from sage.geometry.linear_expression import LinearExpressionModule
sage: L = LinearExpressionModule(QQ, ('x', 'y', 'z'))
sage: L.gen(0)
x + 0*y + 0*z + 0
```

#### gens()

Return the generators of self.

OUTPUT:

A tuple of linear expressions, one for each linear variable.

**EXAMPLES:** 

```
sage: from sage.geometry.linear_expression import LinearExpressionModule
sage: L = LinearExpressionModule(QQ, ('x', 'y', 'z'))
sage: L.gens()
(x + 0*y + 0*z + 0, 0*x + y + 0*z + 0, 0*x + 0*y + z + 0)
```

# ngens()

Return the number of linear variables.

#### **OUTPUT**:

An integer.

## **EXAMPLES:**

```
sage: from sage.geometry.linear_expression import LinearExpressionModule
sage: L = LinearExpressionModule(QQ, ('x', 'y', 'z'))
sage: L.ngens()
3
```

# random\_element()

Return a random element.

## **EXAMPLES:**

```
sage: from sage.geometry.linear_expression import LinearExpressionModule
sage: L.<x,y,z> = LinearExpressionModule(QQ)
sage: L.random_element() in L
True
```

# 4.4 Newton Polygons

This module implements finite Newton polygons and infinite Newton polygons having a finite number of slopes (and hence a last infinite slope).

```
sage.geometry.newton_polygon.NewtonPolygon = Parent for Newton polygons
```

class sage.geometry.newton\_polygon.NewtonPolygon\_element(polyhedron, parent)

```
Bases: sage.structure.element.Element
```

Class for infinite Newton polygons with last slope.

#### last\_slope()

Returns the last (infinite) slope of this Newton polygon if it is infinite and +Infinity otherwise.

## **EXAMPLES:**

```
sage: from sage.geometry.newton_polygon import NewtonPolygon
sage: NP1 = NewtonPolygon([ (0,0), (1,1), (2,8), (3,5) ], last_slope=3)
sage: NP1.last_slope()
3
sage: NP2 = NewtonPolygon([ (0,0), (1,1), (2,5) ])
sage: NP2.last_slope()
+Infinity
```

We check that the last slope of a sum (resp. a product) is the minimum of the last slopes of the summands (resp. the factors):

```
sage: (NP1 + NP2).last_slope()
3
sage: (NP1 * NP2).last_slope()
3
```

# plot(\*\*kwargs)

Plot this Newton polygon.

**Note:** All usual rendering options (color, thickness, etc.) are available.

# **EXAMPLES:**

```
sage: from sage.geometry.newton_polygon import NewtonPolygon
sage: NP = NewtonPolygon([ (0,0), (1,1), (2,6) ])
sage: polygon = NP.plot() # optional - sage.plot
```

#### reverse(degree=None)

Returns the symmetric of self

#### INPUT:

• degree – an integer (default: the top right abscissa of this Newton polygon)

#### **OUTPUT**:

The image this Newton polygon under the symmetry (x,y) maps to (degree-x, y)

#### **EXAMPLES:**

```
sage: from sage.geometry.newton_polygon import NewtonPolygon
sage: NP = NewtonPolygon([ (0,0), (1,1), (2,5) ])
sage: NP2 = NP.reverse(); NP2
Finite Newton polygon with 3 vertices: (0, 5), (1, 1), (2, 0)
```

We check that the slopes of the symmetric Newton polygon are the opposites of the slopes of the original Newton polygon:

```
sage: NP.slopes()
[1, 4]
sage: NP2.slopes()
[-4, -1]
```

### slopes(repetition=True)

Returns the slopes of this Newton polygon

## INPUT:

• repetition – a boolean (default: True)

# OUTPUT:

The consecutive slopes (not including the last slope if the polygon is infinity) of this Newton polygon.

If repetition is True, each slope is repeated a number of times equal to its length. Otherwise, it appears only one time.

#### **EXAMPLES:**

```
sage: from sage.geometry.newton_polygon import NewtonPolygon
sage: NP = NewtonPolygon([ (0,0), (1,1), (3,6) ]); NP
Finite Newton polygon with 3 vertices: (0, 0), (1, 1), (3, 6)
sage: NP.slopes()
[1, 5/2, 5/2]
```

```
sage: NP.slopes(repetition=False)
[1, 5/2]
```

#### vertices(copy=True)

Returns the list of vertices of this Newton polygon

#### INPUT:

• copy – a boolean (default: True)

#### **OUTPUT**:

The list of vertices of this Newton polygon (or a copy of it if copy is set to True)

## **EXAMPLES:**

```
sage: from sage.geometry.newton_polygon import NewtonPolygon
sage: NP = NewtonPolygon([ (0,0), (1,1), (2,5) ]); NP
Finite Newton polygon with 3 vertices: (0, 0), (1, 1), (2, 5)

sage: v = NP.vertices(); v
[(0, 0), (1, 1), (2, 5)]
```

# class sage.geometry.newton\_polygon.ParentNewtonPolygon

Bases: sage.structure.parent.Parent, sage.structure.unique\_representation. UniqueRepresentation

Construct a Newton polygon.

## INPUT:

- arg a list/tuple/iterable of vertices or of slopes. Currently, slopes must be rational numbers.
- sort\_slopes boolean (default: True). Specifying whether slopes must be first sorted
- last\_slope rational or infinity (default: Infinity). The last slope of the Newton polygon

# **OUTPUT**:

The corresponding Newton polygon.

**Note:** By convention, a Newton polygon always contains the point at infinity  $(0, \infty)$ . These polygons are attached to polynomials or series over discrete valuation rings (e.g. padics).

#### **EXAMPLES:**

We specify here a Newton polygon by its vertices:

```
sage: from sage.geometry.newton_polygon import NewtonPolygon
sage: NewtonPolygon([ (0,0), (1,1), (3,5) ])
Finite Newton polygon with 3 vertices: (0, 0), (1, 1), (3, 5)
```

We note that the convex hull of the vertices is automatically computed:

```
sage: NewtonPolygon([ (0,0), (1,1), (2,8), (3,5) ])
Finite Newton polygon with 3 vertices: (0, 0), (1, 1), (3, 5)
```

Note that the value +Infinity is allowed as the second coordinate of a vertex:

```
sage: NewtonPolygon([(0,0), (1,Infinity), (2,8), (3,5)])
Finite Newton polygon with 2 vertices: (0, 0), (3, 5)
```

If last\_slope is set, the returned Newton polygon is infinite and ends with an infinite line having the specified slope:

```
sage: NewtonPolygon([ (0,0), (1,1), (2,8), (3,5) ], last_slope=3)
Infinite Newton polygon with 3 vertices: (0, 0), (1, 1), (3, 5) ending by an
⇒infinite line of slope 3
```

Specifying a last slope may discard some vertices:

```
sage: NewtonPolygon([(0,0), (1,1), (2,8), (3,5)], last_slope=3/2)
Infinite Newton polygon with 2 vertices: (0, 0), (1, 1) ending by an infinite line.
\rightarrow of slope 3/2
```

Next, we define a Newton polygon by its slopes:

```
sage: NP = NewtonPolygon([0, 1/2, 1/2, 2/3, 2/3, 2/3, 1, 1])
sage: NP
Finite Newton polygon with 5 vertices: (0, 0), (1, 0), (3, 1), (6, 3), (8, 5)
sage: NP.slopes()
[0, 1/2, 1/2, 2/3, 2/3, 2/3, 1, 1]
```

By default, slopes are automatically sorted:

```
sage: NP2 = NewtonPolygon([0, 1, 1/2, 2/3, 1/2, 2/3, 1, 2/3])
Finite Newton polygon with 5 vertices: (0, 0), (1, 0), (3, 1), (6, 3), (8, 5)
sage: NP == NP2
True
```

except if the contrary is explicitly mentioned:

```
sage: NewtonPolygon([0, 1, 1/2, 2/3, 1/2, 2/3, 1, 2/3], sort_slopes=False)
Finite Newton polygon with 4 vertices: (0, 0), (1, 0), (6, 10/3), (8, 5)
```

Slopes greater that or equal last\_slope (if specified) are discarded:

```
sage: NP = NewtonPolygon([0, 1/2, 1/2, 2/3, 2/3, 2/3, 1, 1], last_slope=2/3)
sage: NP
Infinite Newton polygon with 3 vertices: (0, 0), (1, 0), (3, 1) ending by an_
⇒infinite line of slope 2/3
sage: NP.slopes()
[0, 1/2, 1/2]
```

Be careful, do not confuse Newton polygons provided by this class with Newton polytopes. Compare:

```
sage: NP = NewtonPolygon([ (0,0), (1,45), (3,6) ]); NP
Finite Newton polygon with 2 vertices: (0, 0), (3, 6)
sage: x, y = polygen(QQ,'x, y')
sage: p = 1 + x*y**45 + x**3*y**6
sage: p.newton_polytope()
```

```
A 2-dimensional polyhedron in ZZ^2 defined as the convex hull of 3 vertices sage: p.newton_polytope().vertices()
(A vertex at (0, 0), A vertex at (1, 45), A vertex at (3, 6))
```

#### **Element**

alias of NewtonPolygon\_element

# 4.5 Relative Interiors of Polyhedra and Cones

```
class sage.geometry.relative_interior.RelativeInterior(polyhedron)
```

Bases: sage.geometry.convex\_set.ConvexSet\_relatively\_open

The relative interior of a polyhedron or cone

This class should not be used directly. Use methods relative\_interior(), interior(), relative\_interior(), interior() instead.

#### **EXAMPLES:**

```
sage: segment = Polyhedron([[1, 2], [3, 4]])
sage: segment.relative_interior()
Relative interior of
    a 1-dimensional polyhedron in ZZ^2 defined as the convex hull of 2 vertices
sage: octant = Cone([(1,0,0), (0,1,0), (0,0,1)])
sage: octant.relative_interior()
Relative interior of 3-d cone in 3-d lattice N
```

### ambient()

Return the ambient convex set or space.

# **EXAMPLES:**

```
sage: segment = Polyhedron([[1, 2], [3, 4]])
sage: ri_segment = segment.relative_interior(); ri_segment
Relative interior of
  a 1-dimensional polyhedron in ZZ^2 defined as the convex hull of 2 vertices
sage: ri_segment.ambient()
Vector space of dimension 2 over Rational Field
```

# ambient\_dim()

Return the dimension of the ambient space.

```
sage: segment = Polyhedron([[1, 2], [3, 4]])
sage: segment.ambient_dim()
2
sage: ri_segment = segment.relative_interior(); ri_segment
Relative interior of
    a 1-dimensional polyhedron in ZZ^2 defined as the convex hull of 2 vertices
sage: ri_segment.ambient_dim()
2
```

#### ambient\_vector\_space(base\_field=None)

Return the ambient vector space.

#### **EXAMPLES:**

```
sage: segment = Polyhedron([[1, 2], [3, 4]])
sage: ri_segment = segment.relative_interior(); ri_segment
Relative interior of
   a 1-dimensional polyhedron in ZZ^2 defined as the convex hull of 2 vertices
sage: ri_segment.ambient_vector_space()
Vector space of dimension 2 over Rational Field
```

## an\_affine\_basis()

Return points that form an affine basis for the affine hull.

The points are guaranteed to lie in the topological closure of self.

#### **EXAMPLES:**

```
sage: segment = Polyhedron([[1, 0], [0, 1]])
sage: segment.relative_interior().an_affine_basis()
[A vertex at (1, 0), A vertex at (0, 1)]
```

#### closure()

Return the topological closure of self.

#### **EXAMPLES:**

```
sage: segment = Polyhedron([[1, 2], [3, 4]])
sage: ri_segment = segment.relative_interior(); ri_segment
Relative interior of
  a 1-dimensional polyhedron in ZZ^2 defined as the convex hull of 2 vertices
sage: ri_segment.closure() is segment
True
```

### dilation(scalar)

Return the dilated (uniformly stretched) set.

## INPUT:

• scalar - A scalar

## **EXAMPLES:**

```
sage: segment = Polyhedron([[1, 2], [3, 4]])
sage: ri_segment = segment.relative_interior(); ri_segment
Relative interior of a
   1-dimensional polyhedron in ZZ^2 defined as the convex hull of 2 vertices
sage: A = ri_segment.dilation(2); A
Relative interior of a
   1-dimensional polyhedron in ZZ^2 defined as the convex hull of 2 vertices
sage: A.closure().vertices()
(A vertex at (2, 4), A vertex at (6, 8))
sage: B = ri_segment.dilation(-1/3); B
Relative interior of a
   1-dimensional polyhedron in QQ^2 defined as the convex hull of 2 vertices
sage: B.closure().vertices()
```

```
(A vertex at (-1, -4/3), A vertex at (-1/3, -2/3))
sage: C = ri_segment.dilation(0); C
A 0-dimensional polyhedron in ZZ^2 defined as the convex hull of 1 vertex
sage: C.vertices()
(A vertex at (0, 0),)
```

#### dim()

Return the dimension of self.

#### **EXAMPLES:**

```
sage: segment = Polyhedron([[1, 2], [3, 4]])
sage: segment.dim()
1
sage: ri_segment = segment.relative_interior(); ri_segment
Relative interior of
    a 1-dimensional polyhedron in ZZ^2 defined as the convex hull of 2 vertices
sage: ri_segment.dim()
1
```

## interior()

Return the interior of self.

### **EXAMPLES:**

```
sage: segment = Polyhedron([[1, 2], [3, 4]])
sage: ri_segment = segment.relative_interior(); ri_segment
Relative interior of
    a 1-dimensional polyhedron in ZZ^2 defined as the convex hull of 2 vertices
sage: ri_segment.interior()
The empty polyhedron in ZZ^2

sage: octant = Cone([(1,0,0), (0,1,0), (0,0,1)])
sage: ri_octant = octant.relative_interior(); ri_octant
Relative interior of 3-d cone in 3-d lattice N
sage: ri_octant.interior() is ri_octant
True
```

# is\_closed()

Return whether self is closed.

OUTPUT:

Boolean.

**EXAMPLES:** 

## is\_universe()

Return whether self is the whole ambient space

#### **OUTPUT**:

Boolean.

## **EXAMPLES:**

```
sage: segment = Polyhedron([[1, 2], [3, 4]])
sage: ri_segment = segment.relative_interior(); ri_segment
Relative interior of
  a 1-dimensional polyhedron in ZZ^2 defined as the convex hull of 2 vertices
sage: ri_segment.is_universe()
False
```

# linear\_transformation(linear\_transf, \*\*kwds)

Return the linear transformation of self.

By [Roc1970], Theorem 6.6, the linear transformation of a relative interior is the relative interior of the linear transformation.

## INPUT:

- linear\_transf a matrix
- \*\*kwds passed to the linear\_transformation() method of the closure of self.

#### **EXAMPLES:**

```
sage: segment = Polyhedron([[1, 2], [3, 4]])
sage: ri_segment = segment.relative_interior(); ri_segment
Relative interior of a
1-dimensional polyhedron in ZZ^2 defined as the convex hull of 2 vertices
sage: T = matrix([[1, 1]])
sage: A = ri_segment.linear_transformation(T); A
Relative interior of a
1-dimensional polyhedron in ZZ^1 defined as the convex hull of 2 vertices
sage: A.closure().vertices()
(A vertex at (3), A vertex at (7))
```

## relative\_interior()

Return the relative interior of self.

As self is already relatively open, this method just returns self.

# **EXAMPLES:**

```
sage: segment = Polyhedron([[1, 2], [3, 4]])
sage: ri_segment = segment.relative_interior(); ri_segment
Relative interior of
    a 1-dimensional polyhedron in ZZ^2 defined as the convex hull of 2 vertices
sage: ri_segment.relative_interior() is ri_segment
True
```

# representative\_point()

Return a "generic" point of self.

#### OUTPUT

A point in self (thus, in the relative interior of self) as a coordinate vector.

```
sage: C = Cone([[1, 2, 0], [2, 1, 0]])
sage: C.relative_interior().representative_point()
(1, 1, 0)
```

## translation(displacement)

Return the translation of self by a displacement vector.

#### INPLIT

 displacement – a displacement vector or a list/tuple of coordinates that determines a displacement vector

#### **EXAMPLES:**

```
sage: segment = Polyhedron([[1, 2], [3, 4]])
sage: ri_segment = segment.relative_interior(); ri_segment
Relative interior of a
1-dimensional polyhedron in ZZ^2 defined as the convex hull of 2 vertices
sage: t = vector([100, 100])
sage: ri_segment.translation(t)
Relative interior of a
1-dimensional polyhedron in ZZ^2 defined as the convex hull of 2 vertices
sage: ri_segment.closure().vertices()
(A vertex at (1, 2), A vertex at (3, 4))
```

# 4.6 Ribbon Graphs

This file implements objects called *ribbon graphs*. These are graphs together with a cyclic ordering of the darts adjacent to each vertex. This data allows us to unambiguously "thicken" the ribbon graph to an orientable surface with boundary. Also, every orientable surface with non-empty boundary is the thickening of a ribbon graph.

#### **AUTHORS:**

• Pablo Portilla (2016)

### class sage.geometry.ribbon\_graph.RibbonGraph(sigma, rho)

```
Bases: sage.structure.sage_object.SageObject, sage.structure.unique_representation. UniqueRepresentation
```

A ribbon graph codified as two elements of a certain permutation group.

A comprehensive introduction on the topic can be found in the beginning of [GGD2011] Chapter 4. More concretely, we will use a variation of what is called in the reference "The permutation representation pair of a dessin". Note that in that book, ribbon graphs are called "dessins d'enfant". For the sake on completeness we reproduce an adapted version of that introduction here.

#### **Brief introduction**

Let  $\Sigma$  be an orientable surface with non-empty boundary and let  $\Gamma$  be the topological realization of a graph that is embedded in  $\Sigma$  in such a way that the graph is a strong deformation retract of the surface.

Let  $v(\Gamma)$  be the set of vertices of  $\Gamma$ , suppose that these are white vertices. Now we mark black vertices in an interior point of each edge. In this way we get a bipartite graph where all the black vertices have valency 2 and there is no restriction on the valency of the white vertices. We call the edges of this new graph *darts* (sometimes they are also called *half edges* of the original graph). Observe that each edge of the original graph is formed by two darts.

Given a white vertex  $v \in v(\Gamma)$ , let d(v) be the set of darts adjacent to v. Let  $D(\Gamma)$  be the set of all the darts of  $\Gamma$  and suppose that we enumerate the set  $D(\Gamma)$  and that it has n elements.

With the orientation of the surface and the embedding of the graph in the surface we can produce two permutations:

- A permutation that we denote by  $\sigma$ . This permutation is a product of as many cycles as white vertices (that is vertices in  $\Gamma$ ). For each vertex consider a small topological circle around it in  $\Sigma$ . This circle intersects each adjacent dart once. The circle has an orientation induced by the orientation on  $\Sigma$  and so defines a cycle that sends the number associated to one dart to the number associated to the next dart in the positive orientation of the circle.
- A permutation that we denote by  $\rho$ . This permutation is a product of as many 2-cycles as edges has  $\Gamma$ . It just tells which two darts belong to the same edge.

#### **Abstract definition**

Consider a graph  $\Gamma$  (not a priori embedded in any surface). Now we can again consider one vertex in the interior of each edge splitting each edge in two darts. We label the darts with numbers.

We say that a ribbon structure on  $\Gamma$  is a set of two permutations  $(\sigma, \rho)$ . Where  $\sigma$  is formed by as many disjoint cycles as vertices had  $\Gamma$ . And each cycle is a cyclic ordering of the darts adjacent to a vertex. The permutation  $\rho$  just tell us which two darts belong to the same edge.

For any two such permutations there is a way of "thickening" the graph to a surface with boundary in such a way that the surface retracts (by a strong deformation retract) to the graph and hence the graph is embedded in the surface in a such a way that we could recover  $\sigma$  and  $\rho$ .

#### **INPUT:**

- sigma a permutation a product of disjoint cycles of any length; singletons (vertices of valency 1) need not be specified
- rho a permutation which is a product of disjoint 2-cycles

Alternatively, one can pass in 2 integers and this will construct a ribbon graph with genus sigma and rho boundary components. See make\_ribbon().

One can also construct the bipartite graph modeling the corresponding Brieskorn-Pham singularity by passing 2 integers and the keyword bipartite=True. See bipartite\_ribbon\_graph().

#### **EXAMPLES:**

Consider the ribbon graph consisting of just 1 edge and 2 vertices of valency 1:

```
sage: s0 = PermutationGroupElement('(1)(2)')
sage: r0 = PermutationGroupElement('(1,2)')
sage: R0 = RibbonGraph(s0,r0); R0
Ribbon graph of genus 0 and 1 boundary components
```

Consider a graph that has 2 vertices of valency 3 (and hence 3 edges). That is represented by the following two permutations:

```
sage: s1 = PermutationGroupElement('(1,3,5)(2,4,6)')
sage: r1 = PermutationGroupElement('(1,2)(3,4)(5,6)')
sage: R1 = RibbonGraph(s1, r1); R1
Ribbon graph of genus 1 and 1 boundary components
```

By drawing the picture in a piece of paper, one can see that its thickening has only 1 boundary component. Since the thickening is homotopically equivalent to the graph and the graph has Euler characteristic -1, we find that the thickening has genus 1:

```
sage: R1.number_boundaries()
1
sage: R1.genus()
1
```

The following example corresponds to the complete bipartite graph of type (2,3), where we have added one more edge (8,15) that ends at a vertex of valency 1. Observe that it is not necessary to specify the vertex (15) of valency 1 when we define sigma:

```
sage: s2 = PermutationGroupElement('(1,3,5,8)(2,4,6)')
sage: r2 = PermutationGroupElement('(1,2)(3,4)(5,6)(8,15)')
sage: R2 = RibbonGraph(s2, r2); R1
Ribbon graph of genus 1 and 1 boundary components
sage: R2.sigma()
(1,3,5,8)(2,4,6)
```

This example is constructed by taking the bipartite graph of type (3,3):

The labeling of the darts can omit some numbers:

```
sage: s4 = PermutationGroupElement('(3,5,10,12)')
sage: r4 = PermutationGroupElement('(3,10)(5,12)')
sage: R4 = RibbonGraph(s4,r4); R4
Ribbon graph of genus 1 and 1 boundary components
```

The next example is the complete bipartite graph of type (3,3), where we have added an edge that ends at a vertex of valency 1:

```
(5,6,8,9,14,15,11,12)
sage: S.rho()
(5,14)(6,11)(8,15)(9,12)
sage: R5.boundary()
[[1, 16, 17, 4, 5, 14, 15, 8, 9, 12, 10, 3],
[2, 13, 14, 5, 6, 11, 12, 9, 7, 18, 19, 20, 20, 19, 16, 1],
[3, 10, 11, 6, 4, 17, 18, 7, 8, 15, 13, 2]]
sage: S.boundary()
[[5, 14, 15, 8, 9, 12], [6, 11, 12, 9, 14, 5], [8, 15, 11, 6]]
sage: R5.homology_basis()
[[[5, 14], [13, 2], [1, 16], [17, 4]],
[[6, 11], [10, 3], [1, 16], [17, 4]],
[[8, 15], [13, 2], [1, 16], [18, 7]],
[[9, 12], [10, 3], [1, 16], [18, 7]]]
sage: S.homology_basis()
[[[5, 14]], [[6, 11]], [[8, 15]], [[9, 12]]]
```

We construct a ribbon graph corresponding to a genus 0 surface with 5 boundary components:

```
sage: R = RibbonGraph(0, 5); R
Ribbon graph of genus 0 and 5 boundary components
sage: R.sigma()
(1,9,7,5,3)(2,4,6,8,10)
sage: R.rho()
(1,2)(3,4)(5,6)(7,8)(9,10)
```

We construct the Brieskorn-Pham singularity of type (2,3):

```
sage: B23 = RibbonGraph(2, 3, bipartite=True); B23
Ribbon graph of genus 1 and 1 boundary components
sage: B23.sigma()
(1,2,3)(4,5,6)(7,8)(9,10)(11,12)
sage: B23.rho()
(1,8)(2,10)(3,12)(4,7)(5,9)(6,11)
```

#### boundary()

Return the labeled boundaries of self.

If you cut the thickening of the graph along the graph. you get a collection of cylinders (recall that the graph was a strong deformation retract of the thickening). In each cylinder one of the boundary components has a labelling of its edges induced by the labelling of the darts.

#### **OUTPUT:**

A list of lists. The number of inner lists is the number of boundary components of the surface. Each list in the list consists of an ordered tuple of numbers, each number comes from the number assigned to the corresponding dart before cutting.

## **EXAMPLES:**

We start with a ribbon graph whose thickening has one boundary component. We compute its labeled boundary, then reduce it and compute the labeled boundary of the reduced ribbon graph:

```
sage: s1 = PermutationGroupElement('(1,3,5)(2,4,6)')
sage: r1 = PermutationGroupElement('(1,2)(3,4)(5,6)')
```

```
sage: R1 = RibbonGraph(s1,r1); R1
Ribbon graph of genus 1 and 1 boundary components
sage: R1.boundary()
[[1, 2, 4, 3, 5, 6, 2, 1, 3, 4, 6, 5]]
sage: H1 = R1.reduced(); H1
Ribbon graph of genus 1 and 1 boundary components
sage: H1.sigma()
(3,5,4,6)
sage: H1.rho()
(3,4)(5,6)
sage: H1.boundary()
[[3, 4, 6, 5, 4, 3, 5, 6]]
```

We now consider a ribbon graph whose thickening has 3 boundary components. Also observe that in one of the labeled boundary components, a numbers appears twice in a row. That is because the ribbon graph has a vertex of valency 1:

# contract\_edge(k)

Return the ribbon graph resulting from the contraction of the k-th edge in self.

For a ribbon graph  $(\sigma, \rho)$ , we contract the edge corresponding to the k-th transposition of  $\rho$ .

#### INPUT:

• k – non-negative integer; the position in  $\rho$  of the transposition that is going to be contracted

## **OUTPUT**:

• a ribbon graph resulting from the contraction of that edge

#### **EXAMPLES:**

We start again with the one-holed torus ribbon graph:

```
sage: s1 = PermutationGroupElement('(1,3,5)(2,4,6)')
sage: r1 = PermutationGroupElement('(1,2)(3,4)(5,6)')
sage: R1 = RibbonGraph(s1,r1); R1
Ribbon graph of genus 1 and 1 boundary components
sage: S1 = R1.contract_edge(1); S1
Ribbon graph of genus 1 and 1 boundary components
sage: S1.sigma()
(1,6,2,5)
sage: S1.rho()
(1,2)(5,6)
```

However, this ribbon graphs is formed only by loops and hence it cannot be longer reduced, we get an error if we try to contract a loop:

```
sage: S1.contract_edge(1)
Traceback (most recent call last):
...
ValueError: the edge is a loop and cannot be contracted
```

In this example, we consider a graph that has one edge (19,20) such that one of its ends is a vertex of valency 1. This is the vertex (20) that is not specified when defining  $\sigma$ . We contract precisely this edge and get a ribbon graph with no vertices of valency 1:

#### extrude\_edge(vertex, dart1, dart2)

Return a ribbon graph resulting from extruding an edge from a vertex, pulling from it, all darts from dart1 to dart2 including both.

# INPUT:

- vertex the position of the vertex in the permutation  $\sigma$ , which must have valency at least 2
- dart1 the position of the first in the cycle corresponding to vertex
- dart2 the position of the second dart in the cycle corresponding to vertex

## **OUTPUT**:

A ribbon graph resulting from extruding a new edge that pulls from vertex a new vertex that is, now, adjacent to all the darts from dart1``to ``dart2 (not including dart2) in the cyclic ordering given by the cycle corresponding to vertex. Note that dart1 may be equal to dart2 allowing thus to extrude a contractible edge from a vertex.

#### **EXAMPLES:**

We try several possibilities in the same graph:

```
sage: s1 = PermutationGroupElement('(1,3,5)(2,4,6)')
sage: r1 = PermutationGroupElement('(1,2)(3,4)(5,6)')
sage: R1 = RibbonGraph(s1,r1); R1
Ribbon graph of genus 1 and 1 boundary components
sage: E1 = R1.extrude_edge(1,1,2); E1
Ribbon graph of genus 1 and 1 boundary components
sage: E1.sigma()
(1,3,5)(2,8,6)(4,7)
sage: E1.rho()
(1,2)(3,4)(5,6)(7,8)
```

```
sage: E2 = R1.extrude_edge(1,1,3); E2
Ribbon graph of genus 1 and 1 boundary components
sage: E2.sigma()
(1,3,5)(2,8)(4,6,7)
sage: E2.rho()
(1,2)(3,4)(5,6)(7,8)
```

We can also extrude a contractible edge from a vertex. This new edge will end at a vertex of valency 1:

```
sage: E1p = R1.extrude_edge(0,0,0); E1p
Ribbon graph of genus 1 and 1 boundary components
sage: E1p.sigma()
(1,3,5,8)(2,4,6)
sage: E1p.rho()
(1,2)(3,4)(5,6)(7,8)
```

In the following example we first extrude one edge from a vertex of valency 3 generating a new vertex of valency 2. Then we extrude a new edge from this vertex of valency 2:

```
sage: s1 = PermutationGroupElement('(1,3,5)(2,4,6)')
sage: r1 = PermutationGroupElement('(1,2)(3,4)(5,6)')
sage: R1 = RibbonGraph(s1,r1); R1
Ribbon graph of genus 1 and 1 boundary components
sage: E1 = R1.extrude\_edge(0,0,1); E1
Ribbon graph of genus 1 and 1 boundary components
sage: E1.sigma()
(1,7)(2,4,6)(3,5,8)
sage: E1.rho()
(1,2)(3,4)(5,6)(7,8)
sage: F1 = E1.extrude_edge(0,0,1); F1
Ribbon graph of genus 1 and 1 boundary components
sage: F1.sigma()
(1,9)(2,4,6)(3,5,8)(7,10)
sage: F1.rho()
(1,2)(3,4)(5,6)(7,8)(9,10)
```

## genus()

Return the genus of the thickening of self.

#### **OUTPUT**:

• g – non-negative integer representing the genus of the thickening of the ribbon graph

## **EXAMPLES:**

4.6. Ribbon Graphs

```
sage: R3 = RibbonGraph(s3,r3); R3.genus()
3
```

#### homology\_basis()

Return an oriented basis of the first homology group of the graph.

#### **OUTPUT:**

• A 2-dimensional array of ordered edges in the graph (given by pairs). The length of the first dimension is μ. Each row corresponds to an element of the basis and is a circle contained in the graph.

#### **EXAMPLES:**

```
sage: R = RibbonGraph(0,6); R
Ribbon graph of genus 0 and 6 boundary components
sage: R.mu()
sage: R.homology_basis()
[[[3, 4], [2, 1]],
  [[5, 6], [2, 1]],
  [[7, 8], [2, 1]],
  [[9, 10], [2, 1]],
  [[11, 12], [2, 1]]]
sage: R = RibbonGraph(1,1); R
Ribbon graph of genus 1 and 1 boundary components
sage: R.mu()
sage: R.homology_basis()
[[[2, 5], [4, 1]], [[3, 6], [4, 1]]]
sage: H = R.reduced(); H
Ribbon graph of genus 1 and 1 boundary components
sage: H.sigma()
(2,3,5,6)
sage: H.rho()
(2,5)(3,6)
sage: H.homology_basis()
[[[2, 5]], [[3, 6]]]
sage: s3 = PermutationGroupElement('(1,2,3,4,5,6,7,8,9,10,11,27,25,23)(12,24,26,
\rightarrow28,13,14,15,16,17,18,19,20,21,22)')
sage: r3 = PermutationGroupElement('(1,12)(2,13)(3,14)(4,15)(5,16)(6,17)(7,12)(1,12)(1,12)(1,13)(1,14)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1,15)(1
\hookrightarrow 18) (8,19) (9,20) (10,21) (11,22) (23,24) (25,26) (27,28) ')
sage: R3 = RibbonGraph(s3,r3); R3
Ribbon graph of genus 5 and 4 boundary components
sage: R3.mu()
13
sage: R3.homology_basis()
[[[2, 13], [12, 1]],
  [[3, 14], [12, 1]],
  [[4, 15], [12, 1]],
   [[5, 16], [12, 1]],
   [[6, 17], [12, 1]],
   [[7, 18], [12, 1]],
```

```
[[8, 19], [12, 1]],
     [[9, 20], [12, 1]],
    [[10, 21], [12, 1]],
    [[11, 22], [12, 1]],
   [[23, 24], [12, 1]],
    [[25, 26], [12, 1]],
   [[27, 28], [12, 1]]]
sage: H3 = R3.reduced(); H3
Ribbon graph of genus 5 and 4 boundary components
sage: H3.sigma()
(2,3,4,5,6,7,8,9,10,11,27,25,23,24,26,28,13,14,15,16,17,18,19,20,21,22)
sage: H3.rho()
(2,13)(3,14)(4,15)(5,16)(6,17)(7,18)(8,19)(9,20)(10,21)(11,22)(23,24)(25,26)(27,18)(11,22)(23,24)(25,26)(27,18)(11,22)(23,24)(25,26)(27,18)(11,22)(23,24)(25,26)(27,18)(11,22)(23,24)(25,26)(27,18)(11,22)(23,24)(25,26)(27,18)(11,22)(23,24)(25,26)(27,18)(11,22)(23,24)(25,26)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(27,18)(
 →28)
sage: H3.homology_basis()
[[[2, 13]],
   [[3, 14]],
    [[4, 15]],
   [[5, 16]],
   [[6, 17]],
    [[7, 18]],
    [[8, 19]],
   [[9, 20]],
    [[10, 21]],
    [[11, 22]],
    [[23, 24]],
    [[25, 26]],
    [[27, 28]]]
```

## make\_generic()

Return a ribbon graph equivalent to self but where every vertex has valency 3.

## **OUTPUT**:

• a ribbon graph that is equivalent to self but is generic in the sense that all vertices have valency 3

## **EXAMPLES**:

```
sage: R = RibbonGraph(1,3); R
Ribbon graph of genus 1 and 3 boundary components
sage: R.sigma()
(1,2,3,9,7)(4,8,10,5,6)
sage: R.rho()
(1,4)(2,5)(3,6)(7,8)(9,10)
sage: G = R.make_generic(); G
Ribbon graph of genus 1 and 3 boundary components
sage: G.sigma()
(2,3,11)(5,6,13)(7,8,15)(9,16,17)(10,14,19)(12,18,21)(20,22)
sage: G.rho()
(2,5)(3,6)(7,8)(9,10)(11,12)(13,14)(15,16)(17,18)(19,20)(21,22)
sage: R.genus() == G.genus() and R.number_boundaries() == G.number_boundaries()
True
sage: R = RibbonGraph(5,4); R
```

```
Ribbon graph of genus 5 and 4 boundary components
sage: R.sigma()
(1,2,3,4,5,6,7,8,9,10,11,27,25,23) (12,24,26,28,13,14,15,16,17,18,19,20,21,22)
sage: R.rho()
(1,12)(2,13)(3,14)(4,15)(5,16)(6,17)(7,18)(8,19)(9,20)(10,21)(11,22)(23,24)(25,12)(11,22)(23,24)(25,12)(11,22)(23,24)(25,12)(11,22)(23,24)(25,12)(11,22)(23,24)(25,12)(11,22)(23,24)(25,12)(11,22)(23,24)(25,12)(11,22)(23,24)(25,12)(11,22)(23,24)(25,12)(11,22)(23,24)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(25,12)(2
 \stackrel{\smile}{\sim}26) (27, 28)
sage: G = R.reduced(); G
Ribbon graph of genus 5 and 4 boundary components
sage: G.sigma()
(2,3,4,5,6,7,8,9,10,11,27,25,23,24,26,28,13,14,15,16,17,18,19,20,21,22)
sage: G.rho()
(2,13)(3,14)(4,15)(5,16)(6,17)(7,18)(8,19)(9,20)(10,21)(11,22)(23,24)(25,26)(27,18)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(11,22)(
sage: G.genus() == R.genus() and G.number_boundaries() == R.number_boundaries()
True
sage: R = RibbonGraph(0,6); R
Ribbon graph of genus 0 and 6 boundary components
sage: R.sigma()
(1,11,9,7,5,3)(2,4,6,8,10,12)
sage: R.rho()
(1,2)(3,4)(5,6)(7,8)(9,10)(11,12)
sage: G = R.reduced(); G
Ribbon graph of genus 0 and 6 boundary components
sage: G.sigma()
(3,4,6,8,10,12,11,9,7,5)
sage: G.rho()
(3,4)(5,6)(7,8)(9,10)(11,12)
sage: G.genus() == R.genus() and G.number_boundaries() == R.number_boundaries()
True
```

#### mu()

Return the rank of the first homology group of the thickening of the ribbon graph.

# **EXAMPLES:**

```
sage: s1 = PermutationGroupElement('(1,3,5)(2,4,6)')
sage: r1 = PermutationGroupElement('(1,2)(3,4)(5,6)')
sage: R1 = RibbonGraph(s1,r1);R1
Ribbon graph of genus 1 and 1 boundary components
sage: R1.mu()
2
```

# normalize()

Return an equivalent graph such that the enumeration of its darts exhausts all numbers from 1 to the number of darts.

#### **OUTPUT**:

• a ribbon graph equivalent to self such that the enumeration of its darts exhausts all numbers from 1 to the number of darts.

```
sage: s0 = PermutationGroupElement('(1,22,3,4,5,6,7,15)(8,16,9,10,11,12,13,14)')
sage: r0 = PermutationGroupElement('(1,8)(22,9)(3,10)(4,11)(5,12)(6,13)(7,12)(6,13)(7,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,13)(1,
\rightarrow14)(15,16)')
sage: R0 = RibbonGraph(s0,r0); R0
Ribbon graph of genus 3 and 2 boundary components
sage: RN0 = R0.normalize(); RN0; RN0.sigma(); RN0.rho()
Ribbon graph of genus 3 and 2 boundary components
(1,16,2,3,4,5,6,14)(7,15,8,9,10,11,12,13)
(1,7)(2,9)(3,10)(4,11)(5,12)(6,13)(8,16)(14,15)
sage: s1 = PermutationGroupElement('(5,10,12)(30,34,78)')
sage: r1 = PermutationGroupElement('(5,30)(10,34)(12,78)')
sage: R1 = RibbonGraph(s1,r1); R1
Ribbon graph of genus 1 and 1 boundary components
sage: RN1 = R1.normalize(); RN1; RN1.sigma(); RN1.rho()
Ribbon graph of genus 1 and 1 boundary components
(1,2,3)(4,5,6)
(1,4)(2,5)(3,6)
```

## number\_boundaries()

Return number of boundary components of the thickening of the ribbon graph.

#### **EXAMPLES:**

The first example is the ribbon graph corresponding to the torus with one hole:

```
sage: s1 = PermutationGroupElement('(1,3,5)(2,4,6)')
sage: r1 = PermutationGroupElement('(1,2)(3,4)(5,6)')
sage: R1 = RibbonGraph(s1,r1)
sage: R1.number_boundaries()
1
```

This example is constructed by taking the bipartite graph of type (3,3):

#### reduced()

Return a ribbon graph with 1 vertex and  $\mu$  edges (where  $\mu$  is the first betti number of the graph).

# **OUTPUT**:

• a ribbon graph whose  $\sigma$  permutation has only 1 non-singleton cycle and whose  $\rho$  permutation is a product of  $\mu$  disjoint 2-cycles

#### **EXAMPLES:**

```
sage: s1 = PermutationGroupElement('(1,3,5)(2,4,6)')
sage: r1 = PermutationGroupElement('(1,2)(3,4)(5,6)')
sage: R1 = RibbonGraph(s1,r1); R1
Ribbon graph of genus 1 and 1 boundary components
```

```
sage: G1 = R1.reduced(); G1
Ribbon graph of genus 1 and 1 boundary components
sage: G1.sigma()
(3,5,4,6)
sage: G1.rho()
(3,4)(5,6)
sage: s2 = PermutationGroupElement('(1,2,3)(4,5,6)(7,8,9)(10,11,12)(13,14,
\hookrightarrow 15) (16, 17, 18, 19) ')
sage: r2 = PermutationGroupElement('(1,16)(2,13)(3,10)(4,17)(5,14)(6,11)(7,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1,16)(1
\rightarrow18) (8, 15) (9, 12) (19, 20) ')
sage: R2 = RibbonGraph(s2,r2); R2
Ribbon graph of genus 1 and 3 boundary components
sage: G2 = R2.reduced(); G2
Ribbon graph of genus 1 and 3 boundary components
sage: G2.sigma()
(5,6,8,9,14,15,11,12)
sage: G2.rho()
(5,14)(6,11)(8,15)(9,12)
sage: s3 = PermutationGroupElement('(1,2,3)(4,5,6)(7,8,9)(10,11,12)(13,14,15,
\rightarrow16) (17, 18, 19, 20) (21, 22, 23, 24) ')
sage: r3 = PermutationGroupElement('(1,21)(2,17)(3,13)(4,22)(7,23)(5,18)(6,
\rightarrow14)(8,19)(9,15)(10,24)(11,20)(12,16)')
sage: R3 = RibbonGraph(s3,r3); R3
Ribbon graph of genus 3 and 1 boundary components
sage: G3 = R3.reduced(); G3
Ribbon graph of genus 3 and 1 boundary components
sage: G3.sigma()
(5,6,8,9,11,12,18,19,20,14,15,16)
sage: G3.rho()
(5,18)(6,14)(8,19)(9,15)(11,20)(12,16)
```

# rho()

Return the permutation  $\rho$  of self.

#### **EXAMPLES:**

```
sage: s1 = PermutationGroupElement('(1,3,5,8)(2,4,6)')
sage: r1 = PermutationGroupElement('(1,2)(3,4)(5,6)(8,15)')
sage: R = RibbonGraph(s1, r1)
sage: R.rho()
(1,2)(3,4)(5,6)(8,15)
```

# sigma()

Return the permutation  $\sigma$  of self.

```
sage: s1 = PermutationGroupElement('(1,3,5,8)(2,4,6)')
sage: r1 = PermutationGroupElement('(1,2)(3,4)(5,6)(8,15)')
sage: R = RibbonGraph(s1, r1)
sage: R.sigma()
(1,3,5,8)(2,4,6)
```

#### sage.geometry.ribbon\_graph.bipartite\_ribbon\_graph(p, q)

Return the bipartite graph modeling the corresponding Brieskorn-Pham singularity.

Take two parallel lines in the plane, and consider p points in one of them and q points in the other. Join with a line each point from the first set with every point with the second set. The resulting is a planar projection of the complete bipartite graph of type (p,q). If you consider the cyclic ordering at each vertex induced by the positive orientation of the plane, the result is a ribbon graph whose associated orientable surface with boundary is homeomorphic to the Milnor fiber of the Brieskorn-Pham singularity  $x^p + y^q$ . It satisfies that it has  $\gcd(p,q)$  number of boundary components and genus  $(pq - p - q - \gcd(p,q) - 2)/2$ .

#### INPUT:

- p a positive integer
- q a positive integer

#### **EXAMPLES:**

```
sage: B23 = RibbonGraph(2,3,bipartite=True); B23; B23.sigma(); B23.rho()
Ribbon graph of genus 1 and 1 boundary components
(1,2,3)(4,5,6)(7,8)(9,10)(11,12)
(1,8)(2,10)(3,12)(4,7)(5,9)(6,11)
sage: B32 = RibbonGraph(3,2,bipartite=True); B32; B32.sigma(); B32.rho()
Ribbon graph of genus 1 and 1 boundary components
(1,2)(3,4)(5,6)(7,8,9)(10,11,12)
(1,9)(2,12)(3,8)(4,11)(5,7)(6,10)
sage: B33 = RibbonGraph(3,3,bipartite=True); B33; B33.sigma(); B33.rho()
Ribbon graph of genus 1 and 3 boundary components
(1,2,3)(4,5,6)(7,8,9)(10,11,12)(13,14,15)(16,17,18)
(1,12)(2,15)(3,18)(4,11)(5,14)(6,17)(7,10)(8,13)(9,16)
sage: B24 = RibbonGraph(2,4,bipartite=True); B24; B24.sigma(); B24.rho()
Ribbon graph of genus 1 and 2 boundary components
(1,2,3,4)(5,6,7,8)(9,10)(11,12)(13,14)(15,16)
(1,10)(2,12)(3,14)(4,16)(5,9)(6,11)(7,13)(8,15)
sage: B47 = RibbonGraph(4,7, bipartite=True); B47; B47.sigma(); B47.rho()
Ribbon graph of genus 9 and 1 boundary components
(1,2,3,4,5,6,7)(8,9,10,11,12,13,14)(15,16,17,18,19,20,21)(22,23,24,25,26,27,28)(29,
430,31,32)(33,34,35,36)(37,38,39,40)(41,42,43,44)(45,46,47,48)(49,50,51,52)(53,54,49)(41,42,43,44)(45,46,47,48)(49,50,51,52)(53,54,49)(41,42,43,44)(45,46,47,48)(49,50,51,52)(53,54,49)(41,42,43,44)(45,46,47,48)(49,50,51,52)(53,54,49)(41,42,43,44)(45,46,47,48)(49,50,51,52)(53,54,49)(41,42,43,44)(45,46,47,48)(49,50,51,52)(53,54,49)(41,42,43,44)(45,46,47,48)(49,50,51,52)(53,54,49)(41,42,43,44)(45,46,47,48)(49,50,51,52)(53,54,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,49)(41,42,43,44)(41,42,43,44)(41,42,43,44)(41,42,43,44)(41,42,43,44)(41,42,43,44)(41,42,43,44)(41,42,43,44)(41,42,43,44)(41,42,43,44)(41,42,43,44)(41,42,43,44)(41,42,43,44)(41,42,43,44)(41,42,43,44)(41,42,43,44)(41,42,43,44)(41,42,44,44)(41,42,44,44)(41,42,44,44)(41,42,44,44)(41,42,44,44)(41,42,44,44)(41,42,44,44)(41,42,44,44)(41,42,44,44)(41,42,44,44)(41,42,44,44)(41,42,44,44)(41,42,44,44)(41,42,44)(41,42,44,44)(41,42,44,44)(41,42,44,44)(41,42,44,44)(41,44,
 -55,56
(1,32)(2,36)(3,40)(4,44)(5,48)(6,52)(7,56)(8,31)(9,35)(10,39)(11,43)(12,47)(13,
\rightarrow51) (14,55) (15,30) (16,34) (17,38) (18,42) (19,46) (20,50) (21,54) (22,29) (23,33) (24,
 \rightarrow 37) (25,41) (26,45) (27,49) (28,53)
```

## sage.geometry.ribbon\_graph.make\_ribbon(g, r)

Return a ribbon graph whose thickening has genus g and r boundary components.

## **INPUT:**

- g non-negative integer representing the genus of the thickening
- r positive integer representing the number of boundary components of the thickening

# **OUTPUT**:

• a ribbon graph that has 2 vertices (two non-trivial cycles in its sigma permutation) of valency 2g + r and it has 2g + r edges (and hence 4g + 2r darts)

#### **EXAMPLES:**

```
sage: from sage.geometry.ribbon_graph import make_ribbon
sage: R = make_ribbon(0,1); R
Ribbon graph of genus 0 and 1 boundary components
sage: R.sigma()
sage: R.rho()
(1,2)
sage: R = make_ribbon(0,5); R
Ribbon graph of genus 0 and 5 boundary components
sage: R.sigma()
(1,9,7,5,3)(2,4,6,8,10)
sage: R.rho()
(1,2)(3,4)(5,6)(7,8)(9,10)
sage: R = make_ribbon(1,1); R
Ribbon graph of genus 1 and 1 boundary components
sage: R.sigma()
(1,2,3)(4,5,6)
sage: R.rho()
(1,4)(2,5)(3,6)
sage: R = make_ribbon(7,3); R
Ribbon graph of genus 7 and 3 boundary components
sage: R.sigma()
(1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,33,31) (16,32,34,17,18,19,20,21,22,23,24,25,26,12,13,14,15,33,31)
427,28,29,30)
sage: R.rho()
(1,16)(2,17)(3,18)(4,19)(5,20)(6,21)(7,22)(8,23)(9,24)(10,25)(11,26)(12,27)(13,
\rightarrow28) (14,29) (15,30) (31,32) (33,34)
```

# 4.7 Pseudolines

This module gathers everything that has to do with pseudolines, and for a start a *PseudolineArrangement* class that can be used to describe an arrangement of pseudolines in several different ways, and to translate one description into another, as well as to display *Wiring diagrams* via the *show* method.

In the following, we try to stick to the terminology given in [Fe1997], which can be checked in case of doubt. And please fix this module's documentation afterwards :-)

#### **Definition**

A *pseudoline* can not be defined by itself, though it can be thought of as a *x*-monotone curve in the plane. A *set* of pseudolines, however, represents a set of such curves that pairwise intersect exactly once (and hence mimic the behaviour of straight lines in general position). We also assume that those pseudolines are in general position, that is that no three of them cross at the same point.

The present class is made to deal with a combinatorial encoding of a pseudolines arrangement, that is the ordering in which a pseudoline  $l_i$  of an arrangement  $l_0, ..., l_{n-1}$  crosses the n-1 other lines.

**Warning:** It is assumed through all the methods that the given lines are numbered according to their y-coordinate on the vertical line  $x = -\infty$ . For instance, it is not possible that the first transposition be (0,2) (or equivalently that the first line  $l_0$  crosses is  $l_2$  and conversely), because one of them would have to cross  $l_1$  first.

# 4.7.1 Encodings

#### **Permutations**

An arrangement of pseudolines can be described by a sequence of n lists of length n-1, where the i list is a permutation of  $\{0, ..., n-1\} \setminus i$  representing the ordering in which the i th pseudoline meets the other ones.

```
sage: from sage.geometry.pseudolines import PseudolineArrangement
sage: permutations = [[3, 2, 1], [3, 2, 0], [3, 1, 0], [2, 1, 0]]
sage: p = PseudolineArrangement(permutations)
sage: p
Arrangement of pseudolines of size 4
sage: p.show()
```

## Sequence of transpositions

An arrangement of pseudolines can also be described as a sequence of  $\binom{n}{2}$  transpositions (permutations of two elements). In this sequence, the transposition (2,3) appears before (8,2) iif  $l_2$  crosses  $l_3$  before it crosses  $l_8$ . This encoding is easy to obtain by reading the wiring diagram from left to right (see the *show* method).

```
sage: from sage.geometry.pseudolines import PseudolineArrangement
sage: transpositions = [(3, 2), (3, 1), (0, 3), (2, 1), (0, 2), (0, 1)]
sage: p = PseudolineArrangement(transpositions)
sage: p
Arrangement of pseudolines of size 4
sage: p.show()
```

Note that this ordering is not necessarily unique.

### Felsner's Matrix

Felser gave an encoding of an arrangement of pseudolines that takes  $n^2$  bits instead of the  $n^2 log(n)$  bits required by the two previous encodings.

Instead of storing the permutation [3, 2, 1] to remember that line  $l_0$  crosses  $l_3$  then  $l_2$  then  $l_1$ , it is sufficient to remember the positions for which each line  $l_i$  meets a line  $l_j$  with j < i. As  $l_0$  – the first of the lines – can only meet pseudolines with higher index, we can store [0, 0, 0] instead of [3, 2, 1] stored previously. For  $l_1$ 's permutation [3, 2, 0] we only need to remember that  $l_1$  first crosses 2 pseudolines of higher index, and then a pseudoline with smaller index, which yields the bit vector [0, 0, 1]. Hence we can transform the list of permutations above into a list of n bit vectors of length n-1, that is

In order to go back from Felsner's matrix to an encoding by a sequence of transpositions, it is sufficient to look for occurrences of  $\begin{pmatrix} 0 \\ 1 \end{pmatrix}$  in the first column of the matrix, as it corresponds in the wiring diagram to a line going up while the line immediately above it goes down – those two lines cross. Each time such a pattern is found it yields a new transposition, and the matrix can be updated so that this pattern disappears. A more detailed description of this algorithm is given in [Fe1997].

4.7. Pseudolines 741

```
sage: from sage.geometry.pseudolines import PseudolineArrangement
sage: felsner_matrix = [[0, 0, 0], [0, 0, 1], [0, 1, 1], [1, 1, 1]]
sage: p = PseudolineArrangement(felsner_matrix)
sage: p
Arrangement of pseudolines of size 4
```

# 4.7.2 Example

Let us define in the plane several lines  $l_i$  of equation y = ax + b by picking a coefficient a and b for each of them. We make sure that no two of them are parallel by making sure all of the a chosen are different, and we avoid a common crossing of three lines by adding a random noise to b:

We can now compute for each i the order in which line i meets the other lines:

```
sage: permutations = [[0..i-1]+[i+1..n-1] for i in range(n)]
sage: a = lambda x : l[x][0]
sage: b = lambda x : l[x][1]
sage: for i, perm in enumerate(permutations):
....: perm.sort(key = lambda j : (b(j)-b(i))/(a(i)-a(j)))
```

And finally build the line arrangement:

```
sage: from sage.geometry.pseudolines import PseudolineArrangement
sage: p = PseudolineArrangement(permutations)
sage: print(p)
Arrangement of pseudolines of size 20
sage: p.show(figsize=[20,8])
```

### **Author**

Nathann Cohen

## 4.7.3 Methods

class sage.geometry.pseudolines.PseudolineArrangement(seq, encoding='auto')
 Bases: object

Creates an arrangement of pseudolines.

INPUT:

- seq (a sequence describing the line arrangement). It can be:
  - A list of n permutations of size n-1.
  - A list of  $\binom{n}{2}$  transpositions

- A Felsner matrix, given as a sequence of n binary vectors of length n-1.
- encoding (information on how the data should be interpreted), and can assume any value among 'transpositions', 'permutations', 'Felsner' or 'auto'. In the latter case, the type will be guessed (default behaviour).

## Note:

- The pseudolines are assumed to be integers 0..(n-1).
- For more information on the different encodings, see the pseudolines module's documentation.

# felsner\_matrix()

Return a Felsner matrix describing the arrangement.

See the *pseudolines module*'s documentation for more information on this encoding.

## **EXAMPLES:**

```
sage: from sage.geometry.pseudolines import PseudolineArrangement
sage: permutations = [[3, 2, 1], [3, 2, 0], [3, 1, 0], [2, 1, 0]]
sage: p = PseudolineArrangement(permutations)
sage: p.felsner_matrix()
[[0, 0, 0], [0, 0, 1], [0, 1, 1], [1, 1, 1]]
```

#### permutations()

Return the arrangements as n permutations of size n-1.

See the *pseudolines module*'s documentation for more information on this encoding.

#### **EXAMPLES:**

```
sage: from sage.geometry.pseudolines import PseudolineArrangement
sage: permutations = [[3, 2, 1], [3, 2, 0], [3, 1, 0], [2, 1, 0]]
sage: p = PseudolineArrangement(permutations)
sage: p.permutations()
[[3, 2, 1], [3, 2, 0], [3, 1, 0], [2, 1, 0]]
```

## show(\*\*args)

Displays the pseudoline arrangement as a wiring diagram.

# INPUT:

• \*\*args – any arguments to be forwarded to the show method. In particular, to tune the dimensions, use the figsize argument (example below).

#### **EXAMPLES:**

```
sage: from sage.geometry.pseudolines import PseudolineArrangement
sage: permutations = [[3, 2, 1], [3, 2, 0], [3, 1, 0], [2, 1, 0]]
sage: p = PseudolineArrangement(permutations)
sage: p.show(figsize=[7,5])
```

## transpositions()

Return the arrangement as  $\binom{n}{2}$  transpositions.

See the *pseudolines module*'s documentation for more information on this encoding.

**EXAMPLES:** 

4.7. Pseudolines 743

```
sage: from sage.geometry.pseudolines import PseudolineArrangement
sage: permutations = [[3, 2, 1], [3, 2, 0], [3, 1, 0], [2, 1, 0]]
sage: p1 = PseudolineArrangement(permutations)
sage: transpositions = [(3, 2), (3, 1), (0, 3), (2, 1), (0, 2), (0, 1)]
sage: p2 = PseudolineArrangement(transpositions)
sage: p1 == p2
True
sage: p1.transpositions()
[(3, 2), (3, 1), (0, 3), (2, 1), (0, 2), (0, 1)]
sage: p2.transpositions()
[(3, 2), (3, 1), (0, 3), (2, 1), (0, 2), (0, 1)]
```

# 4.8 Voronoi diagram

This module provides the class VoronoiDiagram for computing the Voronoi diagram of a finite list of points in  $\mathbb{R}^d$ .

```
class sage.geometry.voronoi_diagram.VoronoiDiagram(points)
```

```
Bases: sage.structure.sage_object.SageObject
```

Base class for the Voronoi diagram.

Compute the Voronoi diagram of a list of points.

**INPUT:** 

• points – a list of points. Any valid input for the *PointConfiguration* will do.

**OUTPUT:** 

An instance of the VoronoiDiagram class.

**EXAMPLES:** 

Get the Voronoi diagram for some points in  $\mathbb{R}^3$ :

```
sage: V = VoronoiDiagram([[1, 3, .3], [2, -2, 1], [-1, 2, -.1]]); V
The Voronoi diagram of 3 points of dimension 3 in the Real Double Field
sage: VoronoiDiagram([])
The empty Voronoi diagram.
```

Get the Voronoi diagram of a regular pentagon in AA^2. All cells meet at the origin:

If the vertices are not converted to AA before, the method throws an error:

#### ALGORITHM:

We use hyperplanes tangent to the paraboloid one dimension higher to get a convex polyhedron and then project back to one dimension lower.

#### **Todo:**

- The dual construction: Delaunay triangulation
- improve 2d-plotting
- implement 3d-plotting
- more general constructions, like Voroi diagrams with weights (power diagrams)

#### REFERENCES:

• [Mat2002] Ch.5.7, p.118.

# **AUTHORS:**

• Moritz Firsching (2012-09-21)

# ambient\_dim()

Return the ambient dimension of the points.

#### **EXAMPLES:**

```
sage: V = VoronoiDiagram([[.5, 3], [2, 5], [4, 5], [4, -1]])
sage: V.ambient_dim()
2
sage: V = VoronoiDiagram([[1, 2, 3, 4, 5, 6]]); V.ambient_dim()
6
```

### base\_ring()

Return the base ring of the regions of the Voronoi diagram.

```
sage: V = VoronoiDiagram([[1, 3, 1], [2, -2, 1], [-1, 2, 1/2]]); V.base_ring()
Rational Field
sage: V = VoronoiDiagram([[1, 3.14], [2, -2/3], [-1, 22]]); V.base_ring()
Real Double Field
sage: V = VoronoiDiagram([[1, 3], [2, 4]]); V.base_ring()
Rational Field
```

```
plot(cell colors=None, **kwds)
```

Return a graphical representation for 2-dimensional Voronoi diagrams.

#### INPUT:

- cell\_colors (default: None) provide the colors for the cells, either as dictionary. Randomly colored cells are provided with None.
- \*\*kwds optional keyword parameters, passed on as arguments for plot().

#### **OUTPUT:**

A graphics object.

## **EXAMPLES:**

```
sage: P = [[0.671, 0.650], [0.258, 0.767], [0.562, 0.406], [0.254, 0.709], [0.
493, 0.879
sage: V = VoronoiDiagram(P); S=V.plot()

→ # optional - sage.plot

sage: show(S, xmin=0, xmax=1, ymin=0, ymax=1, aspect_ratio=1, axes=false)
   # optional - sage.plot
sage: S=V.plot(cell_colors={0:'red', 1:'blue', 2:'green', 3:'white', 4:'yellow'}
→) # optional - sage.plot
sage: show(S, xmin=0, xmax=1, ymin=0, ymax=1, aspect_ratio=1, axes=false)
    # optional - sage.plot
sage: S=V.plot(cell_colors=['red','blue','red','white', 'white'])
    # optional - sage.plot
sage: show(S, xmin=0, xmax=1, ymin=0, ymax=1, aspect_ratio=1, axes=false)
    # optional - sage.plot
sage: S=V.plot(cell_colors='something else')
    # optional - sage.plot
Traceback (most recent call last):
AssertionError: 'cell_colors' must be a list or a dictionary
```

Trying to plot a Voronoi diagram of dimension other than 2 gives an error:

```
sage: VoronoiDiagram([[1, 2, 3], [6, 5, 4]]).plot()

    # optional - sage.plot
Traceback (most recent call last):
...
NotImplementedError: Plotting of 3-dimensional Voronoi diagrams not implemented
```

# points()

Return the input points (as a PointConfiguration).

#### **EXAMPLES:**

```
sage: V = VoronoiDiagram([[.5, 3], [2, 5], [4, 5], [4, -1]]); V.points()
A point configuration in affine 2-space over Real Field
with 53 bits of precision consisting of 4 points.
```

```
The triangulations of this point configuration are assumed to be connected, not necessarily fine, not necessarily regular.
```

#### regions()

Return the Voronoi regions of the Voronoi diagram as a dictionary of polyhedra.

```
sage: V = VoronoiDiagram([[1, 3, .3], [2, -2, 1], [-1, 2, -.1]])
sage: P = V.points()
sage: V.regions() == {P[0]: Polyhedron(base_ring=RDF, lines=[(-RDF(0.375),_
\rightarrow RDF(0.13888888890000001), RDF(1.527777779999999))],
                                                       rays=[(RDF(9), -RDF(1), -
\rightarrow RDF(20)), (RDF(4.5), RDF(1), -RDF(25))],
                                                       vertices=[(-RDF(1.
....:
\hookrightarrow1074999999999), RDF(1.149444444), RDF(9.0138888890000004))]),
                      P[1]: Polyhedron(base_ring=RDF, lines=[(-RDF(0.375),_
\rightarrow RDF(0.13888888890000001), RDF(1.527777779999999))],
                                                       rays=[(RDF(9), -RDF(1), -
\rightarrow RDF(20)), (-RDF(2.25), -RDF(1), RDF(2.5))],
                                                        vertices=[(-RDF(1.
\hookrightarrow 10749999999999), RDF(1.149444444), RDF(9.0138888890000004))]),
                      P[2]: Polyhedron(base_ring=RDF, lines=[(-RDF(0.375),_
\rightarrow RDF(0.13888888890000001), RDF(1.5277777779999999))],
                                                       rays=[(RDF(4.5), RDF(1), -
\neg RDF(25)), (-RDF(2.25), -RDF(1), RDF(2.5))],
                                                       vertices=[(-RDF(1.
True
```

# **HELPER FUNCTIONS**

# 5.1 Find isomorphisms between fans

```
exception sage.geometry.fan_isomorphism.FanNotIsomorphicError
Bases: Exception

Exception to return if there is no fan isomorphism
```

 ${\tt sage.geometry.fan\_isomorphism.fan\_2d\_cyclically\_ordered\_rays} (\textit{fan})$ 

Return the rays of a 2-dimensional fan in cyclic order.

INPUT:

• fan – a 2-dimensional fan.

**OUTPUT**:

A *PointCollection* containing the rays in one particular cyclic order.

**EXAMPLES:** 

```
sage: rays = ((1, 1), (-1, -1), (-1, 1), (1, -1))
sage: cones = [(0,2), (2,1), (1,3), (3,0)]
sage: fan = Fan(cones, rays)
sage: fan.rays()
N(1, 1),
N(-1, -1),
N(-1, 1),
N(1, -1)
in 2-d lattice N
sage: from sage.geometry.fan_isomorphism import fan_2d_cyclically_ordered_rays
sage: fan_2d_cyclically_ordered_rays(fan)
N(-1, -1),
N(-1, 1),
N(1, 1),
N(1, -1)
in 2-d lattice N
```

sage.geometry.fan\_isomorphism.fan\_2d\_echelon\_form(fan)

Return echelon form of a cyclically ordered ray matrix.

INPUT:

• fan – a fan.

#### **OUTPUT**:

A matrix. The echelon form of the rays in one particular cyclic order.

## **EXAMPLES:**

# sage.geometry.fan\_isomorphism.fan\_2d\_echelon\_forms(fan)

Return echelon forms of all cyclically ordered ray matrices.

Note that the echelon form of the ordered ray matrices are unique up to different cyclic orderings.

## INPUT:

• fan – a fan.

#### **OUTPUT:**

A set of matrices. The set of all echelon forms for all different cyclic orderings.

#### **EXAMPLES:**

```
sage: fan = toric_varieties.P2().fan()
                                                                           # optional -
→ palp
sage: from sage.geometry.fan_isomorphism import fan_2d_echelon_forms
sage: fan_2d_echelon_forms(fan)
                                                                           # optional -
→ palp
frozenset({[ 1 0 -1]
           [0 1 -1]
sage: fan = toric_varieties.dP7().fan()
                                                                           # optional -
→ palp
sage: sorted(fan_2d_echelon_forms(fan))
                                                                           # optional -
→ palp
Γ
[ \ 1 \ \ 0 \ -1 \ -1 \ \ 0] \ [ \ 1 \ \ 0 \ -1 \ -1 \ \ 1] \ [ \ 1 \ \ 0 \ -1 \ \ 0 \ \ 1]
[0\ 1\ 0\ -1\ -1], [0\ 1\ 1\ 0\ -1], [0\ 1\ 1\ 0\ -1], [0\ 1\ 0\ -1\ -1],
[1 0 -1 0 1]
[0 1 1 -1 -1]
```

# sage.geometry.fan\_isomorphism.fan\_isomorphic\_necessary\_conditions(fan1, fan2)

Check necessary (but not sufficient) conditions for the fans to be isomorphic.

#### INPUT:

• fan1, fan2 – two fans.

#### **OUTPUT**:

Boolean. False if the two fans cannot be isomorphic. True if the two fans may be isomorphic.

 $\verb|sage.geometry.fan_isomorphism.fan_isomorphism_generator(|\mathit{fan1}, \mathit{fan2})|$ 

Iterate over the isomorphisms from fan1 to fan2.

#### ALGORITHM:

The sage.geometry.fan.Fan.vertex\_graph() of the two fans is compared. For each graph isomorphism, we attempt to lift it to an actual isomorphism of fans.

# INPUT:

• fan1, fan2 – two fans.

#### **OUTPUT:**

Yields the fan isomorphisms as matrices acting from the right on rays.

#### **EXAMPLES:**

```
sage: fan = toric_varieties.P2().fan()
                                                                          # optional -
→ palp
sage: from sage.geometry.fan_isomorphism import fan_isomorphism_generator
sage: sorted(fan_isomorphism_generator(fan, fan))
                                                                          # optional -
[-1 -1] [-1 -1] [0 1] [0 1] [1 0] [1 0]
[0 1], [1 0], [-1 -1], [1 0], [-1 -1], [0 1]
sage: m1 = matrix([(1, 0), (0, -5), (-3, 4)])
sage: m2 = matrix([(3, 0), (1, 0), (-2, 1)])
sage: m1.elementary_divisors() == m2.elementary_divisors() == [1,1,0]
sage: fan1 = Fan([Cone([m1*vector([23, 14]), m1*vector([
                                                            3,100])]),
                  Cone([m1*vector([-1,-14]), m1*vector([-100, -5])])
sage: fan2 = Fan([Cone([m2*vector([23, 14]), m2*vector([
                                                           3,100])]),
                  Cone([m2*vector([-1,-14]), m2*vector([-100, -5])])])
sage: sorted(fan_isomorphism_generator(fan1, fan2))
[-12 \ 1 \ -5]
\begin{bmatrix} -4 & 0 & -1 \end{bmatrix}
[-5 \ 0 \ -1]
sage: m0 = identity_matrix(ZZ, 2)
sage: m1 = matrix([(1, 0), (0, -5), (-3, 4)])
sage: m2 = matrix([(3, 0), (1, 0), (-2, 1)])
sage: m1.elementary_divisors() == m2.elementary_divisors() == [1,1,0]
True
```

```
sage: fan0 = Fan([Cone([m0*vector([1,0]), m0*vector([1,1])]),
                 Cone([m0*vector([1,1]), m0*vector([0,1])]))
sage: fan1 = Fan([Cone([m1*vector([1,0]), m1*vector([1,1])]),
                 Cone([m1*vector([1,1]), m1*vector([0,1])]))
sage: fan2 = Fan([Cone([m2*vector([1,0]), m2*vector([1,1])]),
                 Cone([m2*vector([1,1]), m2*vector([0,1])])])
sage: sorted(fan_isomorphism_generator(fan0, fan0))
[0 1] [1 0]
[1 0], [0 1]
sage: sorted(fan_isomorphism_generator(fan1, fan1))
[ -3 -20
         28] [1 0 0]
          7] [0 1 0]
[-1 -4]
          8], [0 0 1]
[ -1 -5
sage: sorted(fan_isomorphism_generator(fan1, fan2))
[-24 -3
          7] [-12
                     1 -5]
          27 [ -4
0 -17
[ -8 -1
          2], [-5
                     0 -17
sage: sorted(fan_isomorphism_generator(fan2, fan1))
1 -1] [ 0 1 -1]
[ 0
87 [2 -8 17
0 -5
          4], [ 1 0 -3]
]
```

sage.geometry.fan\_isomorphism.find\_isomorphism(fan1, fan2, check=False)

Find an isomorphism of the two fans.

## INPUT:

- fan1, fan2 two fans.
- check boolean (default: False). Passed to the fan morphism constructor, see FanMorphism().

#### **OUTPUT:**

A fan isomorphism. If the fans are not isomorphic, a FanNotIsomorphicError is raised.

# **EXAMPLES:**

```
sage: rays = ((1, 1), (0, 1), (-1, -1), (3, 1))
sage: cones = [(0,1), (1,2), (2,3), (3,0)]
sage: fan1 = Fan(cones, rays)

sage: m = matrix([[-2,3],[1,-1]])
sage: m.det() == -1
True
sage: fan2 = Fan(cones, [vector(r)*m for r in rays])

sage: from sage.geometry.fan_isomorphism import find_isomorphism
```

```
sage: find_isomorphism(fan1, fan2, check=True)
Fan morphism defined by the matrix
Γ-2 31
Domain fan: Rational polyhedral fan in 2-d lattice N
Codomain fan: Rational polyhedral fan in 2-d lattice N
sage: find_isomorphism(fan1, toric_varieties.P2().fan())
                                                                       # optional -
→ palp
Traceback (most recent call last):
FanNotIsomorphicError
sage: fan1 = Fan(cones=[[1,3,4,5],[0,1,2,3],[2,3,4],[0,1,5]],
                rays=[(-1,-1,0),(-1,-1,3),(-1,1,-1),(-1,3,-1),(0,2,-1),(1,-1,1)]
sage: fan2 = Fan(cones=[[0,2,3,5],[0,1,4,5],[0,1,2],[3,4,5]],
                 rays=[(-1,-1,-1),(-1,-1,0),(-1,1,-1),(0,2,-1),(1,-1,1),(3,-1,-1)]
sage: fan1.is_isomorphic(fan2)
True
```

# 5.2 Construction of finite atomic and coatomic lattices from incidences

This module provides the function <code>lattice\_from\_incidences()</code> for computing finite atomic and coatomic lattices in the sense of partially ordered sets where any two elements have meet and joint. For example, the face lattice of a polyhedron.

Compute an atomic and coatomic lattice from the incidence between atoms and coatoms.

# INPUT:

- atom\_to\_coatoms list, atom\_to\_coatom[i] should list all coatoms over the i-th atom;
- coatom\_to\_atoms list, coatom\_to\_atom[i] should list all atoms under the i-th coatom;
- face\_constructor function or class taking as the first two arguments sorted tuple of integers and any
  keyword arguments. It will be called to construct a face over atoms passed as the first argument and under
  coatoms passed as the second argument. Default implementation will just return these two tuples as a tuple;
- required\_atoms list of atoms (default:None). Each non-empty "face" requires at least one of the specified atoms present. Used to ensure that each face has a vertex.
- key any hashable value (default: None). It is passed down to FinitePoset.
- all other keyword arguments will be passed to face\_constructor on each call.

#### **OUTPUT**:

• finite poset with elements constructed by face\_constructor.

**Note:** In addition to the specified partial order, finite posets in Sage have internal total linear order of elements which extends the partial one. This function will try to make this internal order to start with the bottom and

atoms in the order corresponding to atom\_to\_coatoms and to finish with coatoms in the order corresponding to coatom\_to\_atoms and the top. This may not be possible if atoms and coatoms are the same, in which case the preference is given to the first list.

#### ALGORITHM:

The detailed description of the used algorithm is given in [KP2002].

The code of this function follows the pseudo-code description in the section 2.5 of the paper, although it is mostly based on frozen sets instead of sorted lists - this makes the implementation easier and should not cost a big performance penalty. (If one wants to make this function faster, it should be probably written in Cython.)

While the title of the paper mentions only polytopes, the algorithm (and the implementation provided here) is applicable to any atomic and coatomic lattice if both incidences are given, see Section 3.4.

In particular, this function can be used for strictly convex cones and complete fans.

REFERENCES: [KP2002]

#### **AUTHORS:**

• Andrey Novoseltsev (2010-05-13) with thanks to Marshall Hampton for the reference.

#### EXAMPLES:

Let us construct the lattice of subsets of  $\{0, 1, 2\}$ . Our atoms are  $\{0\}$ ,  $\{1\}$ , and  $\{2\}$ , while our coatoms are  $\{0,1\}$ ,  $\{0,2\}$ , and  $\{1,2\}$ . Then incidences are

```
sage: atom_to_coatoms = [(0,1), (0,2), (1,2)]
sage: coatom_to_atoms = [(0,1), (0,2), (1,2)]
```

and we can compute the lattice as

For more involved examples see the *source code* of *sage.geometry.cone*. *ConvexRationalPolyhedralCone.face\_lattice()* and sage.geometry.fan. RationalPolyhedralFan.\_compute\_cone\_lattice().

# 5.3 Cython helper methods to compute integral points in polyhedra.

class sage.geometry.integral\_points.InequalityCollection
 Bases: object

A collection of inequalities.

#### INPUT:

- polyhedron a polyhedron defining the inequalities.
- permutation list; a 0-based permutation of the coordinates. Will be used to permute the coordinates of the inequality.
- box\_min, box\_max the (not permuted) minimal and maximal coordinates of the bounding box. Used for bounds checking.

#### **EXAMPLES:**

```
sage: from sage.geometry.integral_points import InequalityCollection
sage: P_00 = Polyhedron(identity_matrix(3).columns() + [(-2, -1, -1)], base_ring=00)
sage: ieq = InequalityCollection(P_QQ, [0,1,2], [0]*3,[1]*3); ieq
The collection of inequalities
integer: (3, -2, -2) x + 2 >= 0
integer: (-1, 4, -1) \times + 1 >= 0
integer: (-1, -1, 4) \times + 1 >= 0
integer: (-1, -1, -1) \times + 1 >= 0
sage: P_RR = Polyhedron(identity_matrix(2).columns() + [(-2.7, -1)], base_ring=RDF)
sage: InequalityCollection(P_RR, [0,1], [0]*2, [1]*2)
The collection of inequalities
integer: (-1, -1) x + 1 >= 0
generic: (-1.0, 3.7) \times + 1.0 >= 0
generic: (1.0, -1.35) \times + 1.35 >= 0
sage: line = Polyhedron(eqns=[(2,3,7)])
sage: InequalityCollection(line, [0,1], [0]*2, [1]*2 )
The collection of inequalities
integer: (3, 7) x + 2 >= 0
integer: (-3, -7) x + -2 >= 0
```

# are\_satisfied(inner\_loop\_variable)

Return whether all inequalities are satisfied.

You must call *prepare\_inner\_loop()* before calling this method.

### INPUT:

• inner\_loop\_variable – Integer. the 0-th coordinate of the lattice point.

#### **OUTPUT**:

Boolean. Whether the lattice point is in the polyhedron.

# **EXAMPLES:**

```
sage: from sage.geometry.integral_points import InequalityCollection
sage: line = Polyhedron(eqns=[(2,3,7)])
sage: ieq = InequalityCollection(line, [0,1], [0]*2, [1]*2 )
```

```
sage: ieq.prepare_next_to_inner_loop([3,4])
sage: ieq.prepare_inner_loop([3,4])
sage: ieq.are_satisfied(3)
False
```

# prepare\_inner\_loop(p)

Peel off the inner loop.

In the inner loop of  $rectangular\_box\_points()$ , we have to repeatedly evaluate  $Ax + b \ge 0$ . To speed up computation, we pre-evaluate

$$c = Ax - A_0x_0 + b = b + \sum_{i=1}^{n} A_ix_i$$

and only test  $A_0x_0 + c \ge 0$  in the inner loop.

You must call *prepare\_next\_to\_inner\_loop()* before calling this method.

#### INPUT:

• p – the coordinates of the point to loop over. Only the p[1:] entries are used.

#### **EXAMPLES:**

#### prepare\_next\_to\_inner\_loop(p)

Peel off the next-to-inner loop.

In the next-to-inner loop of  $rectangular\_box\_points()$ , we have to repeatedly evaluate  $Ax - A_0x_0 + b$ . To speed up computation, we pre-evaluate

$$c = b + \sum_{i=2} A_i x_i$$

and only compute  $Ax - A_0x_0 + b = A_1x_1 + c \ge 0$  in the next-to-inner loop.

#### INPUT:

- p – the point coordinates. Only p[2:] coordinates are potentially used by this method.

## **EXAMPLES:**

```
integer: (3, 7, 11) x + 2 >= 0
sage: ieq.prepare_next_to_inner_loop([2,1,3])
sage: ieq.prepare_inner_loop([2,1,3])
sage: print_cache(ieq)
Cached inner loop: 3 * x_0 + 42 >= 0
Cached next-to-inner loop: 3 * x_0 + 7 * x_1 + 35 >= 0
```

# satisfied\_as\_equalities(inner\_loop\_variable)

Return the inequalities (by their index) that are satisfied as equalities.

#### INPUT:

• inner\_loop\_variable - Integer. the 0-th coordinate of the lattice point.

#### **OUTPUT**:

A set of integers in ascending order. Each integer is the index of a H-representation object of the polyhedron (either a inequality or an equation).

#### **EXAMPLES:**

```
sage: from sage.geometry.integral_points import InequalityCollection
sage: quadrant = Polyhedron(rays=[(1,0), (0,1)])
sage: ieqs = InequalityCollection(quadrant, [0,1], [-1]*2, [1]*2 )
sage: ieqs.prepare_next_to_inner_loop([-1,0])
sage: ieqs.prepare_inner_loop([-1,0])
sage: ieqs.satisfied_as_equalities(-1)
frozenset({1})
sage: ieqs.satisfied_as_equalities(0)
frozenset({0, 1})
sage: ieqs.satisfied_as_equalities(1)
frozenset({1})
```

## swap\_ineq\_to\_front(i)

Swap the i-th entry of the list to the front of the list of inequalities.

#### INPUT:

• i – Integer. The *Inequality\_int* to swap to the beginning of the list of integral inequalities.

# **EXAMPLES:**

```
integer: (3, -2, -2) \times + 2 >= 0
integer: (-1, 4, -1) \times + 1 >= 0
integer: (-1, -1, 4) \times + 1 >= 0
```

## class sage.geometry.integral\_points.Inequality\_generic

Bases: object

An inequality whose coefficients are arbitrary Python/Sage objects

#### INPUT:

- A list of coefficients
- b element

#### **OUTPUT**:

Inequality  $Ax + b \ge 0$ .

#### **EXAMPLES:**

### class sage.geometry.integral\_points.Inequality\_int

Bases: object

Fast version of inequality in the case that all coefficients fit into machine ints.

#### INPUT:

- A list of integers
- b integer
- max\_abs\_coordinates the maximum of the coordinates that one wants to evaluate the coordinates on; used for overflow checking

# **OUTPUT**:

Inequality  $Ax + b \ge 0$ . A OverflowError is raised if a machine integer is not long enough to hold the results. A ValueError is raised if some of the input is not integral.

#### **EXAMPLES:**

```
sage: from sage.geometry.integral_points import Inequality_int
sage: Inequality_int([2,3,7], -5, [10]*3)
integer: (2, 3, 7) x + -5 >= 0

sage: Inequality_int([1]*21, -5, [10]*21)
Traceback (most recent call last):
...
OverflowError: Dimension limit exceeded.

sage: Inequality_int([2,3/2,7], -5, [10]*3)
Traceback (most recent call last):
...
ValueError: Not integral.
```

sage.geometry.integral\_points.loop\_over\_parallelotope\_points(e, d, VDinv, R, lattice, A=None, b=None)

The inner loop of parallelotope\_points().

#### INPUT:

See parallelotope\_points() for e, d, VDinv, R, lattice.

#### **OUTPUT:**

The points of the half-open parallelotope as a tuple of lattice points.

#### **EXAMPLES:**

```
sage: e = [3]
sage: d = prod(e)
sage: VDinv = matrix(ZZ, [[1]])
sage: R = column_matrix(ZZ,[3,3,3])
sage: lattice = ZZ^3
sage: from sage.geometry.integral_points import loop_over_parallelotope_points
sage: loop_over_parallelotope_points(e, d, VDinv, R, lattice)
((0, 0, 0), (1, 1, 1), (2, 2, 2))
sage: A = vector(ZZ, [1,0,0])
sage: b = 1
sage: loop_over_parallelotope_points(e, d, VDinv, R, lattice, A, b)
((0, 0, 0), (1, 1, 1))
```

### sage.geometry.integral\_points.parallelotope\_points(spanning\_points, lattice)

Return integral points in the parallelotope starting at the origin and spanned by the spanning\_points.

See semigroup\_generators() for a description of the algorithm.

## INPUT:

• spanning\_points – a non-empty list of linearly independent rays (**Z**-vectors or *toric lattice* elements), not necessarily primitive lattice points.

#### **OUTPUT**:

The tuple of all lattice points in the half-open parallelotope spanned by the rays  $r_i$ ,

$$par(\{r_i\}) = \sum_{0 \le a_i < 1} a_i r_i$$

By half-open parallelotope, we mean that the points in the facets not meeting the origin are omitted.

#### **EXAMPLES:**

Note how the points on the outward-facing factes are omitted:

```
sage: from sage.geometry.integral_points import parallelotope_points
sage: rays = list(map(vector, [(2,0), (0,2)]))
sage: parallelotope_points(rays, ZZ^2)
((0, 0), (0, 1), (1, 0), (1, 1))
```

The rays can also be toric lattice points:

```
sage: rays = list(map(ToricLattice(2), [(2,0), (0,2)]))
sage: parallelotope_points(rays, ToricLattice(2))
(N(0, 0), N(0, 1), N(1, 0), N(1, 1))
```

A non-smooth cone:

```
sage: c = Cone([ (1,0), (1,2) ])
sage: parallelotope_points(c.rays(), c.lattice())
(N(0, 0), N(1, 1))
```

A ValueError is raised if the spanning\_points are not linearly independent:

```
sage: rays = list(map(ToricLattice(2), [(1,1)]*2))
sage: parallelotope_points(rays, ToricLattice(2))
Traceback (most recent call last):
...
ValueError: The spanning points are not linearly independent!
```

# sage.geometry.integral\_points.print\_cache(inequality\_collection)

Print the cached values in *Inequality\_int* (for debugging/doctesting only).

# **EXAMPLES:**

```
sage: from sage.geometry.integral_points import InequalityCollection, print_cache
sage: P = Polyhedron(ieqs=[(2,3,7)])
sage: ieq = InequalityCollection(P, [0,1], [0]*2,[1]*2); ieq
The collection of inequalities
integer: (3, 7) x + 2 >= 0
sage: ieq.prepare_next_to_inner_loop([3,5])
sage: ieq.prepare_inner_loop([3,5])
sage: print_cache(ieq)
Cached inner loop: 3 * x_0 + 37 >= 0
Cached next-to-inner loop: 3 * x_0 + 7 * x_1 + 2 >= 0
```

#### sage.geometry.integral\_points.ray\_matrix\_normal\_form(R)

Compute the Smith normal form of the ray matrix for *parallelotope\_points()*.

#### INPUT:

•  $R - \mathbf{Z}$ -matrix whose columns are the rays spanning the parallelotope.

# **OUTPUT**:

A tuple containing e, d, and VDinv.

**EXAMPLES:** 

```
sage: from sage.geometry.integral_points import ray_matrix_normal_form
sage: R = column_matrix(ZZ,[3,3,3])
sage: ray_matrix_normal_form(R)
([3], 3, [1])
```

 $sage.geometry.integral\_points. \textbf{rectangular\_box\_points} (box\_min, box\_max, polyhedron=None, \\ count\_only=False, return\_saturated=False)$ 

Return the integral points in the lattice bounding box that are also contained in the given polyhedron.

#### INPUT:

- box\_min A list of integers. The minimal value for each coordinate of the rectangular bounding box.
- box\_max A list of integers. The maximal value for each coordinate of the rectangular bounding box.
- polyhedron A *Polyhedron\_base*, a PPL C\_Polyhedron, or None (default).
- count\_only Boolean (default: False). Whether to return only the total number of vertices, and not their coordinates. Enabling this option speeds up the enumeration. Cannot be combined with the return\_saturated option.
- return\_saturated Boolean (default: False. Whether to also return which inequalities are saturated for each point of the polyhedron. Enabling this slows down the enumeration. Cannot be combined with the count\_only option.

#### **OUTPUT:**

By default, this function returns a tuple containing the integral points of the rectangular box spanned by box\_min and box\_max and that lie inside the polyhedron. For sufficiently large bounding boxes, this are all integral points of the polyhedron.

If no polyhedron is specified, all integral points of the rectangular box are returned.

If count\_only is specified, only the total number (an integer) of found lattice points is returned.

If return\_saturated is enabled, then for each integral point a pair (point, Hrep) is returned where point is the point and Hrep is the set of indices of the H-representation objects that are saturated at the point.

#### ALGORITHM:

This function implements the naive algorithm towards counting integral points. Given min and max of vertex coordinates, it iterates over all points in the bounding box and checks whether they lie in the polyhedron. The following optimizations are implemented:

- Cython: Use machine integers and optimizing C/C++ compiler where possible, arbitrary precision integers where necessary. Bounds checking, no compile time limits.
- Unwind inner loop (and next-to-inner loop):

$$Ax \le b \quad \Leftrightarrow \quad a_1 x_1 \le b - \sum_{i=2}^d a_i x_i$$

so we only have to evaluate  $a_1 * x_1$  in the inner loop.

- Coordinates are permuted to make the longest box edge the inner loop. The inner loop is optimized to run very fast, so its best to do as much work as possible there.
- Continuously reorder inequalities and test the most restrictive inequalities first.
- Use convexity and only find first and last allowed point in the inner loop. The points in-between must be points of the polyhedron, too.

#### **EXAMPLES:**

```
sage: from sage.geometry.integral_points import rectangular_box_points
sage: rectangular_box_points([0,0,0],[1,2,3])
((0, 0, 0), (0, 0, 1), (0, 0, 2), (0, 0, 3),
(0, 1, 0), (0, 1, 1), (0, 1, 2), (0, 1, 3),
 (0, 2, 0), (0, 2, 1), (0, 2, 2), (0, 2, 3),
 (1, 0, 0), (1, 0, 1), (1, 0, 2), (1, 0, 3),
 (1, 1, 0), (1, 1, 1), (1, 1, 2), (1, 1, 3),
 (1, 2, 0), (1, 2, 1), (1, 2, 2), (1, 2, 3))
sage: from sage.geometry.integral_points import rectangular_box_points
sage: rectangular_box_points([0,0,0],[1,2,3], count_only=True)
24
sage: cell24 = polytopes.twenty_four_cell()
sage: rectangular_box_points([-1]*4, [1]*4, cell24)
((-1, 0, 0, 0), (0, -1, 0, 0), (0, 0, -1, 0), (0, 0, 0, -1),
(0, 0, 0, 0),
(0, 0, 0, 1), (0, 0, 1, 0), (0, 1, 0, 0), (1, 0, 0, 0))
sage: d = 3
sage: dilated_cell24 = d*cell24
sage: len( rectangular_box_points([-d]*4, [d]*4, dilated_cell24) )
305
sage: d = 6
sage: dilated_cell24 = d*cell24
sage: len( rectangular_box_points([-d]*4, [d]*4, dilated_cell24) )
3625
sage: rectangular_box_points([-d]*4, [d]*4, dilated_cell24, count_only=True)
sage: polytope = Polyhedron([(-4,-3,-2,-1),(3,1,1,1),(1,2,1,1),(1,1,3,0),(1,3,2,4)])
sage: pts = rectangular_box_points([-4]*4, [4]*4, polytope); pts
((-4, -3, -2, -1), (-1, 0, 0, 1), (0, 1, 1, 1), (1, 1, 1, 1), (1, 1, 3, 0),
(1, 2, 1, 1), (1, 2, 2, 2), (1, 3, 2, 4), (2, 1, 1, 1), (3, 1, 1, 1))
sage: all(polytope.contains(p) for p in pts)
True
sage: set(map(tuple,pts)) == \
set([(-4,-3,-2,-1),(3,1,1,1),(1,2,1,1),(1,1,3,0),(1,3,2,4),
. . . . :
           (0,1,1,1),(1,2,2,2),(-1,0,0,1),(1,1,1,1),(2,1,1,1)] # computed with.
\hookrightarrow PALP
True
```

Long ints and non-integral polyhedra are explicitly allowed:

Using a PPL polyhedron:

Optionally, return the information about the saturated inequalities as well:

```
sage: cube = polytopes.cube()
sage: cube.Hrepresentation(0)
An inequality (-1, 0, 0) \times + 1 >= 0
sage: cube.Hrepresentation(1)
An inequality (0, -1, 0) \times + 1 >= 0
sage: cube.Hrepresentation(2)
An inequality (0, 0, -1) x + 1 >= 0
sage: rectangular_box_points([0]*3, [1]*3, cube, return_saturated=True)
(((0, 0, 0), frozenset()),
((0, 0, 1), frozenset({2})),
 ((0, 1, 0), frozenset(\{1\})),
 ((0, 1, 1), frozenset({1, 2})),
 ((1, 0, 0), frozenset(\{0\})),
 ((1, 0, 1), frozenset({0, 2})),
 ((1, 1, 0), frozenset({0, 1})),
 ((1, 1, 1), frozenset({0, 1, 2})))
```

#### sage.geometry.integral\_points.simplex\_points(vertices)

Return the integral points in a lattice simplex.

#### INPUT:

• vertices – an iterable of integer coordinate vectors. The indices of vertices that span the simplex under consideration.

# **OUTPUT**:

A tuple containing the integral point coordinates as **Z**-vectors.

#### **EXAMPLES:**

```
sage: from sage.geometry.integral_points import simplex_points
sage: simplex_points([(1,2,3), (2,3,7), (-2,-3,-11)])
((-2, -3, -11), (0, 0, -2), (1, 2, 3), (2, 3, 7))
```

The simplex need not be full-dimensional:

```
sage: simplex = Polyhedron([(1,2,3,5), (2,3,7,5), (-2,-3,-11,5)])
sage: simplex_points(simplex.Vrepresentation())
((2, 3, 7, 5), (0, 0, -2, 5), (-2, -3, -11, 5), (1, 2, 3, 5))
sage: simplex_points([(2,3,7)])
((2, 3, 7),)
```

# **5.4 Helper Functions For Freeness Of Hyperplane Arrangements**

This contains the algorithms to check for freeness of a hyperplane arrangement. See sage.geometry. hyperplane\_arrangement.HyperplaneArrangementElement.is\_free() for details.

Note: This could be extended to a freeness check for more general modules over a polynomial ring.

sage.geometry.hyperplane\_arrangement.check\_freeness.construct\_free\_chain(A) Construct the free chain for the hyperplanes A.

ALGORITHM:

We follow Algorithm 6.5 in [BC2012].

INPUT:

• A – a hyperplane arrangement

## **EXAMPLES:**

sage.geometry.hyperplane\_arrangement.check\_freeness.less\_generators(X)
Reduce the generator matrix of the module defined by X.

This is Algorithm 6.4 in [BC2012] and relies on the row syzygies of the matrix X.

### **EXAMPLES:**

```
sage: m = matrix([[1, 0, 0], [0, z, -1], [0, 0, 0], [0, y, 1]])
sage: less_generators(m)
[ 1  0  0]
[ 0  z -1]
[ 0  y  1]
```

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# **CHAPTER**

# SIX

# **INDICES AND TABLES**

- Index
- Module Index
- Search Page

atorial and Discrete Geomet		

# **PYTHON MODULE INDEX**

```
g
                                                                                                                     sage.geometry.polyhedron.base7,603
                                                                                                                     sage.geometry.polyhedron.base_QQ, 620
sage.geometry.abc, 701
                                                                                                                     sage.geometry.polyhedron.base_RDF, 638
sage.geometry.cone, 352
                                                                                                                     sage.geometry.polyhedron.base_ZZ, 632
sage.geometry.cone_catalog, 412
                                                                                                                     sage.geometry.polyhedron.cdd_file_format, 156
sage.geometry.convex_set, 702
                                                                                                                     sage.geometry.polyhedron.combinatorial_polyhedron.base,
sage.geometry.fan, 417
sage.geometry.fan_isomorphism, 749
                                                                                                                     sage.geometry.polyhedron.combinatorial_polyhedron.combinat
sage.geometry.fan_morphism, 449
sage.geometry.hasse_diagram, 753
sage.geometry.hyperplane_arrangement.affine_subage.geometry.polyhedron.combinatorial_polyhedron.conversi
{\tt sage.geometry.hyperplane\_arrangement.arrangement.geometry.polyhedron.combinatorial\_polyhedron.face\_iteration and the state of the 
sage.geometry.hyperplane_arrangement.check_freenes.geometry.polyhedron.combinatorial_polyhedron.list_of_
{\tt sage.geometry.hyperplane\_arrangement.hyperplane\_age.geometry.polyhedron.combinatorial\_polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedron.polyhedr
{\tt sage.geometry.hyperplane\_arrangement.library, sage.geometry.polyhedron.constructor, 106}
                                                                                                                     sage.geometry.polyhedron.double_description,
sage.geometry.hyperplane_arrangement.plot,56
                                                                                                                     sage.geometry.polyhedron.double_description_inhomogeneous,
sage.geometry.integral_points,755
sage.geometry.lattice_polytope, 159
                                                                                                                     sage.geometry.polyhedron.face, 144
sage.geometry.linear_expression, 713
                                                                                                                     sage.geometry.polyhedron.lattice_euclidean_group_element,
sage.geometry.newton_polygon, 719
                                                                                                                                         213
sage.geometry.point_collection, 465
                                                                                                                     sage.geometry.polyhedron.library, 61
sage.geometry.polyhedral_complex, 310
                                                                                                                     sage.geometry.polyhedron.modules.formal_polyhedra_module,
sage.geometry.polyhedron.backend_cdd, 638
sage.geometry.polyhedron.backend_cdd_rdf,639
                                                                                                                     sage.geometry.polyhedron.palp_database, 215
sage.geometry.polyhedron.backend_field, 639
                                                                                                                     sage.geometry.polyhedron.parent, 114
sage.geometry.polyhedron.backend_normaliz,
                                                                                                                     sage.geometry.polyhedron.plot, 134
                   640
                                                                                                                     sage.geometry.polyhedron.ppl_lattice_polygon,
sage.geometry.polyhedron.backend_polymake,
                                                                                                                     sage.geometry.polyhedron.ppl_lattice_polytope,
sage.geometry.polyhedron.backend_ppl,650
                                                                                                                                         221
sage.geometry.polyhedron.base, 610
                                                                                                                     sage.geometry.polyhedron.representation, 120
sage.geometry.polyhedron.base0,497
                                                                                                                     sage.geometry.pseudolines, 740
sage.geometry.polyhedron.base1,513
                                                                                                                     sage.geometry.relative_interior, 723
sage.geometry.polyhedron.base2,521
                                                                                                                     sage.geometry.ribbon_graph, 727
sage.geometry.polyhedron.base3,527
                                                                                                                     sage.geometry.toric_lattice, 336
sage.geometry.polyhedron.base4,556
                                                                                                                     sage.geometry.toric_plotter, 473
sage.geometry.polyhedron.base5,570
                                                                                                                     sage.geometry.triangulation.base, 684
sage.geometry.polyhedron.base6,587
```

770 Python Module Index

# **INDEX**

A		(sage.geometry.polyh	edron.base6.Polyl	nedron_base6
A() (sage.geometry.linear_expression.LinearExpression		method), 587		
method), 714	affine_l	hull_projection()		
A() (sage.geometry.polyhedron.double_description.Problem method), 657		(sage.geometry.conve.method), 703	x_set.ConvexSet_	base
A() (sage.geometry.polyhedron.representation.Hrepresentation	affine_	hull_projection()		
method), 121		(sage.geometry.polyh	edron.base6.Polyl	nedron_base6
A matrix() (sage geometry polyhedron double description	n.Problem	method), 588		
method) 657	affine	lattice_polytope(	)	
a_maximal_chain() (sage.geometry.polyhedron.base1.Pol method), 513		methoa), 222		
a_maximal_chain() (sage.geometry.polyhedron.base3.Pol method), 527	lyhedron_	space () (sage.geomet method), 223	ry.polyhedron.pp	l_lattice_polytope.Latticel
a_maximal_chain() (sage.geometry.polyhedron.combinat method), 240		(sage.geometry.polyh	itorialPolyhedron edron.face.Polyhe	dronFace
add cell()(sage.geometry.polyhedral complex.Polyhedra	alComplex	<sub>k</sub> method), 146		
method), 313	affine_	transform()(sage.ge		olytope.LatticePolytopeCla
add_hyperplane() (sage.geometry.hyperplane_arrangemented), 8	ent.arrang AffineH	ลูยัหย์หนึ่ง HyperplaneArr ullProjectionData	angementElement (class	t in
add_inequality() (sage.geometry.polyhedron.double_de.method), 659	AffineSi	ubspace	(class	in
adjacency_graph() (sage.geometry.triangulation.element method), 693	t.Triangul	sage.geometry.hyperp 54	lane_arrangemen	t.affine_subspace),
adjacency_matrix() (sage.geometry.polyhedron.base3.Polyhe	allexandi	er <sub>a</sub> whitney()		
method), 528		(sage.geometry.polyh	edral_complex.Po	lyhedralComplex
<pre>adjacent() (sage.geometry.cone.ConvexRationalPolyhedr</pre>	alCone	method), 314		
method), 361	all_cacl	hed_data()	(in	module
<pre>adjacent() (sage.geometry.lattice_polytope.LatticePolytop</pre>	all_fac	<pre>sage.geometry.lattice_ et_equations()</pre>	(in	module
adjacent() (sage.geometry.polyhedron.representation.Hre method), 122	arr_ner	_partruits()	(in	module
adjacent() (sage.geometry.polyhedron.representation.Vre	presentati	ggge.geometry.lattice_	_polytope), 205	
method), 131	arr_por	nts()	(in	module
$\verb"adjust_options"() (\textit{sage.geometry.toric\_plotter.ToricPlotter}) \\$	ici	sage.geometry.lattice		1 1
memoa), 475	all_pol		(in	module
affine() (sage.geometry.triangulation.base.Point method), 685		sage.geometry.lattice_() (sage.geometry.con		PolyhedralCone
${\tt affine\_hull()} \ (sage. geometry. convex\_set. ConvexSet\_base)$	e	method), 362		g , 1
πεποα, 102		() (sage.geometry.co	onvex_set.Convex	Set_base
${\tt affine\_hull()} (sage. geometry. polyhedron. base 6. Polyhedro$	ron_base(	gneinoa), 105 () (saaa aasmatm) 1244	ica nobytona I att	ica Polytona Class
method), 587		() (sage.geometry.latt method), 164	се_рогуюре.∟аш	cer orytopectass
affine hull manifold()		memou j, 10 <del>1</del>		

```
ambient() (sage.geometry.polyhedron.base1.Polyhedron_bambient_module() (sage.geometry.toric_lattice.ToricLattice_ambient
                             method), 513
                                                                                                                                                                                                               method), 340
ambient() (sage.geometry.polyhedron.face.PolyhedronFacembient_ordered_point_indices()
                                                                                                                                                                                                               (sage.geometry.lattice_polytope.LatticePolytopeClass
                             method), 146
ambient() (sage.geometry.relative_interior.RelativeInterior
                                                                                                                                                                                                               method), 165
                            method), 723
                                                                                                                                                                                 ambient_point_indices()
ambient_dim() (sage.geometry.cone.IntegralRayCollection
                                                                                                                                                                                                               (sage.geometry.lattice polytope.LatticePolytopeClass
                             method), 401
                                                                                                                                                                                                               method), 165
ambient_dim() (sage.geometry.convex_set.ConvexSet_basambient_ray_indices()
                            method), 703
                                                                                                                                                                                                               (sage.geometry.cone.Convex Rational Polyhedral Cone
ambient_dim() (sage.geometry.lattice_polytope.LatticePolytopeClasmethod), 363
                                                                                                                                                                                 ambient_space() (sage.geometry.hyperplane_arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrange
                             method), 164
ambient_dim() (sage.geometry.polyhedron.base1.Polyhedron_base1method), 38
                                                                                                                                                                                 ambient_space() (sage.geometry.polyhedron.base1.Polyhedron_base1
                            method), 514
ambient\_dim() (sage.geometry.polyhedron.face.PolyhedronFace
                                                                                                                                                                                                              method), 514
                             method), 148
                                                                                                                                                                                  ambient_space() (sage.geometry.polyhedron.parent.Polyhedra_base
ambient_dim() (sage.geometry.polyhedron.parent.Polyhedra_base method), 117
                                                                                                                                                                                 ambient_space() (sage.geometry.polyhedron.ppl_lattice_polytope.Lattice
                            method), 116
ambient_dim() (sage.geometry.relative_interior.RelativeInterior
                                                                                                                                                                                                              method), 223
                                                                                                                                                                                 ambient_V_indices()
                             method), 723
ambient_dim() (sage.geometry.triangulation.base.PointConfigurations_dgasgeometry.polyhedron.combinatorial_polyhedron.combinato
                            method), 689
                                                                                                                                                                                                              method), 275
ambient_dim() (sage.geometry.voronoi_diagram.VoronoiDeingicent_V_indices()
                             method), 745
                                                                                                                                                                                                               (sage.geometry.polyhedron.face.PolyhedronFace
ambient_dim() (sage.rings.polynomial.groebner_fan.PolyhedralCommethod), 147
                             method), 491
                                                                                                                                                                                 ambient_vector_space()
ambient\_dim() \ (sage.rings.polynomial.groebner\_fan.PolyhedralFan(sage.geometry.cone.IntegralRayCollection) \ (sage.rings.polynomial.groebner\_fan.PolyhedralFan(sage.geometry.cone.IntegralRayCollection) \ (sage.rings.polynomial.groebner\_fan.PolyhedralFan(sage.geometry.cone.IntegralRayCollection) \ (sage.rings.polynomial.groebner\_fan.PolyhedralFan(sage.geometry.cone.IntegralRayCollection) \ (sage.rings.polynomial.groebner\_fan.PolyhedralFan(sage.geometry.cone.IntegralRayCollection) \ (sage.geometry.cone.IntegralRayCollection) \ (sage.geometry.cone.Integral
                            method), 492
                                                                                                                                                                                                               method), 401
ambient_dimension()
                                                                                                                                                                                 ambient_vector_space()
                             (sage.geometry.convex_set.ConvexSet_base
                                                                                                                                                                                                               (sage.geometry.convex_set.ConvexSet_base
                            method), 704
                                                                                                                                                                                                               method), 704
ambient_dimension()
                                                                                                                                                                                 ambient_vector_space()
                             (sage.geometry.polyhedral_complex.PolyhedralComplex
                                                                                                                                                                                                              (sage.geometry.lattice_polytope.LatticePolytopeClass
                            method), 315
                                                                                                                                                                                                               method), 166
                                                                                                                                                                                 ambient_vector_space()
ambient_dimension()
                             (sage.geometry.polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_polyhedron.combinatorial\_poly
                            method), 276
                                                                                                                                                                                                               method), 717
ambient_facet_indices()
                                                                                                                                                                                 ambient_vector_space()
                              (sage.geometry.lattice_polytope.LatticePolytopeClass
                                                                                                                                                                                                               (sage.geometry.polyhedron.base1.Polyhedron_base1
                            method), 164
                                                                                                                                                                                                              method), 514
ambient_H_indices()
                                                                                                                                                                                 ambient_vector_space()
                              (sage.geometry.polyhedron.combinatorial polyhedron.combisago.geonfate;@olyhedronfadaaPolyhedronFace
                            method), 273
                                                                                                                                                                                                              method), 149
ambient_H_indices()
                                                                                                                                                                                 ambient_vector_space()
                             (sage.geometry.polyhedron.face.PolyhedronFace
                                                                                                                                                                                                               (sage.geometry.relative\_interior.RelativeInterior
                             method), 146
                                                                                                                                                                                                               method), 723
                                                                                                                                                                                 ambient_vertex_indices()
ambient_Hrepresentation()
                             (sage.geometry.polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhe
                            method), 274
                                                                                                                                                                                                               method), 166
ambient_Hrepresentation()
                                                                                                                                                                                 ambient_Vrepresentation()
                             (sage.geometry.polyhedron.face.PolyhedronFace
                                                                                                                                                                                                               (sage.geometry.polyhedron.combinatorial_polyhedron.combinato
                            method), 147
                                                                                                                                                                                                               method), 275
ambient_module() (sage.geometry.linear expression.Lineambigents.Wn4fordslentation()
                            method), 717
                                                                                                                                                                                                               (sage.geometry.polyhedron.face.PolyhedronFace
```

```
method), 148
                                                                                                                                                                              base_rays() (sage.geometry.polyhedron.ppl lattice polytope.LatticePolytope.
AmbientVectorSpace
                                                                                                                                                                                                            method), 224
                                                                                                          (class
                                                                                                                                                                 in
                            sage.geometry.hyperplane arrangement.hyperplanease_ring() (sage.geometry.hyperplane arrangement.arrangement.Hype
                                                                                                                                                                                                           method), 38
an_affine_basis() (sage.geometry.cone.ConvexRationalBasterdial@onesage.geometry.polyhedron.base0.Polyhedron base0
                            method), 363
                                                                                                                                                                                                           method), 501
an_affine_basis() (sage.geometry.convex set.ConvexSeb dracering() (sage.geometry.polyhedron.double description.Problem
                            method), 704
                                                                                                                                                                                                            method), 658
an_affine_basis() (sage.geometry.polyhedron.base1.Polyhesebrani.html() (sage.geometry.triangulation.base.PointConfiguration_base
                            method), 515
                                                                                                                                                                                                           method), 689
an_affine_basis() (sage.geometry.relative_interior.Relativestationg() (sage.geometry.voronoi_diagram.VoronoiDiagram
                            method), 724
                                                                                                                                                                                                            method), 745
an_element() (sage.geometry.convex_set.ConvexSet_base basis() (sage.geometry.linear_expression.LinearExpressionModule
                            method), 704
                                                                                                                                                                                                            method), 717
an_element() (sage.geometry.polyhedron.parent.Polyhedrbakiss() (sage.geometry.point_collection.PointCollection
                             method), 117
                                                                                                                                                                                                            method), 466
an_element() (sage.geometry.triangulation.point_configuirealphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalphiintalph
                            method), 669
                                                                                                                                                                                                           method), 43
are_adjacent() (sage.geometry.polyhedron.double_descriptionarDittoledlbbooptgrafthi()
                                                                                                                                                                                                                                                                                                                               module
                                                                                                                                                                                                                                                                                                (in
                             method), 654
                                                                                                                                                                                                           sage.geometry.ribbon graph), 738
are_satisfied() (sage.geometry.integral_points.Inequalibifpylkannical() (sage.geometry.polyhedron.base5.Polyhedron_base5
                            method), 755
                                                                                                                                                                                                           method), 570
as_combinatorial_polyhedron()
                                                                                                                                                                             Birkhoff_polytope()
                             (sage.geometry.polyhedron.combinatorial polyhedron.combisugesielosfiatexscolyhedron.combinatorial polyhedron.combisugesielosfiatexscolyhedron.combinatorial polyhedron.combisugesielosfiatexscolyhedron.combinatorial polyhedron.combisugesielosfiatexscolyhedron.combisugesielosfiatexscolyhedron.combisugesielosfiatexscolyhedron.combisugesielosfiatexscolyhedron.combisugesielosfiatexscolyhedron.combisugesielosfiatexscolyhedron.combisugesielosfiatexscolyhedron.combisugesielosfiatexscolyhedron.combisugesielosfiatexscolyhedron.combisugesielosfiatexscolyhedron.combisugesielosfiatexscolyhedron.combisugesielosfiatexscolyhedron.combisugesielosfiatexscolyhedron.combisugesielosfiatexscolyhedron.combisugesielosfiatexscolyhedron.combisugesielosfiatexscolyhedron.combisugesielosfiatexscolyhedron.combisugesielosfiatexscolyhedron.combisugesielosfiatexscolyhedron.combisugesielosfiatexscolyhedron.combisugesielosfiatexscolyhedron.combisugesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combisusesielosfiatexscolyhedron.combis
                                                                                                                                                                                                          method), 62
                            method), 276
as_polyhedron() (sage.geometry.polyhedron.face.PolyhedrinsEaddar_flips() (sage.geometry.triangulation.point configuration.Po
                            method), 149
                                                                                                                                                                                                           method), 669
                                                                                                                                                                             bitruncated_six_hundred_cell()
В
                                                                                                                                                                                                           (sage.geometry.polyhedron.library.Polytopes
                                                                                                                                                                                                            method), 63
b() (sage.geometry.linear_expression.LinearExpression
                                                                                                                                                                             boundary() (sage.geometry.ribbon_graph.RibbonGraph
                            method), 714
                                                                                                                                                                                                            method), 730
b() (sage.geometry.polyhedron.representation.Hrepresentation
                                                                                                                                                                             boundary() (sage.geometry.triangulation.element.Triangulation
                             method), 122
backend() (sage.geometry.hyperplane_arrangement.arrangement.HyperplaneArrangementElement
                                                                                                                                                                              boundary_complex() (sage.geometry.polyhedron.base.Polyhedron_base
                            method), 9
                                                                                                                                                                                                           method), 611
backend() (sage.geometry.polyhedron.base0.Polyhedron_base0
                                                                                                                                                                              boundary_point_indices()
                             method), 500
                                                                                                                                                                                                           (sage.geometry.lattice_polytope.LatticePolytopeClass
backend() (sage.geometry.polyhedron.parent.Polyhedra_base
                                                                                                                                                                                                            method), 166
                            method), 117
                                                                                                                                                                             boundary_points() (sage.geometry.lattice_polytope.LatticePolytopeClas
barycentric_subdivision()
                                                                                                                                                                                                          method), 167
                             (sage.geometry.polyhedron.base.Polyhedron base
                                                                                                                                                                             boundary_polyhedral_complex()
                            method), 611
{\tt base\_extend()} \ (sage.geometry.polyhedron.base 0. Polyhedron\_base 0 (sage.geometry.triangulation.element. Triangulation) (sage.geometry.polyhedron.base 0. Polyhedron\_base 0 (sage.geometry.triangulation.element. Triangulation) (sage.geometry.triangulation) (sage.geometry.tr
                                                                                                                                                                                                            method), 694
                             method), 500
(sage.geometry.triangulation.element.Triangulation
                            method), 117
                                                                                                                                                                                                         method), 695
base_extend() (sage.geometry.toric_lattice.ToricLattice_quotient
                                                                                                                                                                               boundary_subcomplex()
                             method), 346
{\tt base\_projection()} \ (sage.geometry.polyhedron.ppl\_lattice\_polytopes {\tt PLSC} {\tt polyhedrol} {\tt polyhedrol
                                                                                                                                                                                                            method), 315
                            method), 223
                                                                                                                                                                             bounded_edges() (sage.geometry.polyhedron.base3.Polyhedron_base3
base_projection_matrix()
                             (sage.geometry.polyhedron.ppl_lattice_polytope.LatticePolytopePPS3lass
                                                                                                                                                                              bounded_regions() (sage.geometry.hyperplane_arrangement.arrangement
                            method), 224
                                                                                                                                                                                                           method), 9
```

bounding_box() (sage.geometry.polyhedron.base.Polyhedron), 612	dradd_blasepresentation() (in module sage.geometry.polyhedron.cdd_file_format),
bounding_box() (sage.geometry.polyhedron.ppl_lattice_pmethod), 225	polytope.LatticePolytope_PPL_class cdd_Vrepresentation()
	Hyperplan <b>(Aargangameettl</b> yi <b>þodyl</b> yedron.base0.Polyhedron_base0 method), 502
buchberger() (sage.rings.polynomial.groebner_fan.Groemethod), 483	baelFlariterator() (sage.geometry.polyhedral_complex.PolyhedralComp method), 316
buckyball() (sage.geometry.polyhedron.library.Polytope method), 64	scells() (sage.geometry.polyhedral_complex.PolyhedralComplex method), 316
С	<pre>cells_list_to_cells_dict() (in module</pre>
<pre>cantellated_one_hundred_twenty_cell()</pre>	<pre>cells_sorted() (sage.geometry.polyhedral_complex.PolyhedralComple</pre>
(sage.geometry.polyhedron.library.Polytopes	method), 316
method), 65	$\verb center()  (sage.geometry.hyperplane\_arrangement.arrangement.Hyperplane\_arrangement.arrangement.Hyperplane\_arrangement.hyperplane\_arra$
cantellated_six_hundred_cell()	method), 10
(sage.geometry.polyhedron.library.Polytopes method), 65	<pre>center() (sage.geometry.polyhedron.base.Polyhedron_base method), 612</pre>
cantitruncated_one_hundred_twenty_cell()	centroid() (sage.geometry.polyhedron.base7.Polyhedron_base7
(sage.geometry.polyhedron.library.Polytopes	method), 603
method), 66	<pre>chain_complex() (sage.geometry.polyhedral_complex.PolyhedralComp</pre>
cantitruncated_six_hundred_cell()	change_ring() (sage.geometry.hyperplane_arrangement.arrangement.E
(sage.geometry.polyhedron.library.Polytopes method), 66	method), 11
cardinality() (sage geometry convex set Converset ba	$_{s}$ change_ring() (sage.geometry.hyperplane_arrangement.arrangement.F.
method). 705	method), 39
cardinality() (sage.geometry.point_collection.PointCol method), 467	<pre>pape_ring() (sage.geometry.hyperplane_arrangement.hyperplane.An method), 47</pre>
cartesian_product()	${\tt change\_ring()} \ ({\it sage.geometry.linear\_expression.LinearExpression}$
(sage.geometry.cone.ConvexRationalPolyhedralC	
method), 363	${\tt change\_ring()} \ (sage.geometry.linear\_expression.LinearExpressionModels) \ (sage.geometry.linear\_expression.LinearExp$
<pre>cartesian_product()</pre>	method), 718
(sage.geometry.cone.IntegralRayCollection method), 402	change_ring() (sage.geometry.polyhedron.base0.Polyhedron_base0 method), 502
cartesian_product()	<pre>change_ring() (sage.geometry.polyhedron.parent.Polyhedra_base</pre>
(sage.geometry.convex_set.ConvexSet_base	method), 118
method), 705	characteristic()(sage.rings.polynomial.groebner_fan.GroebnerFan
cartesian_product()	method), 484
(sage.geometry.fan.RationalPolyhedralFan	<pre>characteristic_polynomial()</pre>
method), 429	method), 11
<pre>cartesian_product()           (sage.geometry.point_collection.PointCollection)</pre>	circuits() (sage.geometry.triangulation.point_configuration.PointConf
method), 467	method), 670
cartesian_product()	circuits_support() (sage.geometry.triangulation.point_configuration.
(sage.geometry.polyhedron.base5.Polyhedron_ba	
method), 571	classify_cone_2d() (in module sage.geometry.cone),
Catalan() (sage.geometry.hyperplane_arrangement.libra	ry.HyperplaneArrangementLibrary
method), 40	closed_faces() (sage.geometry.hyperplane_arrangement.arrangement.
cdd_Hrepresentation() (in module	method), 11
$sage.geometry.polyhedron.cdd\_file\_format),$	closure() (sage.geometry.convex_set.ConvexSet_base
156	method), 705
cdd_Hrepresentation()	closure() (sage.geometry.relative_interior.RelativeInterior
(sage.geometry.polyhedron.base0.Polyhedron_bamethod), 501	ase0 method), 724 codim() (sage.geometry.cone.IntegralRayCollection

	method), 402		method), 492
<pre>codim()</pre>	(sage.geometry.convex_set.ConvexSet_base	connect	ed_component()
	method), 705		$(sage.geometry.polyhedral\_complex.PolyhedralComplex\\$
codimen	${\sf sion()}\ (sage.geometry.cone.Integral Ray Collection)$		method), 317
	method), 403		ed_components()
codimen	<pre>sion() (sage.geometry.convex_set.ConvexSet_ba method), 706</pre>		(sage.geometry.polyhedral_complex.PolyhedralComplex method), 318
codomaii	n_dim() (sage.geometry.polyhedron.lattice_eucli		
	method), 213		sage.geometry.triangulation.base), 684
codomai	n_fan() (sage.geometry.fan_morphism.FanMorp method), 452		t_term() (sage.geometry.linear_expression.LinearExpression method), 715
coeffic	ients() (sage.geometry.linear_expression.Linear		
	method), 715		sage.geometry.hyperplane_arrangement.check_freeness),
color_l	<pre>ist() (in module sage.geometry.toric_plotter),</pre>		764
	478		ction() (sage.geometry.toric_lattice.ToricLattice_generic
column_i	<pre>matrix() (sage.geometry.point_collection.Point()</pre>		
	method), 467		ed_simplex()
combina	torial_automorphism_group()		(sage.geometry.triangulation.point_configuration.PointConfigura
	(sage.geometry.polyhedron.base4.Polyhedron_ba		method), 671
combina	method), 556		s() (sage.geometry.cone.ConvexRationalPolyhedralCone method), 364
COMDINA	torial_face_to_polyhedral_face() (in module sage.geometry.polyhedron.face), 155		method), 504 s() (sage.geometry.convex_set.ConvexSet_base
combina	torial_polyhedron()		method), 706
COMDINA	(sage.geometry.polyhedron.base3.Polyhedron_ba		
	method), 530		method), 435
Combina			s() (sage.geometry.lattice_polytope.LatticePolytopeClass
	sage.geometry.polyhedron.combinatorial_polyhe		
	272	contain	s() (sage.geometry.polyhedron.base1.Polyhedron_base1
Combina	torialPolyhedron (class in		method), 515
			ş() (sage.geometry.polyhedron.face.PolyhedronFace
	236		method), 149
common_	refinement()		s() (sage.geometry.polyhedron.ppl_lattice_polytope.LatticePolyto
	(sage.geometry.fan.RationalPolyhedralFan		method), 225
	method), 429		s() (sage.geometry.polyhedron.representation.Equation
complex	() (sage.geometry.fan.RationalPolyhedralFan method), 430		method), 120
computa	_dimension()		s() (sage.geometry.polyhedron.representation.Inequality method), 124
			memod), 124 <b>of_gaiexih(s)Offigee</b> æometry.polyhedron.ppl_lattice_polytope.Lat.
	method), 304		method), 225
Cone()(	in module sage.geometry.cone), 355		t_edge() (sage.geometry.ribbon_graph.RibbonGraph
	sage.geometry.hyperplane_arrangement.arrangen		
\	method), 15	convex_l	
cone()(	sage.geometry.polyhedron.double_description.Do		
	method), 654	convex_l	hull() (sage.geometry.polyhedron.base5.Polyhedron_base5
cone()(	sage.rings.polynomial.groebner_fan.InitialForm		method), 571
	method), 489		hull() (sage.geometry.triangulation.point_configuration.PointCo
	$\verb ntaining()  (sage. geometry. fan. Rational Polyhed) $		method), 671
	method), 432		ationalPolyhedralCone (class in
cone_la	ttice() (sage.geometry.fan.RationalPolyhedralF		sage.geometry.abc), 701
Concor	method), 433		ationalPolyhedralCone (class in
cone_oi	_fan (class in sage.geometry.fan), 420		sage.geometry.cone), 357 et_base (class in sage.geometry.convex_set),
	method), 434	COLLACYO	702
	(sage.rings.polynomial.groebner_fan.Polyhedrall	FaionvexS	

```
710
                                                                                      Delta_polar() (sage.geometry.lattice_polytope.NefPartition
ConvexSet_compact
                                                    (class
                                                                                                     method), 197
                                                                                in
                                                                                                        (sage.geometry.lattice polytope.NefPartition
              sage.geometry.convex set), 711
                                                                                      Deltas()
ConvexSet_open (class in sage.geometry.convex_set),
                                                                                                     method), 197
                                                                                      dense_coefficient_list()
ConvexSet_relatively_open
                                                                                                     (sage.geometry.linear expression.LinearExpression
                                                           (class
                                                                                in
              sage.geometry.convex set), 712
                                                                                                     method), 715
coord_index_of() (sage.geometry.polyhedron.plot.Projection_ivation_module_basis()
              method), 134
                                                                                                     (sage.geometry.hyperplane arrangement.arrangement.Hyperplane
{\tt coord\_indices\_of()}\ (sage.geometry.polyhedron.plot.Projection
                                                                                                    method), 16
                                                                                      derivation_module_free_chain()
              method), 134
coordinate() (sage.geometry.hyperplane_arrangement.library.Hyperplane@mentgehepekpibaneg_arrangement.arrangement.Hyperplane
                                                                                                     method), 17
              method), 44
coordinate_vector()
                                                                                      dilation() (sage.geometry.convex_set.ConvexSet_base
              (sage.geometry.toric_lattice.ToricLattice_quotient
                                                                                                     method), 706
              method), 346
                                                                                       dilation() (sage.geometry.polyhedron.base5.Polyhedron_base5
coordinates_of() (sage.geometry.polyhedron.plot.Projection
                                                                                                     method), 572
              method), 134
                                                                                      dilation()(sage.geometry.relative interior.RelativeInterior
count() (sage.geometry.polyhedron.representation.PolyhedronRepresentation), 724
                                                                                      dim()
              method), 128
                                                                                                           (sage.geometry.cone.IntegralRayCollection
                                                                                                     method), 404
create_key() (sage.geometry.toric_lattice.ToricLatticeFactory
              method), 339
                                                                                                           (sage.geometry.convex_set.ConvexSet_base
create_object() (sage.geometry.toric_lattice.ToricLatticeFactory method), 706
              method), 339
                                                                                      dim() (sage.geometry.lattice polytope.LatticePolytopeClass
                                                                        module
cross_polytope()
                                                                                                    method), 168
              sage.geometry.lattice_polytope), 207
                                                                                      dim()
                                                                                                   (sage.geometry.point_collection.PointCollection
\verb|cross_polytope()| (sage.geometry.polyhedron.library.Polytopes|)|
                                                                                                    method), 468
              method), 66
                                                                                      dim() (sage.geometry.polyhedron.base1.Polyhedron_base1
                                                                                                     method), 516
cross_positive_operators_gens()
              (sage.geometry.cone.ConvexRationalPolyhedralCorian() (sage.geometry.polyhedron.combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_pol
              method), 364
                                                                                                     method), 242
cube()
                  (sage.geometry.polyhedron.library.Polytopes dim() (sage.geometry.polyhedron.combinatorial_polyhedron.combinatoria
              method), 67
                                                                                                     method), 279
cuboctahedron() (sage.geometry.polyhedron.library.Polytalpm() (sage.geometry.polyhedron.double_description.Problem
              method), 68
                                                                                                     method), 658
current() (sage.geometry.polyhedron.combinatorial_polyhedronfiacentometry.polyhedronfiace.PolyhedronFace
              method), 291
                                                                                                     method), 150
current() (sage.geometry.polyhedron.combinatorial_polyhedron(), fa(xagetegeton Finyekthatitær igteenior.RelativeInterior
              method), 301
                                                                                                     method), 725
cyclic_polytope() (sage.geometry.polyhedron.library.Palimon_sage.geometry.triangulation.base.PointConfiguration_base
              method), 68
                                                                                                     method), 689
cyclic_sort_vertices_2d()
                                                                        module
                                                                                      dim() (sage.rings.polynomial.groebner fan.PolyhedralCone
              sage.geometry.polyhedron.plot), 142
                                                                                                     method), 491
                                                                                      dim() (sage.rings.polynomial.groebner_fan.PolyhedralFan
D
                                                                                                     method), 492
                                                                                      dimension() (sage.geometry.convex_set.ConvexSet_base
defining_polynomial()
              (sage.geometry.hyperplane_arrangement.arrangement.HyperplaneArrangementElement
                                                                                      dimension() (sage.geometry.hyperplane_arrangement.affine_subspace.Af
              method), 15
degree_on_basis() (sage.geometry.polyhedron.modules.formal_polyhedra\) in dule. Formal Polyhedra Module
                                                                                       dimension() (sage.geometry.hyperplane_arrangement.arrangement.Hyperplane
              method), 158
{\tt deletion()} \ (sage.geometry.hyperplane\_arrangement.arrangement. \textit{HWBe} \textit{Poll} \textit{in} \textit{e} \textit{A} \textit{rrangement} \textit{Element}
                                                                                      dimension() (sage.geometry.hyperplane arrangement.hyperplane.Ambier
                                                                                                     method), 48
```

dimension() (sage.geometry.hyperplane arrangement.hyperplane.Hyperplane

(sage.geometry.lattice\_polytope.NefPartition

Delta()

method), 196

```
method), 49
                                                                                                                                              dual (sage.geometry.polyhedron.combinatorial polyhedron.face iterator.F
dimension() (sage.geometry.point collection.PointCollection
                                                                                                                                                                     attribute), 292
                       method), 468
                                                                                                                                              dual (sage.geometry.polyhedron.combinatorial polyhedron.polyhedron fav
dimension() (sage.geometry.polyhedral_complex.PolyhedralComplexttribute), 283
                        method), 319
                                                                                                                                              dual() (sage.geometry.cone.ConvexRationalPolyhedralCone
dimension() (sage.geometry.polyhedron.base1.Polyhedron base1 method), 367
                       method), 517
                                                                                                                                              dual() (sage.geometry.lattice polytope.LatticePolytopeClass
dimension() (sage.geometry.polyhedron.combinatorial_polyhedron.busthatbymbbhatorialPolyhedron
                        method), 242
                                                                                                                                              dual()
                                                                                                                                                                            (sage.geometry.lattice polytope.NefPartition
dimension() (sage.geometry.polyhedron.combinatorial_polyhedron.wwthidatafi&l_face.CombinatorialFace
                       method), 279
                                                                                                                                              dual()(sage.geometry.polyhedron.combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Combinatorial_polyhedron.base.Comb
dimension() (sage.geometry.toric_lattice.ToricLattice_quotient
                                                                                                                                                                     method), 243
                       method), 346
                                                                                                                                              dual() (sage.geometry.polyhedron.double_description.DoubleDescription.
dimension_of_homogeneity_space()
                                                                                                                                                                     method), 654
                       (sage.rings.polynomial.groebner_fan.GroebnerFadual() (sage.geometry.toric_lattice.ToricLattice_ambient
                       method), 484
                                                                                                                                                                      method), 340
direct_sum() (sage.geometry.polyhedron.base5.Polyhedrodu.bh()5(sage.geometry.toric_lattice.ToricLattice_quotient
                       method), 572
                                                                                                                                                                     method), 347
direct_sum() (sage.geometry.toric lattice.ToricLattice gedwaik() (sage.geometry.toric lattice.ToricLattice sublattice with basis
                       method), 341
                                                                                                                                                                      method), 350
discard_faces() (in module sage.geometry.fan), 448
                                                                                                                                             dual_lattice() (sage.geometry.cone.IntegralRayCollection
discrete_complementarity_set()
                                                                                                                                                                     method), 404
                        (sage.geometry.cone.ConvexRationalPolyhedralCommal_lattice() (sage.geometry.lattice_polytope.LatticePolytopeClass
                       method), 366
                                                                                                                                                                     method), 170
disjoint_union() (sage.geometry.polyhedral_complex.PalyhadamdColmplex(sage.geometry.point_collection.PointCollection
                       method), 319
                                                                                                                                                                     method), 468
distance() (sage.geometry.triangulation.point_configuration.PointConfiguration
                       method), 671
distance_affine() (sage.geometry.triangulation.point_configuration.point_configuration.try.polyhedron.library.Polytopes
                       method), 672
                                                                                                                                                                      static method), 69
distance_between_regions()
                                                                                                                                              edges() (sage.geometry.lattice_polytope.LatticePolytopeClass
                        (sage.geometry.hyperplane_arrangement.arrangement.HyperplanetArrangementElement
                       method), 18
                                                                                                                                              edges() (sage.geometry.polyhedron.combinatorial_polyhedron.base.Comb
distance_enumerator()
                                                                                                                                                                      method), 243
                        (sage.geometry.hyperplane_arrangement.arrangement.HyperplungArrangementElement
                       method), 18
                                                                                                                                                                      (sage.geometry.polyhedron.base_QQ.Polyhedron_QQ
distance_FS() (sage.geometry.triangulation.point_configuration.Pointforfiguration
                       method), 672
                                                                                                                                              ehrhart_polynomial()
{\tt distances()} \ (sage.geometry.lattice\_polytope. LatticePolytopeClass \ \ (sage.geometry.polyhedron.base\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Polyhedron\_ZZ.Po
                       method), 168
                                                                                                                                                                     method), 632
dodecahedron() (sage.geometry.polyhedron.library.Polytopnfhart_quasipolynomial()
                       method), 69
                                                                                                                                                                      (sage.geometry.polyhedron.base_QQ.Polyhedron_QQ
does_backend_handle_base_ring()
                                                                                                       (in
                       sage.geometry.polyhedron.parent), 120
                                                                                                                                              ehrhart_series()(sage.geometry.polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz
domain_dim() (sage.geometry.polyhedron.lattice_euclidean_group_effenent_LatticeEuclideanGroupElement
                        method), 214
                                                                                                                                              Element (sage.geometry.hyperplane_arrangement.arrangement.Hyperplan
domain_fan() (sage.geometry.fan_morphism.FanMorphism
                                                                                                                                                                      attribute), 38
                       method), 453
                                                                                                                                              {\tt Element} (sage.geometry.hyperplane_arrangement.hyperplane.AmbientVector)
DoubleDescriptionPair
                                                                                           (class
                                                                                                                                                                      attribute), 47
                       sage.geometry.polyhedron.double_description),
                                                                                                                                             Element (sage.geometry.linear_expression.LinearExpressionModule
                                                                                                                                                                      attribute), 717
doubly_indexed_whitney_number()
                                                                                                                                             Element (sage.geometry.newton_polygon.ParentNewtonPolygon
                       (sage.geometry.hyperplane_arrangement.arrangement.HyperplaneArrangementElement
                       method), 18
```

Element (sage.geometry.polyhedron.parent.Polyhedra\_field

Element (sage.geometry.polyhedron.parent.Polyhedra normaliz

Element (sage.geometry.polyhedron.parent.Polyhedra\_polymake

attribute), 120

attribute), 120

```
attribute), 120
                                                                                                                                                                                                                                                                                                                                   exclude_points() (sage.geometry.triangulation.point configuration.Point
Element (sage.geometry.polyhedron.parent.Polyhedra QQ cdd
                                                                                                                                                                                                                                                                                                                                                                                        method), 673
                                                                                                                                                                                                                                                                                                                                    exploded_plot()
                                                     attribute), 115
Element (sage.geometry.polyhedron.parent.Polyhedra_QQ_normaliz sage.geometry.polyhedral_complex), 335
                                                                                                                                                                                                                                                                                                                                   extrude_edge() (sage.geometry.ribbon_graph.RibbonGraph
                                                    attribute), 115
{\tt Element} \ (sage.geometry.polyhedron.parent.Polyhedra\_QQ\_ppl
                                                                                                                                                                                                                                                                                                                                                                                         method), 732
                                                     attribute), 115
Element (sage.geometry.polyhedron.parent.Polyhedra RDF-cdd
                                                    attribute), 115
                                                                                                                                                                                                                                                                                                                                    f_vector() (sage.geometry.polyhedron.base3.Polyhedron_base3
Element (sage.geometry.polyhedron.parent.Polyhedra_ZZ_normaliz method), 530
                                                     attribute), 115
                                                                                                                                                                                                                                                                                                                                    f_vector() (sage.geometry.polyhedron.combinatorial_polyhedron.base.C
Element (sage.geometry.polyhedron.parent.Polyhedra_ZZ_ppl
                                                                                                                                                                                                                                                                                                                                                                                         method), 244
                                                     attribute), 115
                                                                                                                                                                                                                                                                                                                                    f_vector() (sage.rings.polynomial.groebner_fan.PolyhedralFan
Element (sage.geometry.toric lattice.ToricLattice ambient
                                                                                                                                                                                                                                                                                                                                                                                         method), 493
                                                     attribute), 340
                                                                                                                                                                                                                                                                                                                                    face_by_face_lattice_index()
Element (sage.geometry.toric_lattice.ToricLattice_generic
                                                                                                                                                                                                                                                                                                                                                                                         (sage.geometry.polyhedron.combinatorial polyhedron.base.Comb
                                                     attribute), 341
                                                                                                                                                                                                                                                                                                                                                                                         method), 245
{\tt Element} \ (sage.geometry.toric\_lattice\_quotient\ {\tt face\_codimension()}\ (sage.geometry.triangulation.point\_configuration.Particle.) \ (sage.geometry.triangulation.point\_configuration.point\_configuration.point\_configuration.point\_configuration.point\_configuration.point\_configuration.point\_configuration.point\_configuration.point\_configuration.point\_configuration.po
                                                      attribute), 346
                                                                                                                                                                                                                                                                                                                                                                                         method), 673
\textbf{Element} (sage. geometry. triangulation. point\_configuration. \textbf{PaintC}\_\textbf{Finfagr} (\textit{Wige}. geometry. polyhedron. base. Polyhedron\_base (\textit{Polyhedron}\_base))) and triangulation (\textit{Polyhedron}\_base)) an
                                                     attribute), 669
                                                                                                                                                                                                                                                                                                                                                                                         method), 613
\verb|embed()| (sage.geometry.cone.ConvexRationalPolyhedralCofface\_generator()| (sage.geometry.polyhedron.base 3.Polyhedron\_base 3.Polyhedro
                                                     method), 368
                                                                                                                                                                                                                                                                                                                                                                                         method), 531
embed()
                                                                               (sage.geometry.fan.RationalPolyhedralFan
                                                                                                                                                                                                                                                                                                                                  face_generator() (sage.geometry.polyhedron.combinatorial_polyhedron.
                                                     method), 436
                                                                                                                                                                                                                                                                                                                                                                                         method), 246
embed_in_reflexive_polytope()
                                                                                                                                                                                                                                                                                                                                    face_interior() (sage.geometry.triangulation.point_configuration.Point
                                                     (sage.geometry.polyhedron.ppl_lattice_polytope.LatticePolytopen_QP_Lattice_polytope.LatticePolytopen_QP_Lattice_polytopen_lattice_polytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_latticePolytopen_la
                                                    method), 226
                                                                                                                                                                                                                                                                                                                                   face_iter() (sage.geometry.polyhedron.combinatorial_polyhedron.base.
empty() (sage.geometry.polyhedron.parent.Polyhedra_base
                                                                                                                                                                                                                                                                                                                                                                                         method), 248
                                                     method), 118
                                                                                                                                                                                                                                                                                                                                   face_lattice() (sage.geometry.cone.ConvexRationalPolyhedralCone
enumerate_simplices()
                                                                                                                                                                                                                                                                                                                                                                                         method), 369
                                                     (sage.geometry.triangulation.element.Triangulatio \verb|Pace_lattice()| (sage.geometry.lattice\_polytope.LatticePolytopeClass)| (sage.geometry.triangulation.element.TriangulationPace_lattice())| (sage.geometry.triangulationPace_lattice())| (sage.geo
                                                    method), 695
                                                                                                                                                                                                                                                                                                                                                                                         method), 170
\texttt{Equation} (\textit{class in sage.geometry.polyhedron.representation}) \\ \texttt{ace\_lattice()} (\textit{sage.geometry.polyhedron.base4.Polyhedron\_base4}) \\ \texttt{ace\_lattice()} (\textit{sage.geometry.polyhedron.base4}) \\ \texttt{ac
                                                      120
                                                                                                                                                                                                                                                                                                                                                                                         method), 557
equation_generator()
                                                                                                                                                                                                                                                                                                                                   face_lattice() (sage.geometry.polyhedron.combinatorial polyhedron.be
                                                     (sage.geometry.polyhedron.base0.Polyhedron base0
                                                                                                                                                                                                                                                                                                                                                                                         method), 250
                                                    method), 503
                                                                                                                                                                                                                                                                                                                                   face_poset() (sage.geometry.polyhedral_complex.PolyhedralComplex
equations()(sage.geometry.polyhedron.base0.Polyhedron_base0
                                                                                                                                                                                                                                                                                                                                                                                      method), 319
                                                    method), 503
                                                                                                                                                                                                                                                                                                                                     {\tt face\_product()} (sage.geometry.hyperplane\_arrangement.arrangement.H
equations_list() (sage.geometry.polyhedron.base0.Polyhedron_base0hod), 20
                                                     method), 504
                                                                                                                                                                                                                                                                                                                                   face_semigroup_algebra()
essentialization() (sage.geometry.hyperplane_arrangement.arrangement.hyperplane_arrangement.hyperplane
                                                     method), 19
                                                                                                                                                                                                                                                                                                                                                                                         method), 20
 {\tt eval()} \ (sage. geometry. polyhedron. representation. Hreprese \verb| {\tt Rtdie} \verb| {\tt or} \verb| {\tt sage}. geometry. polyhedron. base 5. Polyhedron\_base 5. Polyhedron\_
                                                     method), 122
                                                                                                                                                                                                                                                                                                                                                                                          method), 572
 \textbf{evaluate()} \ (\textit{sage.geometry.linear\_expression.LinearExpression\_truncation()} \ (\textit{sage.geometry.polyhedron.base5.Polyhedron\_base5}) \ (\textit{sage.geometry.linear\_expression.LinearExpression\_truncation()} \ (\textit{sage.geometry.polyhedron.base5.Polyhedron\_base5}) \ (\textit{sage.geometry.linear\_expression.LinearExpression\_truncation()} \ (\textit{sage.geometry.linear\_expression.LinearExpression\_truncation()} \ (\textit{sage.geometry.polyhedron.base5.Polyhedron\_base5}) \ (\textit{sage.geometry.linear\_expression.LinearExpression\_truncation()} \ (\textit{sage.geometry.polyhedron.base5.Polyhedron\_base5}) \ (\textit{sage.geometry.linear\_expression.LinearExpression\_truncation()} \ (\textit{sage.geometry.polyhedron.base5.Polyhedron\_base5}) \ (\textit{sage.geometry.polyhedron.base5.Polyhedron\_base5}) \ (\textit{sage.geometry.polyhedron.base5.Polyhedron\_base5}) \ (\textit{sage.geometry.polyhedron.base5.Polyhedron\_base5}) \ (\textit{sage.geometry.linear\_expression.base6}) \ (\textit{sage.ge
                                                     method), 716
                                                                                                                                                                                                                                                                                                                                                                                         method), 573
 evaluated_on() (sage.geometry.polyhedron.representation.Line
```

method), 127

method), 129

method), 130

evaluated\_on() (sage.geometry.polyhedron.representation.Ray

evaluated\_on() (sage.geometry.polyhedron.representation.Vertex

```
face_vector() (sage.geometry.hyperplane_arrangement.arrangement.dt.graphetry.hyperplane_arrangement.arrangement.dt.graphetry.hyperplane_arrangement.arrangement.dt.graphetry.hyperplane_arrangement.arrangement.dt.graphetry.hyperplane_arrangement.arrangement.dt.graphetry.hyperplane_arrangement.arrangement.dt.graphetry.hyperplane_arrangement.arrangement.dt.graphetry.hyperplane_arrangement.arrangement.dt.graphetry.hyperplane_arrangement.arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.hyperplane_arrangement.dt.graphetry.h
                       method), 22
FaceFan() (in module sage.geometry.fan), 421
                                                                                                                                          factor() (sage.geometry.fan_morphism.FanMorphism
FaceIterator
                                                                           (class
                                                                                                                                in
                                                                                                                                                                 method), 453
                      sage.geometry.polyhedron.combinatorial_polyhedFonf@ckinitemedate,sage.geometry.fan), 422
                                                                                                                                          fan() (sage.geometry.triangulation.element.Triangulation
FaceIterator_base
                                                                                                                                                                 method), 696
                                                                                   (class
                       sage.geometry.polyhedron.combinatorial_polyhedFam.Lik()_(tirrmod), tle sage.geometry.fan), 426
                       291
                                                                                                                                          fan_2d_cyclically_ordered_rays() (in
                                                                                                                                                                                                                                                            module
                                                                                                                                                                 sage.geometry.fan_isomorphism), 749
FaceIterator_geom
                                                                                   (class
                       sage.geometry.polyhedron.combinatorial_polyhedfam_face_eiehedbon_form()
                                                                                                                                                                                                                                (in
                                                                                                                                                                                                                                                             module
                                                                                                                                                                 sage.geometry.fan_isomorphism), 749
faces() (sage.geometry.cone.ConvexRationalPolyhedralCofacn_2d_echelon_forms()
                                                                                                                                                                                                                                  (in
                                                                                                                                                                                                                                                             module
                                                                                                                                                                 sage.geometry.fan_isomorphism), 750
                       method), 371
faces() (sage.geometry.lattice_polytope.LatticePolytopeClan_isomorphic_necessary_conditions() (in mod-
                       method), 172
                                                                                                                                                                 ule sage.geometry.fan_isomorphism), 750
faces() (sage.geometry.polyhedron.base3.Polyhedron_base3n_isomorphism_generator()
                                                                                                                                                                                                                                                             module
                                                                                                                                                                                                                                         (in
                       method), 536
                                                                                                                                                                 sage.geometry.fan_isomorphism), 751
facet_adjacency_matrix()
                                                                                                                                          FanMorphism (class in sage.geometry.fan_morphism),
                       (sage.geometry.polyhedron.base3.Polyhedron_base3
                      method), 537
                                                                                                                                          FanNotIsomorphicError, 749
facet_adjacency_matrix()
                                                                                                                                          farthest_point() (sage.geometry.triangulation.point_configuration.Poir
                       (sage.geometry.polyhedron.combinatorial_polyhedron.base.foethbit)afolyhedron
                      method), 250
                                                                                                                                          felsner_matrix()(sage.geometry.pseudolines.PseudolineArrangement
facet_constant() (sage.geometry.lattice_polytope.LatticePolytope@lathsod), 743
                       method), 173
                                                                                                                                          fibration_generator()
facet\_constants() (sage.geometry.lattice\_polytope.LatticePolytop \\ \& liggs.geometry.polyhedron.base\_ZZ.Polyhedron\_ZZ.polyhedron.base\_ZZ.Polyhedron\_ZZ.polyhedron.base\_ZZ.Polyhedron\_ZZ.polyhedron.base\_ZZ.Polyhedron\_ZZ.polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Polyhedron.base\_ZZ.Poly
                                                                                                                                                                 method), 635
                       method), 174
facet_graph() (sage.geometry.polyhedron.combinatorial fixtyrhedron.lyssasCarubit@torialPolyhedron
                                                                                                                                                                 (sage.geometry.polyhedron.ppl_lattice_polytope.LatticePolytope_
                       method), 251
facet_normal() (sage.geometry.lattice_polytope.LatticePolytopeClassethod), 227
                       method), 174
                                                                                                                                          find_isomorphism()
                                                                                                                                                                                                                            (in
                                                                                                                                                                                                                                                             module
facet_normals() (sage.geometry.cone.ConvexRationalPolyhedralConge.geometry.fan_isomorphism), 752
                                                                                                                                          find_isomorphism() (sage.geometry.polyhedron.ppl_lattice_polygon.Lat
                       method), 372
facet_normals() (sage.geometry.lattice_polytope.LatticePolytopeClasshod), 217
                                                                                                                                          find\_translation() (sage.geometry.polyhedron.base_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Polyhedron_ZZ.Po
                      method), 175
facet_of() (sage.geometry.cone.ConvexRationalPolyhedralCone
                                                                                                                                                                method), 635
                       method), 374
                                                                                                                                          first_coordinate_plane()
facet_of() (sage.geometry.lattice_polytope.LatticePolytopeClass (sage.geometry.polyhedron.double_description.DoubleDescriptio
                       method), 176
                                                                                                                                                                 method), 655
facets() (sage.geometry.cone.ConvexRationalPolyhedralCFineed_subpolytope()
                       method), 374
                                                                                                                                                                 (sage.geometry.polyhedron.base_QQ.Polyhedron_QQ
{\tt facets()} \ (sage.geometry.lattice\_polytope.LatticePolytopeClass
                                                                                                                                                                 method), 627
                                                                                                                                          fixed_subpolytopes()
                       method), 176
facets() (sage.geometry.polyhedron.base3.Polyhedron_base3
                                                                                                                                                                 (sage.geometry.polyhedron.base_QQ.Polyhedron_QQ
                                                                                                                                                                 method), 629
                       method), 538
facets() (sage.geometry.polyhedron.combinatorial_polyhedron<u>biyatsarjælRobrhettron</u>olyhedron.base4.Polyhedron_base4
                                                                                                                                                                 method), 558
                       method), 251
method), 252
                       method), 491
facets_tuple_to_bit_rep_of_facets() (in module flow_polytope() (sage.geometry.polyhedron.library.Polytopes
                      sage.geometry.polyhedron.combinatorial_polyhedron.conversiaoics)method), 70
                                                                                                                                          FormalPolyhedraModule
                                                                                                                                                                                                                                   (class
                                                                                                                                                                                                                                                                          in
                                                                                                                                                                 sage.geometry.polyhedron.modules.formal_polyhedra_module),
facets_tuple_to_bit_rep_of_Vrep() (in module
```

```
157
                                                                                                                                                                              graph() (sage.geometry.polyhedron.combinatorial_polyhedron.base.Comb
                                                                                                                                                                                                            method), 254
G
                                                                                                                                                                              graphical() (sage.geometry.hyperplane_arrangement.library.Hyperplane
G_semiorder() (sage.geometry.hyperplane_arrangement.library.HypmethadeAA+angementLibrary
                             method), 41
                                                                                                                                                                              great_rhombicuboctahedron()
G_Shi() (sage.geometry.hyperplane arrangement.library.HyperplaneAargangementhipholyhedron.library.Polytopes
                                                                                                                                                                                                            method), 77
                             method), 40
{\tt Gale\_transform()} \ ({\it sage.geometry.fan.RationalPolyhedra} \ {\tt Weatest\_common\_subface\_of\_Hrep()}
                                                                                                                                                                                                            (sage.geometry.polyhedron.base3.Polyhedron_base3
                             method), 428
gale_transform() (sage.geometry.polyhedron.base6.Polyhedron_base6hod), 539
                                                                                                                                                                               groebner_cone() (sage.rings.polynomial.groebner_fan.ReducedGroebner
                             method), 596
Gale_transform() (sage.geometry.triangulation.point_configurationmetint) of the first of the configuration of the 
                                                                                                                                                                               GroebnerFan
                                                                                                                                                                                                                                                                            (class
                                                                                                                                                                                                                                                                                                                                                 in
                            method), 669
gale_transform_to_polytope()
                                                                                                                                                  module
                                                                                                                                                                                                            sage.rings.polynomial.groebner_fan), 483
                                                                                                                          (in
                             sage.geometry.polyhedron.library), 101
gale_transform_to_primal()
                                                                                                                                                  module
                             sage.geometry.polyhedron.library), 103
                                                                                                                                                                              h_star_vector() (sage.geometry.polyhedron.base2.Polyhedron_base2
gen() (sage.geometry.hyperplane_arrangement.arrangement.Hyperplane(Assign)gements
                             method), 39
                                                                                                                                                                              has_good_reduction()
gen() (sage.geometry.linear_expression.LinearExpressionModule
                                                                                                                                                                                                           (sage.geometry.hyperplane_arrangement.arrangement.Hyperplane
                            method), 718
                                                                                                                                                                                                            method), 22
generalized_permutahedron()
                                                                                                                                                                               has_IP_property() (sage.geometry.polyhedron.base_ZZ.Polyhedron_ZZ
                             (sage.geometry.polyhedron.library.Polytopes
                                                                                                                                                                                                            method), 635
                            method), 73
                                                                                                                                                                              has_IP_property() (sage.geometry.polyhedron.ppl_lattice_polytope.Latt
generating_cone() (sage.geometry.fan.RationalPolyhedralFan
                                                                                                                                                                                                            method), 227
                             method), 437
                                                                                                                                                                              hasse_diagram() (sage.geometry.polyhedron.base4.Polyhedron_base4
generating_cones() (sage.geometry.fan.RationalPolyhedralFan
                                                                                                                                                                                                           method), 561
                            method), 438
                                                                                                                                                                              hasse_diagram() (sage.geometry.polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.comb
gens () (sage.geometry.hyperplane_arrangement.arrangement.HyperplaneArrangements
                             method), 39
                                                                                                                                                                               Hilbert_basis() (sage.geometry.cone.ConvexRationalPolyhedralCone
gens() (sage.geometry.linear_expression.LinearExpressionModule method), 358
                            method), 718
                                                                                                                                                                              Hilbert_coefficients()
gens() (sage.geometry.toric_lattice.ToricLattice_quotient
                                                                                                                                                                                                            (sage.geometry.cone.ConvexRationalPolyhedralCone
                             method), 347
                                                                                                                                                                                                            method), 360
genus()
                                        (sage.geometry.ribbon_graph.RibbonGraph
                                                                                                                                                                             hilbert_series() (sage.geometry.polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.Polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normaliz.polyhedron.backend_normali
                             method), 733
                                                                                                                                                                                                            method), 642
get_face() (sage.geometry.polyhedron.combinatorial_polyhedron.fage_gettinetPolyhedron.bluedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.combinatorial_polyhedron.c
                             method), 283
                                                                                                                                                                                                            method), 199
get_integral_point()
                                                                                                                                                                              homogeneity_space()
                             (sage.geometry.polyhedron.base2.Polyhedron base2
                                                                                                                                                                                                            (sage.rings.polynomial.groebner_fan.GroebnerFan
                            method), 521
                                                                                                                                                                                                            method), 484
gfan() (sage.rings.polynomial.groebner_fan.GroebnerFan homogeneous_vector()
                             method), 484
                                                                                                                                                                                                            (sage.geometry.polyhedron.representation.Line
gkz_phi() (sage.geometry.triangulation.element.Triangulation
                                                                                                                                                                                                            method), 127
                             method), 697
                                                                                                                                                                              homogeneous_vector()
Gosset_3_21() (sage.geometry.polyhedron.library.Polytopes
                                                                                                                                                                                                            (sage.geometry.polyhedron.representation.Ray
                             method), 63
                                                                                                                                                                                                            method), 129
grand\_antiprism() \ (\textit{sage.geometry.polyhedron.library.Palphage} neous\_vector()
                             method), 76
                                                                                                                                                                                                            (sage.geometry.polyhedron.representation.Vertex
graph() (sage.geometry.polyhedral_complex.PolyhedralComplex
                                                                                                                                                                                                            method), 130
                             method), 320
                                                                                                                                                                              \verb|homology_basis()| (sage.geometry.ribbon\_graph.RibbonGraph|
graph() (sage.geometry.polyhedron.base4.Polyhedron_base4
                                                                                                                                                                                                            method), 734
                             method), 560
                                                                                                                                                                              Hrep2Vrep(class in sage.geometry.polyhedron.double_description_inhomo
                                                                                                                                                                                                            660
```

```
Hrep_generator() (sage.geometry.polyhedron.base0.Polyhedroh() (base0e.rings.polynomial.groebner_fan.ReducedGroebnerBasis
             method), 497
                                                                                                 method), 495
Hrepresentation
                                                                             in ideal_to_gfan_format()
                                                                                                 sage.rings.polynomial.groebner_fan), 496
             sage.geometry.polyhedron.representation),
                                                                                   identity() (sage.geometry.polyhedron.plot.Projection
Hrepresentation() (sage.geometry.polyhedron.backend ppl.Polyhedretmodp)pl135
             method), 651
                                                                                   ignore_subfaces() (sage.geometry.polyhedron.combinatorial polyhedro
Hrepresentation() (sage.geometry.polyhedron.base0.Polyhedron_basetAbd), 292
             method), 498
                                                                                   ignore_supfaces() (sage.geometry.polyhedron.combinatorial_polyhedro
Hrepresentation() (sage.geometry.polyhedron.combinatorial_polyhedhod.haseSCombinatorialPolyhedron
             method), 239
                                                                                   image_cone() (sage.geometry.fan_morphism.FanMorphism
Hrepresentation_space()
                                                                                                 method), 455
             (sage.geometry.polyhedron.base1.Polyhedron\_basixilcidence\_matrix() (sage.geometry.cone.ConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationalPolyhedralConvexRationa
             method), 513
                                                                                                 method), 374
Hrepresentation_space()
                                                                                   incidence_matrix() (sage.geometry.lattice_polytope.LatticePolytopeCla
              (sage.geometry.polyhedron.parent.Polyhedra_base
                                                                                                 method), 177
             method), 116
                                                                                   incidence_matrix() (sage.geometry.polyhedron.base3.Polyhedron_base
Hrepresentation_str()
                                                                                                 method), 540
             (sage.geometry.polyhedron.base0.Polyhedron_baskncidence_matrix() (sage.geometry.polyhedron.combinatorial_polyhedron
             method), 498
                                                                                                 method), 255
Hstar\_function() (sage.geometry.polyhedron.base_QQ.PadyhedroneQQQtrix_to_bit_rep_of_facets()
                                                                                                                                                               (in
             method), 620
                                                                                                 module sage.geometry.polyhedron.combinatorial_polyhedron.com
hypercube() (sage.geometry.polyhedron.library.Polytopes
             method), 77
                                                                                   incidence_matrix_to_bit_rep_of_Vrep() (in mod-
Hyperplane (class in sage.geometry.hyperplane_arrangement.hyperpldms)uge.geometry.polyhedron.combinatorial_polyhedron.convers
hyperplane_arrangement()
                                                                                   incident() (sage.geometry.polyhedron.representation.Hrepresentation
             (sage.geometry.polyhedron.base.Polyhedron_base
                                                                                                 method), 122
             method), 614
                                                                                   incident() (sage.geometry.polyhedron.representation.Vrepresentation
HyperplaneArrangementElement
                                                            (class
                                                                             in
                                                                                                 method), 132
             sage.geometry.hyperplane_arrangement.arrangemiencllude_points() (sage.geometry.toric_plotter.ToricPlotter
                                                                                                 method), 475
HyperplaneArrangementLibrary
                                                                                                     (sage.geometry.fan_morphism.FanMorphism
                                                            (class
                                                                             in index()
             sage.geometry.hyperplane_arrangement.library),
                                                                                                 method), 456
                                                                                   index() (sage.geometry.lattice_polytope.LatticePolytopeClass
HyperplaneArrangements
                                                                                                 method), 177
                                                      (class
                                                                             in
             sage.geometry.hyperplane_arrangement.arrangemixmd);x() (sage.geometry.point_collection.PointCollection
                                                                                                 method), 468
hyperplanes() (sage.geometry.hyperplane_arrangement.cirredege()e(stukky.geoplanesApwhylgadmontEdgenesentation.PolyhedronRepresentation
             method), 22
                                                                                                 method), 128
hypersimplex() (sage.geometry.polyhedron.library.Polytopredex()
                                                                                                           (sage.geometry.triangulation.base.Point
             method), 78
                                                                                                 method), 686
                                                                                   inequalities() (sage.geometry.polyhedron.base0.Polyhedron_base0
                                                                                                 method), 504
\verb|icosahedron(|)| (sage.geometry.polyhedron.library.Polytopinequalities_list(|)|) |
                                                                                                 (sage.geometry.polyhedron.base0.Polyhedron_base0
             method), 79
                                                                                                 method), 504
icosidodecahedron()
                                                                                   Inequality (class in sage.geometry.polyhedron.representation),
              (sage.geometry.polyhedron.library.Polytopes
                                                                                                 124
             method), 80
                                                                                   inequality_generator()
icosidodecahedron_V2()
                                                                                                 (sage.geometry.polyhedron.base0.Polyhedron_base0
             (sage.geometry.polyhedron.library.Polytopes
                                                                                                 method), 505
             method), 80
(class
                                                                                                                                                                in
                                                                                                 sage.geometry.integral_points), 758
             method), 484
```

```
Inequality_int
                                             (class
                                                                          in interior() (sage.geometry.relative_interior.RelativeInterior
             sage.geometry.integral_points), 758
                                                                                              method), 725
                                                   (class
                                                                                interior_contains()
InequalityCollection
                                                                                              (sage.geometry.cone.ConvexRationalPolyhedralCone
             sage.geometry.integral_points), 755
initial_form_systems()
                                                                                              method), 375
             (sage.rings.polynomial.groebner fan.TropicalPrevinterior_contains()
             method), 496
                                                                                              (sage.geometry.polyhedron.base1.Polyhedron base1
initial_forms() (sage.rings.polynomial.groebner_fan.InitialForm method), 518
             method), 490
                                                                                interior_contains()
initial_pair() (sage.geometry.polyhedron.double_description.Protage.geometry.polyhedron.representation.Equation
             method), 658
                                                                                              method), 121
InitialForm
                                                                          in interior_contains()
                                           (class
             sage.rings.polynomial.groebner_fan), 489
                                                                                              (sage.geometry.polyhedron.representation.Inequality
inner_product_matrix()
                                                                                              method), 124
             (sage.geometry.polyhedron.double_description.Double@bissoipfiaoeRai()) (sage.geometry.triangulation.element.Triangulation
             method), 655
                                                                                              method), 697
int_to_simplex() (sage.geometry.triangulation.base.PointCoefigurappointasindices()
             method), 689
                                                                                              (sage.geometry.lattice_polytope.LatticePolytopeClass
integral_hull() (sage.geometry.polyhedron.backend_normaliz.Polyhedlod), hosmaliz
             method), 647
                                                                                interior_points() (sage.geometry.lattice_polytope.LatticePolytopeClas
integral_length() (in module sage.geometry.cone),
                                                                                              method), 179
                                                                                internal_ray() (sage.rings.polynomial.groebner_fan.InitialForm
integral_points() (sage.geometry.polyhedron.backend_normaliz.Polyhedron49QQ_normaliz
             method), 643
                                                                                intersection() (sage.geometry.cone.ConvexRationalPolyhedralCone
integral_points() (sage.geometry.polyhedron.base2.Polyhedron_baset2od), 376
             method), 523
                                                                                intersection() (sage.geometry.convex_set.ConvexSet_base
integral_points() (sage.geometry.polyhedron.ppl_lattice_polytopenkthtidePolytope_PPL_class
             method), 227
                                                                                intersection() (sage.geometry.hyperplane_arrangement.affine_subspace
integral_points_count()
                                                                                              method), 54
             (sage.geometry.polyhedron.base2.Polyhedron_base2tersection() (sage.geometry.hyperplane_arrangement.hyperplane.Hy,
             method), 524
                                                                                              method), 49
integral_points_count()
                                                                                intersection() (sage.geometry.polyhedron.base5.Polyhedron_base5
             (sage.geometry.polyhedron.base_QQ.Polyhedron_QQ
                                                                                              method), 575
                                                                                intersection() (sage.geometry.toric_lattice_ToricLattice_generic
             method), 630
integral_points_generators()
                                                                                              method), 342
             (sage.geometry.polyhedron.backend_normaliz.Polyhtderose_QQonoposkt()
             method), 645
                                                                                              (sage.geometry.hyperplane arrangement.arrangement.Hyperplane
integral_points_not_interior_to_facets()
                                                                                              method), 23
             (sage.geometry.polyhedron.ppl_lattice_polytope.LivstiæeHilwofte (RRe.gelawsetry.triangulation.base.PointConfiguration_base
             method), 228
                                                                                              method), 690
IntegralRayCollection
                                                    (class
                                                                          in is_bipyramid()(sage.geometry.polyhedron.base3.Polyhedron base3
             sage.geometry.cone), 401
                                                                                              method), 542
method), 604
                                                                                              method), 256
interactive() (sage.rings.polynomial.groebner_fan.Groebnebfaational() (sage.geometry.fan_morphism.FanMorphism
             method), 485
                                                                                              method), 457
interactive() (sage.rings.polynomial.groebner_fan.Reduired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uired@uiredwuired@uiredwuiredwuiredwuiredwuiredwuiredwuiredwuiredwuiredwuiredwuiredwuiredwuiredwuiredwuiredwuiredwuiredwuiredwuiredwuiredwuiredwuiredwuiredwuiredwuiredwuiredwuiredwuiredwuiredwuiredwu
             method), 495
                                                                                              method), 229
interior() (sage.geometry.cone.ConvexRationalPolyhedralsCommodle() (sage.geometry.fan_morphism.FanMorphism
             method), 375
                                                                                              method), 457
interior() (sage.geometry.convex_set.ConvexSet_base is_cell() (sage.geometry.polyhedral_complex.PolyhedralComplex
                                                                                              method), 321
             method), 707
interior() (sage.geometry.polyhedron.base1.Polyhedron_basehntral() (sage.geometry.hyperplane_arrangement.arrangement.Hyp
```

method), 517

method), 24

```
is_closed() (sage.geometry.convex_set.ConvexSet_base is_face_of() (sage.geometry.cone.ConvexRationalPolyhedralCone
         method), 707
                                                                method), 378
is_closed() (sage.geometry.convex_set.ConvexSet_closedis_facet_defining_inequality()
                                                                (sage.geometry.polyhedron.representation.Inequality
         method), 710
is_closed() (sage.geometry.convex_set.ConvexSet_open
                                                                method), 125
         method), 712
                                                       is_Fan() (in module sage.geometry.fan), 448
is_closed() (sage.geometry.relative interior.RelativeInterior_fibration() (sage.geometry.fan morphism.FanMorphism
         method), 725
                                                                 method), 459
is_combinatorially_isomorphic()
                                                       is_finite() (sage.geometry.convex_set.ConvexSet_base
         (sage.geometry.polyhedron.base 4. Polyhedron\_base 4
                                                                method), 708
                                                       is_formal() (sage.geometry.hyperplane_arrangement.arrangement.Hyperplane
         method), 562
is_compact() (sage.geometry.cone.ConvexRationalPolyhedralCone method), 25
                                                       is_free() (sage.geometry.hyperplane_arrangement.arrangement.Hyperpl
         method), 377
is_compact() (sage.geometry.convex_set.ConvexSet_base
                                                                method), 25
         method), 707
                                                       is_full_dimensional()
is_compact() (sage.geometry.convex_set.ConvexSet_compact
                                                                (sage.geometry.cone.Convex Rational Polyhedral Cone
         method), 711
                                                                method), 378
is_compact() (sage.geometry.polyhedral_complex.Polyhedral_tolhlpldimensional()
                                                                (sage.geometry.convex_set.ConvexSet_base
         method), 321
is_compact() (sage.geometry.polyhedron.base0.Polyhedron_base0 method), 708
         method), 505
                                                       is_full_dimensional()
is_compact() (sage.geometry.polyhedron.combinatorial_polyhedron.dugæ.geombtnyapolyhlPdryhledomplex.PolyhedralComplex
                                                                method), 323
         method), 257
is_compact() (sage.geometry.polyhedron.face.PolyhedronFscefull_dimensional()
         method), 150
                                                                (sage.geometry.polyhedron.ppl_lattice_polytope.LatticePolytope_
\verb|is_complete()| (sage. geometry. fan. Rational Polyhedral Fan
                                                                method), 229
         method), 438
                                                       \verb|is_full_space()| (sage.geometry.cone.Convex Rational Polyhedral Cone)| \\
is_Cone() (in module sage.geometry.cone), 408
                                                                method), 379
is_connected() (sage.geometry.polyhedral_complex.Polyhedral_complex.polyhedron.representation.Hrepresentation
         method), 321
                                                                method), 123
is_convex() (sage.geometry.polyhedral_complex.PolyhedrixtsCimmplexable() (sage.geometry.polyhedral_complex.PolyhedralComplex
         method), 322
                                                                method), 323
is_dominant() (sage.geometry.fan_morphism.FanMorphisms_immutable() (sage.geometry.polyhedron.base0.Polyhedron_base0
                                                                 method), 506
         method), 459
is_effective() (sage.geometry.polyhedron.base_QQ.PolithedroniQQht() (sage.geometry.polyhedron.representation.Hrepresentation
         method), 631
                                                                method), 123
is_empty() (sage.geometry.cone.ConvexRationalPolyhedrals_inacident() (sage.geometry.polyhedron.representation.Vrepresentation
         method), 377
                                                                method), 132
is_empty() (sage.geometry.convex_set.ConvexSet_base is_inequality() (sage.geometry.polyhedron.representation.Hrepresentation.
         method), 708
                                                                method), 123
is_empty() (sage.geometry.polyhedron.base1.Polyhedron_basahequality() (sage.geometry.polyhedron.representation.Inequality
         method), 518
                                                                method), 126
is_equation() (sage.geometry.polyhedron.representation.Esuiminective() (sage.geometry.fan_morphism.FanMorphism
                                                                method), 460
         method), 121
is_equation() (sage.geometry.polyhedron.representation.\( \frac{H}{B} \) e in secnida ed() (sage.geometry.polyhedron.base.\( Polyhedron \) base
         method), 123
                                                                method), 614
is_equivalent() (sage.geometry.cone.ConvexRationalPohsheilntl@grad() (sage.geometry.polyhedron.representation.Vertex
         method), 377
                                                                method), 131
is\_equivalent() (sage.geometry.fan.RationalPolyhedralFass\_isomorphic() (sage.geometry.cone.ConvexRationalPolyhedralCone
         method), 438
                                                                method), 379
is_essential() (sage.geometry.hyperplane_arrangementinsrainspanoaphHyperplane_derangemy.funtReniontalPolyhedralFan
         method), 25
                                                                method), 439
is_extremal() (sage.geometry.polyhedron.double_descriptioni.DombtqDisxCiptiongPagarometry.polyhedron.ppl_lattice_polygon.Lattice
```

method), 217

method), 656

```
is_lattice_polytope()
                                                                                   is_proper() (sage.geometry.cone.ConvexRationalPolyhedralCone
             (sage.geometry.polyhedron.base2.Polyhedron base2
                                                                                                 method), 380
             method), 525
                                                                                   is_pure() (sage.geometry.polyhedral complex.PolyhedralComplex
is_lattice_polytope()
                                                                                                 method), 325
              (sage.geometry.polyhedron.base_ZZ.Polyhedron_XZ_pyramid() (sage.geometry.polyhedron.base3.Polyhedron_base3
             method), 636
                                                                                                 method), 545
is_LatticePolytope()
                                                   (in
                                                                     module is_pyramid() (sage.geometry.polyhedron.combinatorial polyhedron.base
             sage.geometry.lattice_polytope), 208
                                                                                                 method), 259
is_lawrence_polytope()
                                                                                   is_ray() (sage.geometry.polyhedron.representation.Ray
             (sage.geometry.polyhedron.base3.Polyhedron_base3
                                                                                                 method), 129
                                                                                   is_ray() (sage.geometry.polyhedron.representation.Vrepresentation
             method), 542
is_lawrence_polytope()
                                                                                                 method), 133
             (sage.geometry.polyhedron.combinatorial_polyhedrsyrbase@wwb())drangalRalyhadydattice_polytope.LatticePolytopeClass
             method), 257
                                                                                                 method), 179
is_line() (sage.geometry.polyhedron.representation.Line is_reflexive() (sage.geometry.polyhedron.base_ZZ.Polyhedron_ZZ
              method), 127
                                                                                                 method), 636
is_line() (sage.geometry.polyhedron.representation.Vrepriesentellautrively_open()
                                                                                                 (sage.geometry.cone.Convex Rational Polyhedral Cone
             method), 132
is_linear() (sage.geometry.hyperplane_arrangement.arrangement.hkefterd)an&ArrangementElement
                                                                                   is_relatively_open()
             method), 26
is_maximal_cell() (sage.geometry.polyhedral_complex.Polyhedral_Gomephewmetry.convex_set.ConvexSet_base
             method), 324
                                                                                                 method), 709
is_minkowski_summand()
                                                                                   is_relatively_open()
              (sage.geometry.polyhedron.base.Polyhedron base
                                                                                                 (sage.geometry.convex set.ConvexSet compact
             method), 615
                                                                                                 method), 711
is_mutable()(sage.geometry.polyhedral_complex.Polyhedrsul@elratiavely_open()
             method), 324
                                                                                                 (sage.geometry.convex_set.ConvexSet_relatively_open
is_mutable() (sage.geometry.polyhedron.base0.Polyhedron_base0 method), 712
                                                                                   is_relatively_open()
             method), 506
is_NefPartition()
                                                                     module
                                                                                                 (sage.geometry.polyhedron.base1.Polyhedron_base1
                                                (in
              sage.geometry.lattice_polytope), 208
                                                                                                 method), 519
is_neighborly()(sage.geometry.polyhedron.base3.Polyhadsrone_basta3vely_open()
                                                                                                 (sage.geometry.polyhedron.face.PolyhedronFace
             method), 543
is_neighborly() (sage.geometry.polyhedron.combinatorial_polyhedreth.bdty.e160mbinatorialPolyhedron
                                                                                   is_self_dual() (sage.geometry.polyhedron.base4.Polyhedron_base4
             method), 258
                                                                                                 method), 564
is_open() (sage.geometry.convex_set.ConvexSet_base
             method), 708
                                                                                   is_separating_hyperplane()
is_open() (sage.geometry.convex_set.ConvexSet_closed
                                                                                                 (sage.geometry.hyperplane_arrangement.arrangement.Hyperplane
             method), 710
                                                                                                 method), 27
is_open() (sage.geometry.convex_set.Convex_Set_open is_simple() (sage.geometry.polyhedron.base3.Polyhedron_base3
                                                                                                 method), 546
             method), 712
is_open() (sage.geometry.convex_set.ConvexSet_relatively_spsimple() (sage.geometry.polyhedron.combinatorial_polyhedron.base.
             method), 712
                                                                                                 method), 260
is_PointCollection()
                                                                     module is_simplex() (sage.geometry.polyhedron.base3.Polyhedron_base3
                                                   (in
             sage.geometry.point_collection), 471
                                                                                                 method), 546
                                                                                   is\_simplex() (sage.geometry.polyhedron.combinatorial\_polyhedron.base
is_polyhedral_fan()
             (sage.geometry.polyhedral_complex.PolyhedralComplex
                                                                                                 method), 260
             method), 324
                                                                                   is_simplex() (sage.geometry.polyhedron.ppl_lattice_polytope.LatticePol
is_Polyhedron()
                                                                     module
                                                                                                 method), 229
             sage.geometry.polyhedron.base), 620
                                                                                   is_simplicial() (sage.geometry.cone.ConvexRationalPolyhedralCone
is\_prism() (sage.geometry.polyhedron.base3.Polyhedron_base3
                                                                                                 method), 381
             method), 544
                                                                                   is_simplicial() (sage.geometry.fan.RationalPolyhedralFan
is_prism() (sage.geometry.polyhedron.combinatorial_polyhedron.basetKathyb4AQtorialPolyhedron
             method), 259
                                                                                   is_simplicial() (sage.geometry.hyperplane arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.arrangement.
```

```
method), 27
                                                                                                                                                                                                                                                 isomorphism() (sage.geometry.fan.RationalPolyhedralFan
is_simplicial() (sage.geometry.polyhedron.base3.Polyhedron base2thod), 441
                                        method), 546
is_simplicial() (sage.geometry.polyhedron.combinatorial_polyhedron.base.CombinatorialPolyhedron
                                         method), 260
                                                                                                                                                                                                                                                  join() (sage.geometry.polyhedral complex.PolyhedralComplex
is_simplicial() (sage.rings.polynomial.groebner_fan.PolyhedralFanethod), 326
                                        method), 493
                                                                                                                                                                                                                                                  join() (sage.geometry.polyhedron.base5.Polyhedron_base5
is_simplicial_complex()
                                                                                                                                                                                                                                                                                         method), 576
                                        (sage.geometry.polyhedral\_complex.PolyhedralCopplex\_of\_Vrep() \ (sage.geometry.polyhedron.base 3.Polyhedron\_base 3.Pol
                                        method), 325
                                                                                                                                                                                                                                                                                         method), 547
is_simplicial_fan()
                                                                                                                                                                                                                                                  join_of_Vrep() (sage.geometry.polyhedron.combinatorial_polyhedron.be
                                         (sage.geometry.polyhedral_complex.PolyhedralComplex
                                                                                                                                                                                                                                                                                         method), 261
                                        method), 325
                                                                                                                                                                                                                                                  join_of_Vrep() (sage.geometry.polyhedron.combinatorial_polyhedron.fa
is_smooth() (sage.geometry.cone.ConvexRationalPolyhedralCone method), 293
                                        method), 381
                                                                                                                                                                                                                                                 Κ
is_smooth() (sage.geometry.fan.RationalPolyhedralFan
                                         method), 441
                                                                                                                                                                                                                                                 kernel_fan() (sage.geometry.fan_morphism.FanMorphism
is\_solid() (sage.geometry.cone.ConvexRationalPolyhedralCone
                                                                                                                                                                                                                                                                                         method), 462
                                        method), 382
                                                                                                                                                                                                                                                 Kirkman_icosahedron()
is_strictly_convex()
                                                                                                                                                                                                                                                                                          (sage.geometry.polyhedron.library.Polytopes
                                        (sage.geometry.cone.Convex Rational Polyhedral Cone
                                                                                                                                                                                                                                                                                         method), 63
                                        method), 382
is_subcomplex() (sage.geometry.polyhedral_complex.PolyhedralComplex
                                        method), 326
method), 279
                                                                                                                                                                                                                                                 last_slope() (sage.geometry.newton_polygon.NewtonPolygon_element
is_surjective() (sage.geometry.fan_morphism.FanMorphism
                                                                                                                                                                                                                                                                                          method), 719
                                        method), 461
                                                                                                                                                                                                                                                 lattice()
                                                                                                                                                                                                                                                                                                        (sage.geometry.cone.IntegralRayCollection
is_ToricLattice()
                                                                                                                                                                                                          module
                                                                                                                                             (in
                                                                                                                                                                                                                                                                                          method), 405
                                         sage.geometry.toric_lattice), 351
                                                                                                                                                                                                                                                 lattice() (sage.geometry.lattice_polytope.LatticePolytopeClass
is_ToricLatticeQuotient()
                                                                                                                                                                                                          module
                                                                                                                                                                                                                                                                                          method), 180
                                         sage.geometry.toric_lattice), 351
sage.geometry.toric_lattice), 351
lattice_automorphism_group()
is_torsion_free()(sage.geometry.toric_lattice_ToricLattice_quotient(sage.geometry.polyhedron.ppl_lattice_polytope_LatticePolytope_
                                         method), 347
                                                                                                                                                                                                                                                                                         method), 230
is\_trivial() \ (sage.geometry.cone.Convex Rational Polyhedral Cone\_dim() \ (sage.geometry.cone.Integral Ray Collection Language Content of the Content of 
                                        method), 382
                                                                                                                                                                                                                                                                                          method), 405
is\_universe() \ (sage.geometry.cone.Convex Rational Polyhedral Cone\_dim() \ (sage.geometry.lattice\_polytope.LatticePolytopeClass) \ (sage.geometry.lattice\_polytope.LatticePolytopeClass) \ (sage.geometry.lattice\_polytope.LatticePolytopeClass) \ (sage.geometry.lattice\_polytope.LatticePolytopeClass) \ (sage.geometry.lattice\_polytope.LatticePolytopeClass) \ (sage.geometry.lattice\_polytope.LatticePolytopeClass) \ (sage.geometry.lattice\_polytopeClass) \ (sage.geometry.lattice\_polytopeC
                                        method), 383
                                                                                                                                                                                                                                                                                         method), 180
is_universe() (sage.geometry.convex_set.ConvexSet_base_lattice_from_incidences()
                                                                                                                                                                                                                                                                                                                                                                                                                                                          module
                                        method), 709
                                                                                                                                                                                                                                                                                          sage.geometry.hasse diagram), 753
is\_universe() \ (sage.geometry.convex\_set.ConvexSet\_compact\_compact\_lice\_polytope() \ (sage.geometry.polyhedron.base 2.Polyhedron\_base 2
                                         method), 711
                                                                                                                                                                                                                                                                                         method), 525
\verb|is_universe()| (sage. geometry. polyhedron. base 1. Polyhedron
                                                                                                                                                                                                                                                                                                                                                                                                                               (class
                                        method), 519
                                                                                                                                                                                                                                                                                          sage.geometry.polyhedron.lattice_euclidean_group_element),
is\_universe() (sage.geometry.relative_interior.RelativeInterior
                                                                                                                                                                                                                                                                                          213
                                         method), 725
                                                                                                                                                                                                                                                 LatticePolygon_PPL_class
                                                                                                                                                                                                                                                                                                                                                                                                                    (class
is_V() (sage.geometry.polyhedron.representation.Vrepresentation
                                                                                                                                                                                                                                                                                         sage.geometry.polyhedron.ppl_lattice_polygon),
                                        method), 132
is_vertex() (sage.geometry.polyhedron.representation.Vertex LatticePolytope (class in sage.geometry.abc), 701
                                         method), 131
                                                                                                                                                                                                                                                 LatticePolytope()
                                                                                                                                                                                                                                                                                                                                                                                                                                                          module
                                                                                                                                                                                                                                                                                                                                                                                             (in
\verb|is_vertex()| (sage. geometry. polyhedron. representation. V representation\_ sage. geometry. lattice\_polytope), 160
                                        method), 133
                                                                                                                                                                                                                                                 LatticePolytope_PPL()
                                                                                                                                                                                                                                                                                                                                                                                                                                                          module
Ish() (sage.geometry.hyperplane_arrangement.library.HyperplaneArrangementLibrary.hyperplaneLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hyperplaneArrangementLibrary.hype
                                        method), 41
```

221

```
method), 709
LatticePolytope_PPL_class
                                                                                 (class
                                                                                                              in
                   sage.geometry.polyhedron.ppl_lattice_polytope), linear_transformation()
                                                                                                                                          (sage.geometry.polyhedron.base5.Polyhedron base5
LatticePolytopeClass
                                                                                                             in
                                                                                                                                          method), 577
                                                                          (class
                                                                                                                      linear_transformation()
                   sage.geometry.lattice_polytope), 161
LatticePolytopeError, 214
                                                                                                                                          (sage.geometry.relative interior.RelativeInterior
LatticePolytopeNoEmbeddingError, 214
                                                                                                                                          method), 726
LatticePolytopesNotIsomorphicError, 214
                                                                                                                      LinearExpression
                                                                                                                                                                                            (class
                                                                                                                                                                                                                                    in
lawrence_extension()
                                                                                                                                           sage.geometry.linear_expression), 713
                   (sage.geometry.polyhedron.base 5. Polyhedron\_bas \verb|effnearExpressionModule|) \\
                                                                                                                                                                                                                                    in
                   method), 576
                                                                                                                                          sage.geometry.linear_expression), 716
lawrence_polytope()
                                                                                                                      linearly_independent_vertices()
                    (sage.geometry.polyhedron.base5.Polyhedron_base5
                                                                                                                                           (sage.geometry.lattice_polytope.LatticePolytopeClass
                   method), 576
                                                                                                                                           method), 180
least_common_superface_of_Vrep()
                                                                                                                      lines() (sage.geometry.cone.ConvexRationalPolyhedralCone
                    (sage.geometry.polyhedron.base3.Polyhedron_base3
                                                                                                                                          method), 384
                   method), 548
                                                                                                                      lines() (sage.geometry.polyhedron.base0.Polyhedron_base0
legend_3d()
                                                                                                   module
                                                                                                                                          method), 506
                                                             (in
                   sage.geometry.hyperplane_arrangement.plot),
                                                                                                                      lines() (sage.geometry.polyhedron.face.PolyhedronFace
                                                                                                                                           method), 151
less_generators()
                                                                    (in
                                                                                                   module lines_list() (sage.geometry.polyhedron.base0.Polyhedron_base0
                   sage.geometry.hyperplane_arrangement.check_freeness), method), 506
                   764
                                                                                                                      linial() (sage.geometry.hyperplane_arrangement.library.HyperplaneArr
lexicographic_triangulation()
                                                                                                                                          method), 44
                   (sage.geometry.triangulation.point_configuration.PointConfiguexationmetry.polyhedron.parent.Polyhedra_base
                   method), 674
                                                                                                                                          method), 118
Line (class in sage.geometry.polyhedron.representation), ListOfFaces
                                                                                                                                                                                      (class
                                                                                                                                                                                                                                    in
                                                                                                                                          sage.geometry.polyhedron.combinatorial_polyhedron.list_of_face
line() (in module sage.geometry.polyhedron.ppl_lattice_polytope), 303
                                                                                                                      loop_over_parallelotope_points() (in module
line_generator() (sage.geometry.polyhedron.base0.Polyhedron_base0.geometry.integral_points), 759
                   method), 506
                                                                                                                      lyapunov_like_basis()
line_generator() (sage.geometry.polyhedron.face.PolyhedronFace(sage.geometry.cone.ConvexRationalPolyhedralCone
                                                                                                                                          method), 385
                    method), 150
lineality() (sage, geometry, cone. ConvexRationalPolyhedhylapunov_rank() (sage, geometry, cone. ConvexRationalPolyhedralCone
                   method), 383
                                                                                                                                          method), 386
lineality_dim() (sage.rings.polynomial.groebner fan.PolyhedralCone
                   method), 491
\label{lineality_dim} {\tt lineality\_dim()} \ (sage.rings.polynomial.groebner\_fan.Polynedredredredred()) \ (sage.geometry.ribbon\_graph.RibbonGraph) \ (sage.geometry.ribbon\_graph.RibbonGraph.RibbonGraph) \ (sage.geometry.ribbon\_graph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.RibbonGraph.Ri
                   method), 493
                                                                                                                                          method), 735
linear_equivalence_ideal()
                                                                                                                      make_parent()
                                                                                                                                                                                      (in
                                                                                                                                                                                                                          module
                    (sage.geometry.fan.RationalPolyhedralFan
                                                                                                                                          sage.geometry.hyperplane_arrangement.library),
                   method), 442
linear_part() (sage.geometry.hyperplane_arrangement.affine_subspace (in
                                                                                                                                                                                                                          module
                   method), 55
                                                                                                                                           sage.geometry.ribbon graph), 739
{\tt linear\_part()} \ (sage.geometry. hyperplane\_arrangement. hyperplane\_by hyperplane\_arrangement. hyperplane\_by hyperplane\_arrangement. hyperplane\_by hyperplane\_arrangement. hyperplane\_by hyperplane\_arrangement. hyperplane\_by hyperplane\_arrangement. hyperplane\_by hyperplane\_by hyperplane\_arrangement. hyperplane\_by hyperp
                   method), 49
                                                                                                                                          method), 442
linear_part_projection()
                                                                                                                      matrix() (sage.geometry.point_collection.PointCollection
                   (sage.geometry.hyperplane_arrangement.hyperplane.Hyperplane.Hyperplane), 469
                                                                                                                      matrix() (sage.geometry.polyhedron.combinatorial_polyhedron.list_of_fa
linear_subspace() (sage.geometry.cone.ConvexRationalPolyhedralficanod), 304
                   method), 384
                                                                                                                      matrix_space() (sage.geometry.polyhedron.double_description.DoubleD
linear_transformation()
                                                                                                                                          method), 656
                    (sage.geometry.convex set.ConvexSet base
```

```
matroid() (sage.geometry.hyperplane_arrangement.arrangemensat/gep.eyedmet.AryrdwgpeneplElwon_eastrangement.check_freeness,
        method), 27
max_degree()
                                         module
                                                      sage.geometry.hyperplane_arrangement.hyperplane,
        sage.rings.polynomial.groebner_fan), 496
maximal_cell_iterator()
                                                      sage.geometry.hyperplane_arrangement.library,
        (sage.geometry.polyhedral complex.PolyhedralComplex
                                                      sage.geometry.hyperplane_arrangement.plot,
        method), 326
maximal_cells() (sage.geometry.polyhedral_complex.PolyhedralComplex
        method), 327
                                                      sage.geometry.integral_points, 755
                                                      sage.geometry.lattice_polytope, 159
maximal_cells_sorted()
        (sage.geometry.polyhedral_complex.PolyhedralComplexage.geometry.linear_expression, 713
                                                      sage.geometry.newton_polygon, 719
        method), 327
maximal_cones() (sage.rings.polynomial.groebner_fan.Polyhedrangeometry.point_collection, 465
        method), 493
                                                      sage.geometry.polyhedral_complex, 310
maximal_total_degree_of_a_groebner_basis()
                                                      sage.geometry.polyhedron.backend_cdd, 638
        (sage.rings.polynomial.groebner_fan.GroebnerFan
                                                      sage.geometry.polyhedron.backend_cdd_rdf,
        method), 485
                                                          639
meet_of_Hrep() (sage.geometry.polyhedron.base3.Polyhedron_dage3geometry.polyhedron.backend_field,
                                                          639
        method), 549
meet_of_Hrep() (sage.geometry.polyhedron.combinatorial_polshegdrogelonset&ymboilcylocilutBolybradkond_normaliz,
        method), 261
meet_of_Hrep() (sage.geometry.polyhedron.combinatorial_polshegtropefome_tityrapoilfhedtronutora_thand_polymake,
        method), 295
minimal_generated_number()
                                                      sage.geometry.polyhedron.backend_ppl, 650
        (sage.geometry.hyperplane_arrangement.arrangement.blagper.gleometrayngeoleyhEdmownibase, 610
        method), 28
                                                      sage.geometry.polyhedron.base0,497
minimal_total_degree_of_a_groebner_basis()
                                                      sage.geometry.polyhedron.base1,513
        (sage.rings.polynomial.groebner_fan.GroebnerFan
                                                      sage.geometry.polyhedron.base2,521
        method), 485
                                                      sage.geometry.polyhedron.base3,527
minkowski_decompositions()
                                                      sage.geometry.polyhedron.base4,556
        (sage.geometry.polyhedron.base_ZZ.Polyhedron_ZZ
                                                      sage.geometry.polyhedron.base5,570
        method), 637
                                                      sage.geometry.polyhedron.base6, 587
minkowski_difference()
                                                      sage.geometry.polyhedron.base7,603
        (sage.geometry.polyhedron.base5.Polyhedron_base5
                                                      sage.geometry.polyhedron.base_QQ,620
        method), 578
                                                      sage.geometry.polyhedron.base_RDF, 638
minkowski_sum()
                                                      sage.geometry.polyhedron.base_ZZ, 632
                           (in
                                         module
        sage.geometry.lattice_polytope), 208
                                                      sage.geometry.polyhedron.cdd_file_format,
minkowski_sum() (sage.geometry.polyhedron.base5.Polyhedron_base56
        method), 579
                                                      sage.geometry.polyhedron.combinatorial_polyhedron.base
mixed_volume() (sage.rings.polynomial.groebner_fan.GroebnerFan235
        method), 485
                                                      sage.geometry.polyhedron.combinatorial_polyhedron.comb
module
    sage.geometry.abc, 701
                                                      sage.geometry.polyhedron.combinatorial_polyhedron.comv
    sage.geometry.cone, 352
                                                      sage.geometry.polyhedron.combinatorial_polyhedron.face
    sage.geometry.cone_catalog, 412
    sage.geometry.convex_set, 702
    sage.geometry.fan, 417
                                                      sage.geometry.polyhedron.combinatorial_polyhedron.list
    sage.geometry.fan_isomorphism, 749
    sage.geometry.fan_morphism, 449
                                                      sage.geometry.polyhedron.combinatorial_polyhedron.poly
    sage.geometry.hasse_diagram, 753
    sage.geometry.hyperplane_arrangement.affine_subsageacometry.polyhedron.constructor, 106
                                                      sage.geometry.polyhedron.double_description,
    sage.geometry.hyperplane_arrangement.arrangement, 653
        3
                                                      sage.geometry.polyhedron.double_description_inhomogene
```

```
660
                                                                                  n_facets()(sage.geometry.polyhedron.base0.Polyhedron base0
      sage.geometry.polyhedron.face, 144
                                                                                                method), 507
      sage.geometry.polyhedron.lattice_euclideanngfaupts[]emange.geometry.polyhedron.combinatorial polyhedron.base.C
                                                                                                method), 262
      sage.geometry.polyhedron.library, 61
                                                                                  n_Hrepresentation()
      sage.geometry.polyhedron.modules.formal_polyhedra_(moduleeometry.polyhedron.base0.Polyhedron base0
                                                                                                method), 507
      sage.geometry.polyhedron.palp_database,
                                                                                  n_hyperplanes() (sage.geometry.hyperplane arrangement.arrangement.
             215
                                                                                                method), 28
                                                                                  n_inequalities()(sage.geometry.polyhedron.base0.Polyhedron_base0
      sage.geometry.polyhedron.parent, 114
      sage.geometry.polyhedron.plot, 134
                                                                                                method), 508
      sage.geometry.polyhedron.ppl_lattice_polygmintegral_points()
                                                                                                (sage.geometry.polyhedron.ppl_lattice_polytope.LatticePolytope_
      sage.geometry.polyhedron.ppl_lattice_polytope,
                                                                                                method), 231
                                                                                  n_lines() (sage.geometry.polyhedron.base0.Polyhedron_base0
      sage.geometry.polyhedron.representation,
                                                                                                method), 508
             120
                                                                                  n_lines() (sage.geometry.polyhedron.face.PolyhedronFace
      sage.geometry.pseudolines, 740
                                                                                                method), 152
      sage.geometry.relative_interior,723
                                                                                  n_maximal_cells() (sage.geometry.polyhedral complex.PolyhedralComp
      sage.geometry.ribbon_graph, 727
                                                                                                method), 328
      sage.geometry.toric_lattice, 336
                                                                                  n_points() (sage.geometry.triangulation.base.PointConfiguration_base
      sage.geometry.toric_plotter, 473
                                                                                                method), 690
      sage.geometry.triangulation.base, 684
                                                                                  n_rays() (sage.geometry.polyhedron.base0.Polyhedron_base0
      sage.geometry.triangulation.element, 693
                                                                                                method), 508
      sage.geometry.triangulation.point_configurations() (sage.geometry.polyhedron.face.PolyhedronFace
                                                                                                method), 152
      sage.geometry.voronoi_diagram, 744
                                                                                  n_regions() (sage.geometry.hyperplane_arrangement.arrangement.Hyperplane
      sage.rings.polynomial.groebner_fan, 482
                                                                                                method), 29
module() (sage.geometry.point_collection.PointCollection n_skeleton() (sage.geometry.polyhedral_complex.PolyhedralComplex
             method), 469
                                                                                                method), 328
monomial_coefficients()
                                                                                  n_vertices()(sage.geometry.polyhedron.base0.Polyhedron_base0
             (sage.geometry.linear_expression.LinearExpression
                                                                                                method), 508
             method), 716
                                                                                  n_vertices() (sage.geometry.polyhedron.combinatorial_polyhedron.base
mu()
                  (sage.geometry.ribbon_graph.RibbonGraph
                                                                                                method), 263
             method), 736
                                                                                  n_vertices()(sage.geometry.polyhedron.face.PolyhedronFace
                                                                                                method), 152
Ν
                                                                                  n_vertices() (sage.geometry.polyhedron.ppl lattice polytope.LatticePol
                                                                                                method), 231
n_ambient_Hrepresentation()
             (sage.geometry.polyhedron.combinatorial_polyhedroNrennsati 906.CombinatorialFace
                                                                                                (sage.geometry.polyhedron.base0.Polyhedron_base0
             method), 281
                                                                                               method), 507
n_ambient_Hrepresentation()
             (sage.geometry.polyhedron.face.PolyhedronFace nabla()
                                                                                                   (sage.geometry.lattice_polytope.NefPartition
                                                                                                method), 199
             method), 151
                                                                                  nabla_polar() (sage.geometry.lattice_polytope.NefPartition
n_ambient_Vrepresentation()
             (sage.geometry.polyhedron.combinatorial_polyhedron.combinathsAdi Ade.CombinatorialFace
                                                                                  nablas() (sage.geometry.lattice_polytope.NefPartition
             method), 281
                                                                                                method), 200
n_ambient_Vrepresentation()
             (sage.geometry.polyhedron.face.PolyhedronFace \ \texttt{nef\_partitions()} \ (sage.geometry.lattice\_polytope.LatticePolytopeClasser) \ (sage.geometry.polyhedron.face.PolyhedronFace \ \texttt{nef\_partitions()} \ (sage.geometry.lattice\_polytope.LatticePolytopeClasser) \ (sage.geometry.lattice\_polytopeClasser) \ (sage.geomet
                                                                                                method), 180
             method), 151
                                                                                  nef_x() (sage.geometry.lattice_polytope.LatticePolytopeClass
n_bounded_regions()
             (sage.geometry.hyperplane_arrangement.arrangement.HyperplaneArrangementElement
                                                                                  NefPartition (class in sage.geometry.lattice_polytope),
             method), 28
n_equations()(sage.geometry.polyhedron.base0.Polyhedron base0194
                                                                                  neighborliness() (sage.geometry.polyhedron.base3.Polyhedron base3
             method), 507
```

```
method), 551
                                                                                                                  nvertices() (sage.geometry.lattice_polytope.LatticePolytopeClass
neighborliness() (sage.geometry.polyhedron.combinatorial_polyhedrondysk&GombinatorialPolyhedron
                  method), 263
neighbors() (sage.geometry.polyhedron.representation.Hrepresentation
                   method), 123
                                                                                                                   octahedron() (sage.geometry.polyhedron.library.Polytopes
neighbors() (sage.geometry.polyhedron.representation.Vrepresentation), 81
                  method), 133
                                                                                                                   omnitruncated_one_hundred_twenty_cell()
NewtonPolygon
                                                                                                module
                                                             (in
                                                                                                                                      (sage.geometry.polyhedron.library.Polytopes
                   sage.geometry.newton_polygon), 719
                                                                                                                                      method), 81
NewtonPolygon_element
                                                                          (class
                                                                                                                  omnitruncated_six_hundred_cell()
                   sage.geometry.newton_polygon), 719
                                                                                                                                      (sage.geometry.polyhedron.library.Polytopes
\verb"next()" (sage.geometry.polyhedron.combinatorial\_polyhedron.face\_iterator\_base") and the property of the pr
                  method), 296
                                                                                                                   one_hundred_twenty_cell()
nfacets() (sage.geometry.lattice_polytope.LatticePolytopeClass
                                                                                                                                      (sage.geometry.polyhedron.library.Polytopes
                   method), 183
                                                                                                                                      method), 82
ngenerating_cones()
                                                                                                                   one_point_suspension()
                   (sage.geometry.fan.RationalPolyhedralFan
                                                                                                                                      (sage.geometry.polyhedron.base5.Polyhedron_base5
                  method), 443
                                                                                                                                      method), 580
ngens() (sage.geometry.hyperplane_arrangement.arrangement_Hyperplanes(ryangengentsnetry.polyhedron.combinatorial_polyhedron.j
                   method), 39
                                                                                                                                      method), 296
{\tt ngens()} \ (sage.geometry.linear\_expression.Linear Expression {\tt Modula} {\tt polyhedron.j} (sage.geometry.polyhedron.combinatorial\_polyhedron.j) (sage.geometry.polyhedron.j) (sage.geometry.polyhedron.j
                  method), 718
                                                                                                                                      method), 297
nonnegative_orthant()
                                                                                                module
                                                                                                                  options() (in module sage.geometry.toric_plotter), 479
                   sage.geometry.cone catalog), 413
                                                                                                                   ordered_vertices() (sage.geometry.polyhedron.ppl_lattice_polygon.Lat
normal() (sage.geometry.hyperplane_arrangement.hyperplane.Hyperplansd), 218
                  method), 50
                                                                                                                   oriented_boundary()
normal\_cone() (sage.geometry.polyhedron.face.PolyhedronFace
                                                                                                                                      (sage.geometry.fan.RationalPolyhedralFan
                  method), 152
                                                                                                                                      method), 443
normal_cone() (sage.geometry.triangulation.element.Triangulation) (sage.geometry.lattice_polytope.LatticePolytopeClass
                   method), 698
                                                                                                                                      method), 186
normal_fan()(sage.geometry.polyhedron.base.Polyhedron_krukk_solomon_algebra()
                  method), 615
                                                                                                                                      (sage.geometry.hyperplane_arrangement.arrangement.Hyperplane
normal_form() (sage.geometry.lattice_polytope.LatticePolytopeClassnethod), 29
                  method), 183
                                                                                                                   orlik_terao_algebra()
NormalFan() (in module sage.geometry.fan), 427
                                                                                                                                      (sage.geometry.hyperplane_arrangement.arrangement.Hyperplane
normalize() (sage.geometry.ribbon_graph.RibbonGraph
                                                                                                                                      method), 29
                   method), 736
                                                                                                                   orthogonal_projection()
normalize_rays() (in module sage.geometry.cone),
                                                                                                                                      (sage.geometry.hyperplane_arrangement.hyperplane.Hyperplane
                   409
                                                                                                                                      method), 50
nparts() (sage.geometry.lattice_polytope.NefPartition
                                                                                                                  orthogonal_sublattice()
                  method), 201
                                                                                                                                      (sage.geometry.cone.ConvexRationalPolyhedralCone
{\tt npoints()} \ (sage.geometry.lattice\_polytope.LatticePolytopeClass
                                                                                                                                      method), 388
                  method), 185
                                                                                                                   outer_normal() (sage.geometry.polyhedron.representation.Inequality
                           (sage.geometry.cone.IntegralRayCollection
nrays()
                                                                                                                                      method), 126
                  method), 405
                                                                                                                  output_format() (sage.geometry.point_collection.PointCollection
number_boundaries()
                                                                                                                                      static method), 469
                   (sage.geometry.ribbon_graph.RibbonGraph
                                                                                                                   P
                  method), 737
number_of_reduced_groebner_bases()
                                                                                                                  P(sage.geometry.polyhedron.combinatorial_polyhedron.face_iterator.Facel
                   (sage.rings.polynomial.groebner_fan.GroebnerFan
                                                                                                                                      attribute), 301
                  method), 485
                                                                                                                  pair_class(sage.geometry.polyhedron.double_description.Problem
number_of_variables()
                                                                                                                                      attribute), 658
                   (sage.rings.polynomial.groebner_fan.GroebnerFan_pair_class (sage.geometry.polyhedron.double_description.StandardAlgor
                  method), 486
```

attribute), 659

```
PALPreader (class in sage.geometry.polyhedron.palp_databake), () (sage.geometry.toric_lattice.ToricLattice_ambient
         215
                                                                 method), 340
parallelotope() (sage.geometry.polyhedron.library.Polyhot() (sage.geometry.toric_lattice_ToricLattice_sublattice_with_basis
         method), 83
                                                                 method), 350
parallelotope_points()
                                              module plot() (sage.geometry.triangulation.element.Triangulation
         sage.geometry.integral points), 759
                                                                 method), 698
parent() (sage, geometry, lattice_polytope, LatticePolytope Glasst() (sage, geometry, triangulation, point_configuration. PointConfiguration
         method), 186
                                                                 method), 675
                                                      plot() (sage.geometry.voronoi_diagram.VoronoiDiagram
ParentNewtonPolygon
                                  (class
         sage.geometry.newton_polygon), 721
                                                                 method), 745
part()
           (sage.geometry.lattice_polytope.NefPartition plot3d() (sage.geometry.lattice_polytope.LatticePolytopeClass
         method), 201
                                                                 method), 186
part_of() (sage.geometry.lattice_polytope.NefPartition
                                                      plot_generators() (sage.geometry.toric_plotter.ToricPlotter
         method), 202
                                                                 method), 475
part_of_point() (sage.geometry.lattice_polytope.NefPartpilort_hyperplane()
                                                                                                      module
                                                                                        (in
         method), 202
                                                                 sage.geometry.hyperplane_arrangement.plot),
           (sage.geometry.lattice_polytope.NefPartition
parts()
         method), 203
                                                       plot_labels() (sage.geometry.toric_plotter.ToricPlotter
pentakis_dodecahedron()
                                                                 method), 476
         (sage.geometry.polyhedron.library.Polytopes
                                                       plot_lattice() (sage.geometry.toric plotter.ToricPlotter
         method), 83
                                                                 method), 476
permutahedron() (sage.geometry.polyhedron.library.Polyhedronton() (sage.geometry.toric_plotter.ToricPlotter
         method), 84
                                                                 method), 476
permutations() (sage.geometry.pseudolines.PseudolineAphotemant_labels() (sage.geometry.toric plotter.ToricPlotter
         method), 743
                                                                 method), 477
permutations_to_matrices()
                                                       plot_rays() (sage.geometry.toric_plotter.ToricPlotter
         (sage.geometry.polyhedron.base.Polyhedron_base
                                                                 method), 477
         method), 617
                                                       plot_walls() (sage.geometry.toric_plotter.ToricPlotter
PivotedInequalities
                                                                method), 477
                                  (class
                                                   in
         sage.geometry.polyhedron.double_description_inhpoinganeoup) lynomial()
         662
                                                                 (sage.geometry.hyperplane_arrangement.arrangement.Hyperplane
placing_triangulation()
                                                                 method), 30
         (sage.geometry.triangulation.point_configuration.PointConfiguration.ge.geometry.triangulation.base), 685
         method), 674
                                                       point() (in module sage.geometry.polyhedron.ppl_lattice_polytope),
plot() (in module sage.geometry.hyperplane_arrangement.plot),
                                                       point() (sage.geometry.hyperplane_arrangement.affine_subspace.AffineSt
plot() (sage.geometry.cone.ConvexRationalPolyhedralCone
                                                                 method), 55
         method), 389
                                                       point() (sage.geometry.hyperplane_arrangement.hyperplane.Hyperplane
plot()
             (sage.geometry.cone.IntegralRayCollection
                                                                 method), 51
                                                       point() (sage.geometry.lattice_polytope.LatticePolytopeClass
         method), 405
plot()
             (sage.geometry.fan.RationalPolyhedralFan
                                                                 method), 187
         method), 444
                                                       point() (sage.geometry.triangulation.base.PointConfiguration_base
plot() (sage.geometry.hyperplane_arrangement.arrangement.HyperphaticAt); and comment Element
         method), 30
                                                       point_configuration()
plot() (sage.geometry.hyperplane_arrangement.hyperplane.Hyperpl(wwge.geometry.triangulation.base.Point
                                                                 method), 686
         method), 51
plot() (sage.geometry.newton_polygon.NewtonPolygon_elpoint_configuration()
                                                                 (sage.geometry.triangulation.element.Triangulation
         method), 719
plot() (sage.geometry.polyhedral_complex.PolyhedralComplex
                                                                 method), 698
                                                       PointCollection
         method), 329
                                                                                        (class
                                                                                                           in
plot() (sage.geometry.polyhedron.base6.Polyhedron_base6
                                                                 sage.geometry.point_collection), 466
                                                       PointConfiguration
         method), 597
                                                                                         (class
plot() (sage.geometry.polyhedron.ppl_lattice_polygon.LatticePolygong@PQleonlassy.triangulation.point_configuration),
         method), 218
                                                                 668
```

sage.geometry.polyhedron.ppl_lattice_polygon), Polyhedron_base1 (class in sage.geometry.polyhedron.base1), 513  poly_x() (sage.geometry.lattice_polytope.LatticePolytopeCHalyhedron_base2) (class in sage.geometry.polyhedron.base2), 521  Polyhedra() (in module sage.geometry.polyhedron.parent), 114  Polyhedra_base (class in sage.geometry.polyhedron.base3), 527  Polyhedra_base (class in sage.geometry.polyhedron.base3), 527  Polyhedra_field (class in sage.geometry.polyhedron.base4), 556  Polyhedra_normaliz (class in sage.geometry.polyhedron.parent), 120  Polyhedra_polymake (class in sage.geometry.polyhedron.parent), 120  Polyhedra_QQ_cdd (class in sage.geometry.polyhedron.parent), 115  Polyhedra_QQ_normaliz (class in sage.geometry.polyhedron.parent), 115  Polyhedra_QQ_normaliz (class in sage.geometry.polyhedron.parent), 115  Polyhedra_QQ_ppl (class in sage.geometry.polyhedron.parent), 115  Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.parent), 115  Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.parent), 115  Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.parent), 115  Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.parent), 115  Polyhedra_ZZ	PointConfiguration_base	(class	in	metho	d), 699			
points O (sage, geometry, polyhedran, Dase Polyhedral Fan method), 461 points C (sage, geometry, polyhedran, ppl_lattice_polytope. Idas (sage, geometry, polyhedran, Dase Polyhedran, O) sage, geometry, polyhedran, Dase Polyhedran, O) points O (sage, geometry, polyhedran, Dase Polyhedran, O) polar O) (sage, geometry, polyhedran, Dase Polyhedran, O) polar P2, 112, polytope O) polar P3, polyhedran, parent, polyhedran, polyhedran, parent, polyhedran	sage.geometry.triangulo	ation.base), 688		PolyhedralCon	nplex	(class	in	
points() (sage_geometry_riangulation-base_foint(Configuration_baseage_rings_polymonial_groebner_fam), 490 method), 691 points() (sage_geometry_voronoi_diagram.VoronoiDiagram method), 746 pointsets_mod_automorphism()     (sage_geometry_polyhedron_parent), 120     (sage_geometry_polyhedron_parent), 120     (sage_geometry_polyhedron_parent), 120 points() (sage_geometry_polyhedron_parent), 120 points() (sage_geometry_polyhedron_parent), 120 point()	<pre>points() (sage.geometry.lattice_</pre>	_polytope.LatticePo	lytope	Class sage.g	eometry.polyhe	dral_complex).	, 312	
method), 691 method), 746 method), 746 method), 746 method), 746 method), 746 method), 241 polar C) (sage, geometry, solyhedron, ppt_lattice_polytope_lattice_p	method), 188					_		
method), 691 method), 746 method), 746 method), 746 method), 746 method), 746 method), 241 polar C) (sage, geometry, solyhedron, ppt_lattice_polytope_lattice_p	points() (sage.geometry.triangu	ılation.base.PointC	onfigu	ration_bas&age.r	ings.polynomia	l.groebner_fan	), 490	
points() (sage, geometry, voronoi_diagram, VoronoiDiagram					~			
pointsets_mod_automorphismO (suge.geometry.polyhedron.ppi lattice polytope. LatticePolytopeClass suge.geometry.polyhedron.base5.Polyhedron.base6.Polyhedron.Dase2.Polyhedron.O (suge.geometry.polyhedron.comstructor), 111 polyhedronO (suge.geometry.polyhedron.face.PolytopeClass polyhedronO (suge.geometry.polyhedron.face.PolytopeClass polyhedronO (suge.geometry.polyhedron.face.PolyhedronCo (suge.geometry.polyhedron.face.PolyhedronExperimentation.Polyhedron.base (class in suge.geometry.polyhedron.parent), 114 polyhedra_polyhedron_polyhedron.parent), 114 polyhedra_base (class in suge.geometry.polyhedron.parent), 115 polyhedra_polymake	**	i diagram.Voronoi	Diagra	-		l.groebner fan		
points ets. mod. automorphism() (sage geometry,polyhedron,ppl_lattice_polytope_Detolytidyrope_CRE lythrage_geometry.abc), 702 method), 231 method), 231 method), 231 method), 190 polar() (sage_geometry,lattice_polytope_LatticePolytopeClass method), 581 polar() (sage_geometry,polyhedron.base5.Polyhedron method), 581 polar() (sage_geometry,polyhedron.base2_ZP.olyhedron polar() (sage_geometry,polyhedron.base2_ZP.olyhedron polar() (sage_geometry,polyhedron.combinatorial polyhedron() (sage_geometry,lattice_polytope) method), 264 polar() (sage_geometry,polyhedron.combinatorial polyhedron() (sage_geometry,lattice_polytopeClass polyhedron() (sage_geometry,lattice_polytopeLatticePolytopeClass polyhedron() (sage_geometry,lattice_polytopeClass polyhedron() (sage_geometry,lattice_polytopeClass polyhedron() (sage_geometry,lattice_polytopeClass polyhedron() (sage_geometry,lattice_polytopeClass polyhedron() (sage_geometry,lattice_polytopeClass method), 264 polar() (sage_geometry,lattice_polytopeClass method), 154 method		8						bnerFan
(sage, geometry, polyhedron, ppl_lattice_polytope_LatticePolytope Class	**	n()				r - i j · · · · · · · · · · · · · · · · · ·	<b>_</b>	
method), 231 Polyhedron() (in module polar() (sage, geometry, lattice polytope Lattice Polytope Class sage, geometry, polyhedron, constructor), 111 method), 190 polar() (sage, geometry, polyhedron, base5 method), 389 method), 581 polar() (sage, geometry, polyhedron, base5. Polyhedron Dase5 method), 581 polar() (sage, geometry, polyhedron, base5. Polyhedron Dase6 method), 581 polar() (sage, geometry, polyhedron, base5. Polyhedron Dase6 method), 582 polar() (sage, geometry, polyhedron, combinatorial polyhedron() (sage, geometry, lattice_polytopeClass polyhedron() (sage, geometry, lattice_polytopeClass polyhedron() (sage, geometry, polyhedron, face. Polyhedron Face method), 154 polyhedron() (sage, geometry, polyhedron, face. Polyhedron Face method), 154 polyhedron, polyhedron, polyhedron() (sage, geometry, polyhedron, face. Polyhedron Face method), 154 polyhedron() (sage, geometry, polyhedron, face. Polyhedron Face method), 154 polyhedron() (sage, geometry, polyhedron, face. Polyhedron Face method), 154 polyhedron() (sage, geometry, polyhedron, face. Polyhedron Face method), 154 polyhedron() (sage, geometry, polyhedron, face. Polyhedron Face method), 154 polyhedron() (sage, geometry, polyhedron, face. Polyhedron Face method), 154 polyhedron() (sage, geometry, polyhedron, face. Polyhedron Face method), 154 polyhedron() (sage, geometry, polyhedron, face. Po	= = = = = = = = = = = = = = = = = = = =		lytone.		* *	metry.abc). 702	2.	
polar() (sage.geometry.lattice_polytope.LatticePolytopeClass method), 190		ron.ppi_iannee_poi	yrope					
method), 190 polar () (sage, geometry, polyhedron, base5. Polyhedron, base5. method), 381 method), 581 method), 581 method), 582 method), 583 polar () (sage, geometry, polyhedron, base7. Polyhedron, C) (sage, geometry, bethod), 582 polar () (sage, geometry, polyhedron, base7. Polyhedron, C) (sage, geometry, bethod), 582 polar () (sage, geometry, polyhedron, base6. Polyhedron, C) (sage, geometry, bethod), 584 polar () (sage, geometry, polyhedron, base7. Polyhedron, C) (sage, geometry, bethod), 584 polar () (sage, geometry, polyhedron, polyhedron, base6. Bethod), 154 method), 154 metho	The state of the s	nolytone LatticePol	vtone(	-		`		
polar () (sage_geometry-polyhedron_base_5.Polyhedron_base_5 method), 581 polar () (sage_geometry-polyhedron_base_ZZ_Polyhedron_ZZ_method), 582 method), 638 polar () (sage_geometry-polyhedron_base_ZZ_Polyhedron_ZZ_method), 582 polar () (sage_geometry-polyhedron_combinatorial_polyhedron_base_dembihithithithithithithithithithithithithit		oiyiope.Emineer oi	yiopec					alCone
method), 581 polar() (sage, geometry, polyhedron, base ZZZ Polyhedron Z ZZ method), 532 method), 638 polar() (sage, geometry, polyhedron, combinatorial polyhedron), 264 polar() (sage, geometry, polyhedron, polyhedron), 264 polar() (sage, geometry, polyhedron, polyhedron), 264 polar() (sage, geometry, polyhedron, face, Polyhedron, face, Polyhedron, Polyhedron, polyhedron), 129 polar() (sage, geometry, polyhedron, face, Polyhedron, face, Polyhedron, face, Polyhedron, base, geometry, polyhedron, base, geometry, polyhedron, polyhedron, polyhedron, polyhedron, polyhedron, base, geometry, polyhedron, base, geometry, polyhedron, polyhedron, polyhedron, polyhedron, polyhedron, base, geometry, polyhedron, polyhedron, base, geometry, polyhedron, porent, l10 polyhedra_Qo_polymake (class in sage, geometry, polyhedron, parent), l10 sage, g	The state of the s	ron basa5 Polyhadi	on ha			.cone.convexio	инонин отупсин	ucone
polar() (sage.geometry.polyhedron.base ZZ.Polyhedron ZZ method), 52 method), 638 polar() (sage.geometry.polyhedron.combinatorial_polyhedron.base.fisethbit@tible\text{polyhedron} (sage.geometry.polyhedron.face.PolyhodronFace method), 264 polar_PlxPl_polytope() (in module sage.geometry.polyhedron.ppl_lattice_polygon), 219 polar_P2_1112_polytope() (in module sage.geometry.polyhedron.ppl_lattice_polygon), 219 polar_P2_polytope() (in module sage.geometry.polyhedron.pase() (class in sage.geometry.polyhedron.base(), 497 polyhedra_190 polar_P2_polytope() (in module sage.geometry.polyhedron.parent), 114 polyhedra_field (class in sage.geometry.polyhedron.parent), 115 polyhedra_field (class in sage.geometry.polyhedron.parent), 120 polyhedra_OQ_o_cdd (class in sage.geometry.polyhedron.parent), 120 polyhedra_Qo_o_cdd (class in sage.geometry.polyhedron.parent), 115 polyhedra_Qo_o_cdd (class in sage.geometry.polyhedron.parent), 115 polyhedra_Qo_o_cdd (class in sage.geometry.polyhedron.parent), 115 polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.parent), 11		on.bases.1 orynear	on_ou.		* *	hyparnlana ar	rangoment hype	rnlana Hyna
method), 638 polar () (sage, geometry, polyhedron.combinatorial polyhedron () (sage, geometry, polyhedron.face. PolytopeClass polyhedron.face. Polyhedron.face.face. Polyhedron.face.face.face.face.face.face.face.face	The state of the s	uan hasa 77 Daluk	a duan			.nyperpiane_ar	rangemeni.nypei	риапе.пуре.
polar() (sage geometry-polyhedron.combinatorial_polyhedron_base (sembithatthatlPolyhedron method), 264 polar_PlxPl_polytope() (in module sage.geometry.polyhedron.ppl_lattice_polygon), 219 polar_P2_1112_polytope() (in module sage.geometry.polyhedron.ppl_lattice_polygon), 219 polar_P2_polytope() (in module sage.geometry.polyhedron.pse() (class in sage.geometry.polyhedron.base(), 497 polyhedra_P2_polytope() (in module sage.geometry.polyhedron.base(), 497 polyhedra_P2_polytope() (in module sage.geometry.polyhedron.base(), 497 polyhedra_P2_polyhedron.parent), 114 polyhedra_base (class in sage.geometry.polyhedron.base(), 513 poly_x() (sage.geometry.polyhedron.base(), 610 polyhedra_P2_polyhedron.base(), 610 polyhedra_p2_polyhedron.parent), 116 polyhedra_base (class in polyhedron_base(), 610 polyhedra_polyhedron.parent), 115 polyhedra_polymake (class in sage.geometry.polyhedron.parent), 115 polyhedra_Q0_pol (class in sage.geometry.polyhedron.parent), 115 polyhedra_Q0_pol (class in sage.geometry.polyhedron.parent), 115 polyhedra_Q0_pol (class in sage.geometry.polyhedron.base(), 497 polyhedra_p2_polyhedron.parent), 115 polyhedra_Q0_pol (class in sage.geometry.polyhedron.base(), 497 polyhedra_p2_polyhedron.parent), 116 polyhedra_Q0_polyhedron.parent), 115 polyhedra_Q0_polyhedron.parent), 115 polyhedra_Q0_polyhedron_parent), 115 polyhedra_Q0_polyhedron_parent), 115 polyhedra_Z2_polyhedron.parent), 115 polyhedra_Z2_polyhedron.parent), 115 polyhedra_Z2_polyhedron.parent), 115 polyhedra_Z2_polyhedron.parent), 115 polyhedra_Z2_polyhedron_parent		ron.base_ZZ.Potyno	earon_		* *	1	I w DI	CI
method), 264 polar_PlxPl_polytope() (in module sage_geometry.polyhedron.ppl_lattice_polygon), 219 polar_P2_112_polytope() (in module sage_geometry.polyhedron.ppl_lattice_polygon), 219 polar_P2_polytope() (in module sage_geometry.polyhedron.ppl_lattice_polygon), 219 polar_P2_polytope() (in module sage_geometry.polyhedron.ppl_lattice_polygon), 219 polar_P2_polytope() (in module sage_geometry.polyhedron.ppl_lattice_polygon), 219 poly_x() (sage_geometry.polyhedron.ppl_lattice_polygon), 219 poly_x() (sage_geometry.polyhedron.pal_lattice_polygon), 219 poly_x() (sage_geometry.polyhe	, , , , , , , , , , , , , , , , , , ,	1 1	, ,				e.LatticePolytop	eClass
polar_PlxPl_polytope() (in module sage_geometry.polyhedron.ppl_lattice_polygon), 219 polar_P2_112_polytope() (in module sage_geometry.polyhedron.ppl_lattice_polygon), 219 polar_P2_polytope() (in module sage_geometry.polyhedron.ppl_lattice_polygon), 219 polar_P2_polytope() (in module sage_geometry.polyhedron.ppl_lattice_polygon), 219 poly_x() (sage_geometry.polyhedron.ppl_lattice_polygon), 219 poly_x() (sage_geometry.polyhedron.ppl_lattice_polygon), 219 poly_x() (sage_geometry.polyhedron.ppl_lattice_polytope(Holyhedron_base0), (class in sage_geometry.polyhedron.base1), 513 poly_x() (sage_geometry.polyhedron.ppl_lattice_polytope(Holyhedron_base1), 513 poly_x() (sage_geometry.polyhedron.parent), 114 polyhedra_() (in module sage_geometry.polyhedron.base1), 513 polyhedra_() (in module sage_geometry.polyhedron.base2), 521 polyhedra_() (in module sage_geometry.polyhedron.base2), 521 polyhedra_() (in module sage_geometry.polyhedron.base3), 527 polyhedra_non_base1, 516 polyhedra_non_base1, 516 polyhedra_non_base2, 521 polyhedra_non_base3, 527 polyhedron_base4 (class in sage_geometry.polyhedron.base3), 527 polyhedra_non_base4, 556 polyhedra_non_base5, 570 polyhedra_non_base6 (class in sage_geometry.polyhedron.base6), 587 polyhedra_non_base6, (class in sage_geometry.polyhedron.base7), 603 polyhedra_non_base6, (class in sage_geometry.polyhedron.base8), 570 polyhedra_non_base6, (class		ron.combinatorial_	polyhe					
sage.geometry.polyhedron.ppl_lattice_polygon), polyhedron() (sage.geometry.polyhedron.representation.PolyhedronRepresentation.PolyhedronRepresentationPolyhedronRepresentationPolyhedronRepresentationPolyhedronRepresentationPolyhedronRepresentationPolyhedronRepresentationPolyhedronRepresentationPolyhedronRepresentationPolyhedronRepresentationPolyhedron.pase (class in sage.geometry.polyhedron.pase (class in sage.geometry.polyhedron.base (class in sage.geometry.polyhedron.base (class in sage.geometry.polyhedron.pase (class in sage.geometry.polyhedron.parent), 116 (class in sage.geometry.polyhedron.parent), 116 (class in sage.geometry.polyhedron.parent), 116 (class in sage.geometry.polyhedron.parent), 120 (class in sage.geometry.polyhedron.parent), 120 (class in sage.geometry.polyhedron.parent), 120 (class in sage.geometry.polyhedron.parent), 115 (class in sage.geometry.polyhedron.paren	, , , , , , , , , , , , , , , , , , ,					.polyhedron.fac	ce.PolyhedronFa	ce
method), 128  Polyar_P2_112_polytope() (in module sage.geometry.polyhedron.ppl_lattice_polygon), 219  polar_P2_plytope() (in module sage.geometry.polyhedron.ppl_lattice_polygon), 219  polar_P2_plytope() (in module sage.geometry.polyhedron.ppl_lattice_polygon), 219  polar_P2_plytope() (in module sage.geometry.polyhedron.ppl_lattice_polygon), 219  poly_x() (sage.geometry.polyhedron.ppl_lattice_polygon), 219  poly_x() (sage.geometry.plattice_polytope_LatticePolytope_Class_in method), 190  poly_x() (sage.geometry.polyhedron.parent), 114  polyhedra_() (in module sage.geometry.polyhedron.pase1), 513  polypaction_base2 (class in sage.geometry.polyhedron.base2), 521  Polyhedra_base (class in sage.geometry.polyhedron.parent), 116  polyhedra_base (class in sage.geometry.polyhedron.parent), 110  polyhedra_normaliz (class in sage.geometry.polyhedron.parent), 120  polyhedra_Qo_dd (class in sage.geometry.polyhedron.parent), 120  polyhedra_Qo_cdd (class in sage.geometry.polyhedron.parent), 115  polyhedra_Qo_pol (class in sage.geometry.polyhedron.parent), 115  polyhedra_Acd (class in sage.geometry.polyhedron.parent), 115  polyhedra_Acd (class in sage.geometry.polyhedron.parent), 115  polyhedra_Qo_normaliz (class in sage.geometry.polyhedron.parent), 115  polyhedra_Acd (class in sage.geometry.polyhedron.parent), 115  polyhedra_Qo_normaliz (class in sage.geometry.polyhedron.parent), 115  polyhedra_Acd (class in		`			* *			
polar_P2_112_polytope() (in module sage.geometry.polyhedron.ppl_lattice_polygon), 219 polar_P2_polytope() (in module sage.geometry.polyhedron.ppl_lattice_polygon), 219 polar_P2_polytope() (in module sage.geometry.polyhedron.ppl_lattice_polygon), 219 poly_xO(sage.geometry.polyhedron.ppl_lattice_polygon), 219 poly_xO(sage.geometry.lattice_polytope.LatticePolytopeCHolyhedron_base1 (class in method), 190 polyx_O(sage.geometry.polyhedron.parent), 114 polyhedra() (in module sage.geometry.polyhedron.parent), 114 polyhedra() (in module sage.geometry.polyhedron.parent), 116 polyhedra() (in module sage.geometry.polyhedron.parent), 116 polyhedra() (in module sage.geometry.polyhedron.parent), 116 polyhedra() (class in sage.geometry.polyhedron.parent), 120 polyhedra_polymake (class in sage.geometry.polyhedron.parent), 120 polyhedra_QQ_cdd (class in sage.geometry.polyhedron.parent), 115 polyhedra_QQ_ppl (class in sage.geometry.polyhedron.parent), 115 polyhedra_QD_ppl (class in sage.geometry.polyhedron.parent), 115 polyhedra_ZZ_pormaliz (class in sage.geometry.polyhedron.parent), 115 polyhedra_ZZ_pormaliz (class in sage.geometry.polyhedron.parent), 115 polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.parent), 115 polyhedra_Complex() (class in sage.geometry.polyhedron.parent), 115 polyhedra		on.ppl_lattice_poly	vgon),			.polyhedron.rep	presentation.Poly	hedronRepr
sage.geometry.polyhedron.ppl_lattice_polygon), 219 polar_P2_polytope() (in module sage.geometry.polyhedron.ppl_lattice_polygon), 219 poly_x() (sage.geometry.polyhedron.ppl_lattice_polygon), 219 poly_x() (sage.geometry.lattice_polytope.LatticePolytopeCffdsyhedron_base2 (class in sage.geometry.polyhedron.base3), 513 poly_x() (sage.geometry.lattice_polytope.LatticePolytopeCffdsyhedron_base2 (class in sage.geometry.polyhedron.base2), 521 polyhedra() (in module sage.geometry.polyhedron.parent), 114 polyhedra_base (class in sage.geometry.polyhedron.parent), 116 polyhedra_field (class in sage.geometry.polyhedron.parent), 120 polyhedra_polymake (class in sage.geometry.polyhedron.parent), 120 polyhedra_polymake (class in sage.geometry.polyhedron.parent), 120 polyhedra_QQ_cdd (class in sage.geometry.polyhedron.parent), 115 polyhedra_QQ_ppl (class in sage.geometry.polyhedron.parent), 115 polyhedra_QD_ppl (class in sage.geometry.polyhedron.parent), 115 polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.parent), 115 polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.parent), 115 polyhedra_Complex() (plotefield sage.geometry.polyh					* *			
polar_P2_polytope() (in module sage.geometry.polyhedron.ppl_lattice_polygon), sage.geometry.polyhedron.ppl_lattice_polytope.LatticePolytopeCHoisynedron.base1 (class in method), 190  Polyhedra() (in module sage.geometry.polyhedron.base2 (class in method), 190  Polyhedra() (in module sage.geometry.polyhedron.parent), 114  Polyhedra base (class in sage.geometry.polyhedron.parent), 116  Polyhedra_field (class in sage.geometry.polyhedron.parent), 120  Polyhedra_anormaliz (class in sage.geometry.polyhedron.parent), 120  Polyhedra_polymake (class in sage.geometry.polyhedron.parent), 120  Polyhedra_Q_C_dd (class in sage.geometry.polyhedron.parent), 115  Polyhedra_QQ_normaliz (class in sage.geometry.polyhedron.parent), 115  Polyhedra_QQ_ppl (class in sage.geometry.polyhedron.parent), 115  Polyhedra_ZZ_normaliz (class in sage.geometry.po				-		*		
polar_P2_polytope() (in module sage.geometry.polyhedron.ppl_lattice_polygon), 219	sage.geometry.polyhedr	on.ppl_lattice_poly	vgon),			dron.base), 610	0	
sage.geometry.polyhedron.ppl_lattice_polygon), Polyhedron_base1 (class in sage.geometry.polyhedron.base1), 513  poly_x() (sage.geometry.lattice_polytope_LatticePolytope CHolyhedron_base2) (class in sage.geometry.polyhedron.base2), 521  Polyhedra() (in module sage.geometry.polyhedron.parent), 114  Polyhedra_base (class in sage.geometry.polyhedron.parent), 116  Polyhedra_field (class in sage.geometry.polyhedron.parent), 110  Polyhedra_normaliz (class in sage.geometry.polyhedron.parent), 120  Polyhedra_polymake (class in sage.geometry.polyhedron.parent), 120  Polyhedra_QO_dd (class in sage.geometry.polyhedron.parent), 115  Polyhedra_QO_normaliz (class in sage.geometry.polyhedron.parent), 115  Polyhedra_QO_ppl (class in sage.geometry.polyhedron.parent), 115  Polyhedra_ZZ_polymaliz (class in sage.geometry.polyhedron.parent), 115  Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.parent), 115  Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.parent), 115  Polyhedra_Complex()  Polyhedron_polymake (class in sage.geometry.polyhedron.backend_polymake), 649  Polyhedra_Complex()  Polyhedron_polymake (class in sage.geometry.polyhedron.backend_polymake), 649	219			Polyhedron_ba	ase0	(class	in	
sage.geometry.polyhedron.base1), 513  poly_x() (sage.geometry.lattice_polytope_LatticePolytope_Glasy_hedron_base2) (class in method), 190  Polyhedra() (in module sage.geometry.polyhedron.parent), 114  Polyhedra_base (class in sage.geometry.polyhedron.parent), 116  Polyhedra_base (class in sage.geometry.polyhedron.parent), 116  Polyhedra_field (class in sage.geometry.polyhedron.parent), 120  Polyhedra_normaliz (class in sage.geometry.polyhedron.parent), 120  Polyhedra_normaliz (class in sage.geometry.polyhedron.parent), 120  Polyhedra_polymake (class in sage.geometry.polyhedron.parent), 120  Polyhedra_Q_Cdd (class in sage.geometry.polyhedron.parent), 115  Polyhedra_QQ_normaliz (class in sage.geometry.polyhedron.parent), 115  Polyhedra_QQ_ppl (class in sage.geometry.polyhedron.parent), 115  Polyhedra_RDF_cdd (class in sage.geometry.polyhedron.parent), 115  Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.parent), 115  Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.parent), 115  Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.parent), 115  Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.parent), 115  Polyhedra_Complex()  Polyhedron_polymake (class in sage.geometry.polyhedron.backend_normaliz), 640  Polyhedron_polymake (class in sage.geometry.polyhedron.backend_normaliz), 640  Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.backend_normaliz), 640  Polyhedra_Complex()  Polyhedron_polymake (class in sage.geometry.polyhedron.backend_normaliz), 640  Polyhedron_polymake (class in sage.geometry.polyhedron.backend_normaliz), 64	<pre>polar_P2_polytope()</pre>					dron.base0), 49	97	
poly_x() (sage.geometry.lattice_polytope.LatticePolytopeClolyhedron_base2 (class in method), 190  Polyhedra() (in module sage.geometry.polyhedron.parent), 114 Polyhedra_base (class in sage.geometry.polyhedron.parent), 116 Polyhedra_field (class in sage.geometry.polyhedron.parent), 116 Polyhedra_normaliz (class in sage.geometry.polyhedron.parent), 120 Polyhedra_polymake (class in sage.geometry.polyhedron.parent), 120 Polyhedra_QO_cdd (class in sage.geometry.polyhedron.parent), 120 Polyhedra_QO_cdd (class in sage.geometry.polyhedron.parent), 115 Polyhedra_QO_normaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_QO_ppl (class in sage.geometry.polyhedron.parent), 115 Polyhedra_RDF_cdd (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.parent), 115 Polyhedra_Complex() Polyhedro_ppl (class in sage.geometry.polyhedron.backend_normaliz), 649 Polyhedro_ppl (class in sage.geometry.polyhedron.backend_polymake), sage.geometry.polyhedron.parent), 115 Polyhedra_Complex() Polyhedro_ppl (class in sage.geometry.polyhedron.backend_polymake), sage.geometry.polyhedron.parent), 115 Polyhedra_Complex() Polyhedro_ppl (class in sage.geometry.polyhedron.backend_polymake), sage.geometry.polyhedron.parent), 115	sage.geometry.polyhedr	on.ppl_lattice_poly	vgon),	Polyhedron_ba	ase1	(class	in	
method), 190  Polyhedra() (in module sage.geometry.polyhedron.base2), 521  Polyhedra_base (class in sage.geometry.polyhedron.parent), 116  Polyhedra_field (class in sage.geometry.polyhedron.parent), 120  Polyhedra_normaliz (class in sage.geometry.polyhedron.parent), 120  Polyhedra_polymake (class in sage.geometry.polyhedron.parent), 120  Polyhedra_polymake (class in sage.geometry.polyhedron.parent), 120  Polyhedra_Qoldd (class in sage.geometry.polyhedron.parent), 120  Polyhedra_Qolnormaliz (class in sage.geometry.polyhedron.parent), 115  Polyhedra_Qolnormaliz (class in sage.geometry.polyhedron.parent), 115  Polyhedra_Qolnormaliz (class in sage.geometry.polyhedron.parent), 115  Polyhedra_RDF_cdd (class in sage.geometry.polyhedron.parent), 115  Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.parent), 115  Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.parent), 115  Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.parent), 115  Polyhedron_parent), 115  Po	219			sage.g	eometry.polyhe	dron.base1), 5	13	
Polyhedra() (in module sage.geometry.polyhedron.parent), 114 sage.geometry.polyhedron.parent), 115 sage.geometry.polyhedron.backend_normaliz), 640 Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.backend_polymake), 649 Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.parent), 115 sage.geometry.polyhedron.backend_polymake), 649 Polyhedron_parenty.polyhedron.parent), 115 sage.geometry.polyhedron.backend_polymake), 649 Polyhedra_CQ_ppl (class in sage.geometry.polyhedron.parent), 115 sage.geometry.polyhedron.backend_polymake), 649	<pre>poly_x() (sage.geometry.lattice_</pre>	_polytope.LatticePo	lytope	(Aalyhedron_ba	ase2	(class	in	
Polyhedra() (in module sage.geometry.polyhedron.parent), 114 sage.geometry.polyhedron.parent), 115 sage.geometry.polyhedron.backend_normaliz), 640 Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.backend_polymake), 649 Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.parent), 115 sage.geometry.polyhedron.backend_polymake), 649 Polyhedron_parenty.polyhedron.parent), 115 sage.geometry.polyhedron.backend_polymake), 649 Polyhedra_CQ_ppl (class in sage.geometry.polyhedron.parent), 115 sage.geometry.polyhedron.backend_polymake), 649	method), 190			sage.g	eometry.polyhe	dron.base2), 52	21	
sage.geometry.polyhedron.parent), 114 Polyhedra_base (class sage.geometry.polyhedron.parent), 116 Polyhedra_field (class in sage.geometry.polyhedron.parent), 120 Polyhedra_normaliz (class sage.geometry.polyhedron.parent), 120 Polyhedra_polymake (class sage.geometry.polyhedron.parent), 120 Polyhedra_polymake (class sage.geometry.polyhedron.parent), 120 Polyhedra_QQ_cdd (class sage.geometry.polyhedron.parent), 115 Polyhedra_QQ_normaliz (class sage.geometry.polyhedron.parent), 115 Polyhedra_QQ_ppl (class sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.backend_normaliz), 115 Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.backend_polymake), 115 Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.backend_polymake), 115		, me	odule					
Polyhedra_base (class sage.geometry.polyhedron.parent), 116 Polyhedra_field (class in sage.geometry.polyhedron.parent), 120 Polyhedra_normaliz (class in sage.geometry.polyhedron.parent), 120 Polyhedra_polymake (class in sage.geometry.polyhedron.parent), 120 Polyhedra_QQ_cdd (class in sage.geometry.polyhedron.parent), 115 Polyhedra_QQ_normaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_QQ_ppl (class in sage.geometry.polyhedron.parent), 115 Polyhedra_RDF_cdd (class sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.backend_polymake), sage.geometry.polyhedron.parent), 115						dron.base3), 52	27	
sage.geometry.polyhedron.parent), 116 Polyhedra_field (class sage.geometry.polyhedron.parent), 120 Polyhedra_normaliz (class sage.geometry.polyhedron.parent), 120 Polyhedra_polymake (class in sage.geometry.polyhedron.parent), 120 Polyhedra_QO_mormaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_QO_normaliz (class sage.geometry.polyhedron.parent), 115 Polyhedra_QO_ppl (class sage.geometry.polyhedron.parent), 115 Polyhedra_RDF_cdd (class in sage.geometry.polyhedron.parent), 115 Polyhedra_RDF_cdd (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.backend_polymake), sage.geometry.polyhedron.parent), 115 Polyhedra_CZ_ppl (class in sage.geometry.polyhedron.backend_polymake), sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.backend_polymake), sage.geometry.polyhedron.parent), 115 Polyhedra_CZ_ppl (class in sage.geometry.polyhedron.backend_polymake), sage.geometry.polyhedron.parent), 115 Polyhedra_CZ_ppl (class in sage.geometry.polyhedron.backend_polymake), sage.geometry.polyhedron.parent), 115			in					
Polyhedra_field (class sage.geometry.polyhedron.parent), 120 Polyhedra_normaliz (class sage.geometry.polyhedron.parent), 120 Polyhedra_polymake (class in sage.geometry.polyhedron.parent), 120 Polyhedra_polymake (class in sage.geometry.polyhedron.parent), 120 Polyhedra_QCdd (class in sage.geometry.polyhedron.parent), 115 Polyhedra_QQ_normaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_QQ_ppl (class sage.geometry.polyhedron.parent), 115 Polyhedra_QQ_ppl (class sage.geometry.polyhedron.parent), 115 Polyhedra_RNF_cdd (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.backend_normaliz), 115 Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.backend_polymake), 115 Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.backend_polymake), 115	-	*				`		
sage.geometry.polyhedron.parent), 120 Polyhedra_normaliz (class in sage.geometry.polyhedron.parent), 120 Polyhedra_polymake (class in sage.geometry.polyhedron.parent), 120 Polyhedra_QQ_cdd (class in sage.geometry.polyhedron.parent), 115 Polyhedra_QQ_normaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_QQ_ppl (class in sage.geometry.polyhedron.parent), 115 Polyhedra_RDF_cdd (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.backend_polymake), 649 Polyhedron_ppl (class in sage.geometry.polyhedron.ppl (class in sage.geometry.polyhedron.backend_polymake), 649			in					
Polyhedra_normaliz (class in sage.geometry.polyhedron.parent), 120 Polyhedra_polymake (class in sage.geometry.polyhedron.parent), 120 Polyhedra_QQ_cdd (class in sage.geometry.polyhedron.parent), 115 Polyhedra_QQ_normaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_QQ_ppl (class in sage.geometry.polyhedron.parent), 115 Polyhedra_RDF_cdd (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.backend_polymake), sage.geometry.polyhedron.parent), 115		`	.,,			`		
sage.geometry.polyhedron.parent), 120 Polyhedra_polymake (class in sage.geometry.polyhedron.parent), 120 Polyhedra_QQ_cdd (class in sage.geometry.polyhedron.parent), 115 Polyhedra_QQ_normaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_QQ_ppl (class in sage.geometry.polyhedron.parent), 115 Polyhedra_RDF_cdd (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.backend_polymake), sage.geometry.polyhedron.parent), 115 Polyhedra_Complex() Polyhedron_parent, 115 Polyhedron_parent), 115		_	in					
Polyhedra_polymake (class in sage.geometry.polyhedron.parent), 120 Polyhedra_QQ_cdd (class in sage.geometry.polyhedron.parent), 115 Polyhedra_QQ_normaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_QQ_ppl (class in sage.geometry.polyhedron.parent), 115 Polyhedra_RDF_cdd (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.backend_polymake), sage.geometry.polyhedron.parent), 115 Polyhedral_complex() Polyhedron_ppl (class in sage.geometry.polyhedron.backend_polymake), 649 Polyhedron_ppl (class in sage.geometry.polyhedron.backend_polymake), 649 Polyhedron_ppl (class in sage.geometry.polyhedron.ppl)		*	iii	-		`		
sage.geometry.polyhedron.base7), 603  Polyhedra_QQ_cdd (class in sage.geometry.polyhedron.backend_cdd), in Sage.geometry.polyhedron.backend_cdd), in Sage.geometry.polyhedron.backend_cdd), in Sage.geometry.polyhedron.backend_cdd), in Sage.geometry.polyhedron.backend_cdd), in Sage.geometry.polyhedron.parent), 115  Polyhedra_QQ_ppl (class in sage.geometry.polyhedron.backend_field), Sage.geometry.polyhedron.parent), 115  Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.backend_normaliz), in Sage.geometry.polyhedron.backend_normaliz), in Sage.geometry.polyhedron.backend_normaliz), in Sage.geometry.polyhedron.backend_polymake (class in sage.geometry.polyhedron.backend_polymake), sage.geometry.polyhedron.parent), 115  Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.backend_polymake), sage.geometry.polyhedron.parent), 115  Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.backend_polymake), 649  Polyhedron_ppl (class in sage.geometry.polyhedron.backend_polymake), 649			in				_	
Polyhedra_QQ_cdd (class in sage.geometry.polyhedron.parent), 115 Polyhedra_QQ_normaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_QQ_ppl (class in sage.geometry.polyhedron.parent), 115 Polyhedra_RDF_cdd (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.backend_polymake), sage.geometry.polyhedron.parent), 115 Polyhedral_complex() Polyhedron_ppl (class in sage.geometry.polyhedron.backend_polymake), 649 Polyhedron_ppl (class in sage.geometry.polyhedron_ppl (class in sage.geo		`	iri	-		`		
sage.geometry.polyhedron.parent), 115  Polyhedra_QQ_normaliz (class in 639  Polyhedra_QQ_ppl (class in sage.geometry.polyhedron.backend_field), 640  Polyhedra_RDF_cdd (class in 8age.geometry.polyhedron.parent), 115  Polyhedra_ZZ_normaliz (class in 8age.geometry.polyhedron.parent), 115  Polyhedra_ZZ_normaliz (class in 8age.geometry.polyhedron.parent), 115  Polyhedra_ZZ_normaliz (class in 646  Polyhedra_ZZ_ppl (class in 8age.geometry.polyhedron.parent), 115  Polyhedra_ZZ_ppl (class in 8age.geometry.polyhedron.parent), 115  Polyhedra_ZZ_ppl (class in 8age.geometry.polyhedron.backend_normaliz), 8age.geometry.polyhedron.polymake (class in 8age.geometry.polyhedron.backend_polymake), 8age.geometry.polyhedron.parent), 115  Polyhedral_complex()  Polyhedron_ppl (class in 8age.geometry.polyhedron.backend_polymake), 649  Polyhedron_ppl (class in 8age.geometry.polyhedron.ppl) (class in 8age.geometry.polyhedron.backend_polymake), 649  Polyhedron_ppl (class in 8age.geometry.polyhedron.ppl) (class in 8age.geometry.polyhedron.backend_polymake), 649		_					_	
Polyhedra_QQ_normaliz (class in 639  Sage.geometry.polyhedron.parent), 115  Polyhedra_QQ_ppl (class in sage.geometry.polyhedron.parent), 115  Polyhedra_RDF_cdd (class in Sage.geometry.polyhedron.parent), 115  Polyhedra_ZZ_normaliz (class in Sage.geometry.polyhedron.parent), 115  Polyhedra_ZZ_normaliz (class in 646  Sage.geometry.polyhedron.parent), 115  Polyhedra_ZZ_ppl (class in 646  Polyhedron_polymake (class in 646  Polyhedron_polymake (class in sage.geometry.polyhedron.backend_normaliz), in 646  Polyhedron_polymake (class in sage.geometry.polyhedron.backend_polymake), 649  polyhedral_complex()  Polyhedron_ppl (class in 649)	-	•	ın	-		`		
sage.geometry.polyhedron.parent), 115 Polyhedra_QQ_ppl (class in sage.geometry.polyhedron.parent), 115 Polyhedra_RDF_cdd (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.backend_polymake), sage.geometry.polyhedron.parent), 115 Polyhedron_ppl (class in sage.geometry.polyhedron.backend_polymake), 649 Polyhedron_ppl (class in sage.geometry.polyhedron.ppl (class in sage.geometry.polyhedron.backend_polymake), 649 Polyhedron_ppl (class in sage.geometry.polyhedron.ppl (class in sage.geometry.polyhedron.backend_polymake), 649 Polyhedron_ppl (class in sage.geometry.polyhedron.backend_polymake), 649		•			eometry.potyne	aron.backena_	caa),	
Polyhedra_QQ_ppl (class in sage.geometry.polyhedron.backend_field), sage.geometry.polyhedron.parent), 115  Polyhedra_RDF_cdd (class in sage.geometry.polyhedron.parent), 115  Polyhedra_ZZ_normaliz (class in sage.geometry.polyhedron.backend_normaliz), in sage.geometry.polyhedron.backend_normaliz), in 646  Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.backend_polymake), sage.geometry.polyhedron.parent), 115  polyhedral_complex() Polyhedron_ppl (class in sage.geometry.polyhedron.backend_polymake),	-	•	ın			( 1		
sage.geometry.polyhedron.parent), 115  Polyhedra_RDF_cdd (class in Sage.geometry.polyhedron.parent), 115  Polyhedra_ZZ_normaliz (class in Sage.geometry.polyhedron.parent), 115  Polyhedra_ZZ_normaliz (class in Sage.geometry.polyhedron.parent), 115  Polyhedra_ZZ_ppl (class in Sage.geometry.polyhedron.backend_polymake), Sage.geometry.polyhedron.parent), 115  polyhedral_complex() Polyhedron_ppl (class in Sage.geometry.polyhedron.backend_polymake), Sage.geometry.polyhedron_ppl (class in Sage.geometry.polyhedron.backend_polymake), Sage.geometry.polyhedron.backend_polymake), Sage.geometry.polyhedron.backend_polymake), Sage.geometry.polyhedron.backend_polymake), Sage.geometry.polyhedron.backend_polymake), Sage.geometry.polyhedron.backend_polymake), Sage.geometry.polyhedron.parent), 115		_		-		•		
Polyhedra_RDF_cdd (class in sage.geometry.polyhedron.parent), 115 sage.geometry.polyhedron.backend_normaliz), 2 sage.geometry.polyhedron.backend_normaliz), 3 in 646 sage.geometry.polyhedron.parent), 115 Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.backend_polymake), 3 sage.geometry.polyhedron.parent), 115 polyhedral_complex() Polyhedron_ppl (class in sage.geometry.polyhedron.backend_polymake), 649 Polyhedron_ppl (class in sage.geometry.polyhedron_ppl)		,	in		eometry.polyhe	dron.backend_	field),	
sage.geometry.polyhedron.parent), 115  Polyhedra_ZZ_normaliz (class in 646  sage.geometry.polyhedron.parent), 115  Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.backend_polymake), sage.geometry.polyhedron.parent), 115  polyhedral_complex()  Polyhedron_ppl (class in 649)  Polyhedron_ppl (class in 649)		_						
Polyhedra_ZZ_normaliz (class in 646  sage.geometry.polyhedron.parent), 115  Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.backend_polymake), sage.geometry.polyhedron.parent), 115  polyhedral_complex() Polyhedron_ppl (class in	-	,	in	-		•		
sage.geometry.polyhedron.parent), 115 Polyhedron_polymake (class in sage.geometry.polyhedron.backend_polymake), sage.geometry.polyhedron.parent), 115 polyhedral_complex() Polyhedron_polymake (class in sage.geometry.polyhedron.backend_polymake), 649 polyhedral_complex() Polyhedron_ppl (class in		_			eometry.polyhe	dron.backend_	normaliz),	
Polyhedra_ZZ_ppl (class in sage.geometry.polyhedron.backend_polymake), sage.geometry.polyhedron.parent), 115 649 polyhedral_complex() Polyhedron_ppl (class in	Polyhedra_ZZ_normaliz	(class	in	646				
sage.geometry.polyhedron.parent), 115 649 polyhedral_complex() Polyhedron_ppl (class in	sage.geometry.polyhedr	on.parent), 115				,		
sage.geometry.polyhedron.parent), 115 649 polyhedral_complex() Polyhedron_ppl (class in	Polyhedra_ZZ_ppl	(class	in	sage.g	eometry.polyhe	dron.backend_	polymake),	
	sage.geometry.polyhedr	on.parent), 115						
	<pre>polyhedral_complex()</pre>			Polyhedron_pp	ol	(class	in	
	(sage.geometry.triangul	lation.element.Tria	ngulati	on sage.g	eometry.polyhe	dron.backend_	ppl),	

651	method), 462
Polyhedron_QQ (class in	<pre>preimage_fan() (sage.geometry.fan_morphism.FanMorphism</pre>
$sage.geometry.polyhedron.base\_QQ), 620$	method), 463
	<pre>prepare_inner_loop()</pre>
sage.geometry.polyhedron.backend_cdd), 638	(sage.geometry.integral_points.InequalityCollection method), 756
Polyhedron_QQ_normaliz (class in	<pre>prepare_next_to_inner_loop()</pre>
sage.geometry.polyhedron.backend_normaliz),	(sage.geometry.integral_points.InequalityCollection
640	method), 756
Polyhedron_QQ_polymake (class in	<pre>primitive() (sage.geometry.hyperplane_arrangement.hyperplane.Hyper</pre>
sage.geometry.polyhedron.backend_polymake),	method), 52
648	<pre>primitive_collections()</pre>
Polyhedron_QQ_ppl (class in	(sage.geometry.fan.RationalPolyhedralFan
sage.geometry.polyhedron.backend_ppl),	method), 445
650	<pre>primitive_preimage_cones()</pre>
Polyhedron_RDF (class in	(sage.geometry.fan_morphism.FanMorphism
sage.geometry.polyhedron.base_RDF), 638	method), 463
Polyhedron_RDF_cdd (class in	<pre>print_cache()</pre>
sage.geometry.polyhedron.backend_cdd_rdf),	sage.geometry.integral_points), 760
639	$\verb"prism()" (sage.geometry.polyhedron.base 5. Polyhedron\_base 5$
Polyhedron_ZZ (class in	method), 581
sage.geometry.polyhedron.base_ZZ), 632	${\tt Problem}({\it classinsage.geometry.polyhedron.double\_description}),$
Polyhedron_ZZ_normaliz (class in	657
sage.geometry.polyhedron.backend_normaliz),	product() (sage.geometry.polyhedral_complex.PolyhedralComplex
645	method), 330
	product() (sage.geometry.polyhedron.base5.Polyhedron_base5
sage.geometry.polyhedron.backend_polymake), 648	method), 581
	project_points() (in module
, – –	sage.geometry.polyhedron.library), 105
sage.geometry.polyhedron.backend_ppl), 651	Projection (class in sage.geometry.polyhedron.plot), 134
	<pre>projection() (sage.geometry.polyhedron.base6.Polyhedron_base6</pre>
sage.geometry.polyhedron.face), 145	method), 599
·	<pre>projection_func_identity() (in module</pre>
sage.geometry.polyhedron.combinatorial_polyhe	
282	ProjectionFuncSchlegel (class in
PolyhedronRepresentation (class in	sage.geometry.polyhedron.plot), 142
sage.geometry.polyhedron.representation),	ProjectionFuncStereographic (class in
127	sage.geometry.polyhedron.plot), 142
Polytopes (class in sage.geometry.polyhedron.library),	<pre>projective() (sage.geometry.triangulation.base.Point</pre>
62	method), 686
<pre>poset_of_regions() (sage.geometry.hyperplane_arrang</pre>	,
method), 30	sage.geometry.pseudolines), 742
<pre>positive_circuits()</pre>	<pre>pushing_triangulation()</pre>
	n.PointConf <b>(gagatgeo</b> metry.triangulation.point_configuration.PointConfigur
method), 675	method), 676
	pyramid() (sage.geometry.polyhedron.base5.Polyhedron_base5
sage.geometry.lattice_polytope), 209	method), 582
positive_operators_gens()  (sage geometry cone Convex Pational Polyhedrall	<pre>pyramid() (sage.geometry.polyhedron.combinatorial_polyhedron.base.Come method), 264</pre>
(sage.geometry.cone.ConvexRationalPolyhedral) method), 389	_one method), 204  pyramid() (sage.geometry.polyhedron.combinatorial_polyhedron.list_of_
prefix_check() (in module	method), 305
sage.rings.polynomial.groebner_fan), 496	нинои), 505
suge.i ings.porynomiai.groedner_jani, 490	

preimage\_cones() (sage.geometry.fan\_morphism.FanMorphism

Q	read_palp_point_collection() (in module
<pre>quotient() (sage.geometry.toric_lattice_ToricLattice_gen</pre>	eric sage.geometry.point_collection), 472
method), 342	rearrangement() (in module
D	sage.geometry.cone_catalog), 413
R	rectangular_box_points() (in module
R_by_sign() (sage.geometry.polyhedron.double_description method), 653	rectified_one_nundred_twenty_cerr()
radius() (sage.geometry.polyhedron.base.Polyhedron_ba	se (sage.geometry.polyhedron.library.Polytopes
mathad) 618	method), 85
radius_square() (sage.geometry.polyhedron.base.Polyhe	rectified_six_hundred_cell() edron_base
method), 618	(sage.geometry.polyhedron.library.Polytopes method), 85
random_cone() (in module sage.geometry.cone), 409	recycle() (sage geometry polyhedron parent Polyhedra, base
*** at lead \ 201	Precycle (sage geometry polyhedron parent Polyhedra base method), 119
random_element() (sage.geometry.linear_expression.Lin method), 719	reduced() (sage geometry.ribbon_graph.RibbonGraph earExpressionModule method), 737
random_inequalities() (in module	<pre>reduced_affine() (sage.geometry.triangulation.base.Point</pre>
sage.geometry.polyhedron.double_description),	method), 687
660	reduced_affine_vector()
<pre>random_integral_point()</pre>	(sage.geometry.triangulation.base.Point
(sage.geometry.polyhedron.base2.Polyhedron_ba	method), 687
method), 526	reduced_affine_vector_space()
rank() (sage.geometry.hyperplane_arrangement.arrangement.dr angement.dr arrangement.dr arrangeme	nent.HyperpianeArrangementElement method), 691
rank() (sage.geometry.toric_lattice.ToricLattice_quotient	reduced_groebner_bases()
method), 348	(sage.rings.polynomial.groebner_fan.GroebnerFan
RationalPolyhedralFan (class in sage.geometry.fan),	method), 486
428	reduced_projective()
Ray (class in sage.geometry.polyhedron.representation),	(sage.geometry.triangulation.base.Point
129	<pre>method), 688 reduced_projective_vector()</pre>
ray() (sage.geometry.cone.IntegralRayCollection	(sage.geometry.triangulation.base.Point
method), 406	
ray_generator() (sage.geometry.polyhedron.base0.Polyhedron), 509	
<pre>ray_generator() (sage.geometry.polyhedron.face.Polyhe</pre>	edronFace (sage.geometry.triangulation.base.PointConfiguration_base
method), 154	method), 692
ray_matrix_normal_form() (in module	ReducedGroebnerBasis (class in sage.rings.polynomial.groebner_fan), 494
sage.geometry.integral_points), 760	Reflexive4dHodge (class in
rays() (sage.geometry.cone.IntegralRayCollection	sage.geometry.polyhedron.palp_database),
method), 406	216
rays() (sage.geometry.polyhedron.base0.Polyhedron_base method), 509	ReflexivePolytope() (in module
rays() (sage.geometry.polyhedron.face.PolyhedronFace method), 154	sage.geometry.lattice_polytope), 204 ReflexivePolytopes() (in module
rays() (sage.rings.polynomial.groebner_fan.InitialForm	sage.geometry.lattice_polytope), 204
method), 490	region_containing_point()
rays() (sage.rings.polynomial.groebner_fan.PolyhedralFa	in (sage.geometry.hyperplane_arrangement.arrangement.Hyperplan
J. D. 404	method), 31
rays_list() (sage.geometry.polyhedron.base0.Polyhedro method), 509	regions() (sage.geometry.hyperplane_arrangement.arrangement.Hyperpl method), 32
read_all_polytopes() (in module	$\verb"regions"()" (sage.geometry.voronoi\_diagram.VoronoiDiagram")$
sage.geometry.lattice_polytope), 209	method), 747
read_palp_matrix() (in module	regular_polygon() (sage.geometry.polyhedron.library.Polytopes

sage.geometry.lattice\_polytope), 210

method), 86

relative_boundary_cells()	_	(sage.geometry.polyh	edron.plot.Projec	etion
(sage.geometry.polyhedral_complex.PolyhedralC	_	method), 137		7 . 70
method), 330	render_	points_1d() (sage.g	eometry.polyhedr	on.plot.Projection
relative_interior()	~mamdam	method), 137	a a a a a tura e a la la a de	non mlat Duaisation
(sage.geometry.cone.ConvexRationalPolyhedralC	aneenaer_	.points_2d() (sage.g method), 138	eometry.potynear	on.pioi.Projection
<pre>method), 392 relative_interior()</pre>	rondor	, · ·	try nolyhadron ha	use6.Polyhedron_base6
(sage.geometry.convex_set.ConvexSet_base	renuer_	method), 599	ır y.porynearon.bc	iseo.1 oryneuron_baseo
method), 709	render	_solid_3d()(sage.ge	ometry polyhedro	n plot Projection
relative_interior()	r chacr_	method), 138	omen y.porymeuro	n.pioi.i rojection
(sage.geometry.polyhedron.base1.Polyhedron_ba	<i>ıs</i> ₽ <b>∉</b> nder_	* *		
method), 520		(sage.geometry.polyh	edron.plot.Projec	rtion
relative_interior()		method), 138	1	
(sage.geometry.relative_interior.RelativeInterior	render_	wireframe()(sage.g	eometry.polyhedr	on.base6.Polyhedron_bas
method), 726		method), 599		
relative_interior_contains()	render_	wireframe_3d()		
(sage. geometry. cone. Convex Rational Polyhedral Rational Polyhedral Rational Polyhedral Rational R	Cone	(sage.geometry.polyh	edron.plot.Projec	rtion
method), 393		method), 138		
relative_interior_contains()	repr_pr	• "	(in	module
(sage.geometry.polyhedron.base1.Polyhedron_ba	ise1	sage.geometry.polyhe	edron.representati	ion),
method), 520		133		
relative_interior_point()			y.polyhedron.rep	resentation.Hrepresentati
(sage.rings.polynomial.groebner_fan.Polyhedral		method), 124		
method), 491	represe	ntative_point()		7
relative_orthogonal_quotient()	~	(sage.geometry.conve	x_set.ConvexSet_	_base
(sage.geometry.cone.ConvexRationalPolyhedralC		method), 709		
<pre>method), 393 relative_quotient()</pre>	represe	entative_point() (sage.geometry.polyh	adron basal Poly	hadron hasal
(sage.geometry.cone.ConvexRationalPolyhedralC	Cone	method), 521	earon.vase1.1 oiy	neuron_ouser
method), 394		entative_point()		
relative_star_generators()	represe	(sage.geometry.relati	ve interior Relati	veInterior
(sage.geometry.fan_morphism.FanMorphism		method), 726	re_inierioniteiaii	retitiertor
method), 464	reset()		edron.combinator	rial_polyhedron.face_itera
RelativeInterior (class in	()	method), 298		···· <b>_</b> r · · , · · · · · · · · · · · · · · · ·
sage.geometry.relative_interior), 723	reset()	* *	edron.combinatoi	rial_polyhedron.face_itera
remove_cell() (sage.geometry.polyhedral_complex.Polyh				<b>4</b>
method), 331		ptions()	(in	module
render() (sage.rings.polynomial.groebner_fan.Groebnerl	Fan	sage.geometry.toric_p	plotter), 481	
method), 487		t_to_connected_tr	iangulations(	)
render3d() (sage.rings.polynomial.groebner_fan.Groebner_f	erFan	(sage.geometry.triang method), 677	gulation.point_co	nfiguration.PointConfigur
<pre>render_0d() (sage.geometry.polyhedron.plot.Projection</pre>	restric	t_to_fine_triangu	lations()	
method), 135		(sage.geometry.triang	gulation.point_co	nfiguration.PointConfigur
${\tt render\_1d()} \ (sage.geometry.polyhedron.plot.Projection$		method), 677		
method), 135	restric	t_to_regular_tria		
render_2d() (sage.geometry.polyhedron.plot.Projection method), 135		(sage.geometry.triang method), 678	gulation.point_co	nfiguration.PointConfigur
render_3d() (sage.geometry.polyhedron.plot.Projection	restric			
method), 136			gulation.point_co	nfiguration.PointConfigur
render_fill_2d() (sage.geometry.polyhedron.plot.Proje		method), 678		
method), 137		ted_automorphism_		1 1 1 4
render_line_1d() (sage.geometry.polyhedron.plot.Proje	ection	(sage.geometry.polyh	earon.base4.Poly	nearon_base4
method), 137	maa+	method), 565	~~~·~ ()	
render_outline_2d()	restric	ted_automorphism_	group()	

```
(sage.geometry.polyhedron.ppl_lattice_polytope.Lattige_RgdomptryPhlypotryplane_arrangement.affine_subspace
        method), 232
                                                      module, 53
restricted_automorphism_group()
                                                  sage.geometry.hyperplane_arrangement.arrangement
        (sage.geometry.triangulation.point_configuration.PointCodyfigeration
        method), 679
                                                  sage.geometry.hyperplane_arrangement.check_freeness
restriction() (sage.geometry.hyperplane arrangement.arrangementElement
                                                  sage.geometry.hyperplane_arrangement.hyperplane
        method), 33
reverse() (sage.geometry.newton_polygon.NewtonPolygon_elemodule, 46
        method), 720
                                                  sage.geometry.hyperplane_arrangement.library
           (sage.geometry.ribbon_graph.RibbonGraph
rho()
                                                      module, 40
        method), 738
                                                  sage.geometry.hyperplane_arrangement.plot
rhombic_dodecahedron()
                                                      module, 56
        (sage.geometry.polyhedron.library.Polytopes
                                                  sage.geometry.integral_points
        method), 86
                                                      module, 755
rhombicosidodecahedron()
                                                  sage.geometry.lattice_polytope
        (sage.geometry.polyhedron.library.Polytopes
                                                      module, 159
                                                  sage.geometry.linear_expression
        method), 87
RibbonGraph (class in sage.geometry.ribbon_graph),
                                                      module, 713
                                                  sage.geometry.newton_polygon
ridges() (sage.geometry.polyhedron.combinatorial polyhedronmodsirl@oinbinatorialPolyhedron
        method), 266
                                                  sage.geometry.point_collection
ring() (sage.rings.polynomial.groebner_fan.GroebnerFan
                                                      module, 465
        method), 487
                                                  sage.geometry.polyhedral_complex
ring_to_gfan_format()
                                         module
                                                      module, 310
                               (in
        sage.rings.polynomial.groebner_fan), 497
                                                  sage.geometry.polyhedron.backend_cdd
run() (sage.geometry.polyhedron.double_description.StandardAngoduilhen 638
        method), 659
                                                  sage.geometry.polyhedron.backend_cdd_rdf
runcinated_one_hundred_twenty_cell()
                                                      module, 639
        (sage.geometry.polyhedron.library.Polytopes
                                                  sage.geometry.polyhedron.backend_field
        method), 88
                                                      module, 639
runcitruncated_one_hundred_twenty_cell()
                                                  sage.geometry.polyhedron.backend_normaliz
        (sage.geometry.polyhedron.library.Polytopes
                                                      module, 640
        method), 88
                                                  sage.geometry.polyhedron.backend_polymake
runcitruncated_six_hundred_cell()
                                                      module, 648
        (sage.geometry.polyhedron.library.Polytopes
                                                  sage.geometry.polyhedron.backend_ppl
        method), 89
                                                      module, 650
                                                  sage.geometry.polyhedron.base
S
                                                      module, 610
                                                  sage.geometry.polyhedron.base0
sage.geometry.abc
                                                      module, 497
    module, 701
                                                  sage.geometry.polyhedron.base1
sage.geometry.cone
                                                      module, 513
    module, 352
                                                  sage.geometry.polyhedron.base2
sage.geometry.cone_catalog
                                                      module, 521
    module, 412
                                                  sage.geometry.polyhedron.base3
sage.geometry.convex_set
                                                      module, 527
    module, 702
                                                  sage.geometry.polyhedron.base4
sage.geometry.fan
                                                      module, 556
    module, 417
                                                  sage.geometry.polyhedron.base5
sage.geometry.fan_isomorphism
                                                      module, 570
    module, 749
                                                  sage.geometry.polyhedron.base6
sage.geometry.fan_morphism
                                                      module, 587
    module, 449
                                                  sage.geometry.polyhedron.base7
sage.geometry.hasse_diagram
                                                      module, 603
    module, 753
```

```
sage.geometry.polyhedron.base_QQ
                                                                                  sage.geometry.toric_plotter
                                                                                         module, 473
      module, 620
sage.geometry.polyhedron.base_RDF
                                                                                  sage.geometry.triangulation.base
      module, 638
                                                                                         module, 684
sage.geometry.polyhedron.base_ZZ
                                                                                  sage.geometry.triangulation.element
      module, 632
                                                                                         module, 693
sage.geometry.polyhedron.cdd_file_format
                                                                                  sage.geometry.triangulation.point_configuration
      module, 156
                                                                                         module, 665
sage.geometry.polyhedron.combinatorial_polyhedramge bgwsmmetry.voronoi_diagram
      module, 235
                                                                                         module, 744
sage.geometry.polyhedron.combinatorial_polyhedragecoimbgsnaptoolryiadmifalcegroebner_fan
                                                                                         module, 482
      module, 271
sage.geometry.polyhedron.combinatorial_polyhedravnischieversioence.lities()
      module, 306
                                                                                                (sage.geometry.integral_points.InequalityCollection
sage.geometry.polyhedron.combinatorial_polyhedron.fac@naiheda,tor/
      module, 284
                                                                                  saturation() (sage.geometry.toric_lattice.ToricLattice_generic
sage.geometry.polyhedron.combinatorial_polyhedron.listmedfiedaces
                                                                                  schlegel() (sage.geometry.polyhedron.plot.Projection
      module, 302
sage.geometry.polyhedron.combinatorial_polyhedron.polyhedron.polyhedron.face_lattice
      module, 282
                                                                                  schlegel_projection()
sage.geometry.polyhedron.constructor
                                                                                                (sage.geometry.polyhedron.base6.Polyhedron_base6
      module, 106
                                                                                                method), 600
sage.geometry.polyhedron.double_description
                                                                                  schur() (in module sage.geometry.cone_catalog), 415
                                                                                  secondary_polytope()
      module, 653
sage.geometry.polyhedron.double_description_inhomogen@mage.geometry.triangulation.point_configuration.PointConfigura
      module, 660
                                                                                               method), 680
sage.geometry.polyhedron.face
                                                                                  sector() (in module sage.geometry.toric_plotter), 481
      module, 144
                                                                                  semigroup_generators()
sage.geometry.polyhedron.lattice_euclidean_group_elementge.geometry.cone.ConvexRationalPolyhedralCone
      module, 213
                                                                                                method), 395
sage.geometry.polyhedron.library
                                                                                  semiorder() (sage.geometry.hyperplane_arrangement.library.Hyperplane
      module, 61
                                                                                                method), 45
{\tt sage.geometry.point\_collection.modules.formal\_polyheskra()} nod ({\tt winge.geometry.point\_collection.PointCollection}) and {\tt collection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.pointCollection.p
                                                                                                method), 471
      module, 157
sage.geometry.polyhedron.palp_database
                                                                                  set_engine() (sage.geometry.triangulation.point_configuration.PointCon
      module, 215
                                                                                                class method), 680
sage.geometry.polyhedron.parent
                                                                                  set_immutable() (sage.geometry.polyhedral_complex.PolyhedralComple
      module, 114
                                                                                                method), 332
sage.geometry.polyhedron.plot
                                                                                  set_immutable() (sage.geometry.polyhedron.backend_ppl.Polyhedron_ppl
      module, 134
                                                                                               method), 652
sage.geometry.polyhedron.ppl_lattice_polygon set_immutable() (sage.geometry.toric_lattice_ToricLattice_quotient_elen
                                                                                               method), 348
      module, 217
sage.geometry.polyhedron.ppl_lattice_polytope set_palp_dimension()
                                                                                                                                    (in
                                                                                                                                                       module
      module, 221
                                                                                               sage.geometry.lattice_polytope), 211
sage.geometry.polyhedron.representation
                                                                                  set_rays()
                                                                                                        (sage.geometry.toric_plotter.ToricPlotter
      module, 120
                                                                                                method), 478
sage.geometry.pseudolines
                                                                                  SetOfAllLatticePolytopesClass
                                                                                                                                              (class
      module, 740
                                                                                                sage.geometry.lattice_polytope), 205
sage.geometry.relative_interior
                                                                                  Shi() (sage.geometry.hyperplane_arrangement.library.HyperplaneArrangement.library.
      module, 723
                                                                                                method), 42
                                                                                  show() (sage.geometry.polyhedron.base6.Polyhedron_base6
sage.geometry.ribbon_graph
      module, 727
                                                                                               method), 601
sage.geometry.toric_lattice
                                                                                  show() (sage.geometry.pseudolines.PseudolineArrangement
      module, 336
                                                                                               method), 743
```

```
show3d() (sage.geometry.lattice_polytope.LatticePolytopeCpan() (sage.geometry.toric_lattice_ToricLattice_generic
                  method), 191
                                                                                                                                    method), 343
                         (sage.geometry.ribbon graph.RibbonGraph span_of_basis() (sage.geometry.toric lattice.ToricLattice generic
sigma()
                                                                                                                                    method), 344
                  method), 738
sign_vector() (sage.geometry.hyperplane_arrangement.astacqe()e(stuble):geophatryApvly);qudmontblusmeiPolyhedron_base5
                                                                                                                                    method), 582
                  method), 34
simplex() (sage.geometry.polyhedron.library.Polytopes stacking_locus() (sage.geometry.polyhedron.face.PolyhedronFace
                  method), 89
                                                                                                                                    method), 154
simplex_points()
                                                                (in
                                                                                              module StandardAlgorithm
                                                                                                                                                                                     (class
                                                                                                                                                                                                                          in
                  sage.geometry.integral_points), 763
                                                                                                                                    sage.geometry.polyhedron.double_description),
simplex\_to\_int() (sage.geometry.triangulation.base.PointConfiguration\_base
                                                                                                                 {\tt StandardDoubleDescriptionPair}
                  method), 692
simplicial_complex()
                                                                                                                                    sage.geometry.polyhedron.double_description),
                                                                                                                                    659
                  (sage.geometry.triangulation.element.Triangulation
                  method), 699
                                                                                                                 Stanley_Reisner_ideal()
{\tt simpliciality()} \ (sage.geometry.polyhedron.base 3. Polyhedron\_bas (sage.geometry.fan.Rational Polyhedral Fannal P
                  method), 551
                                                                                                                                    method), 429
simpliciality() (sage.geometry.polyhedron.combinatorist_axolybeadvon.DaksaGeogdvimetwyithildvolghkadion.point_configuration.PointCo
                  method), 267
                                                                                                                                    method), 681
simplicity()(sage.geometry.polyhedron.base3.Polyhedrost_brasgenerator_indices()
                  method), 552
                                                                                                                                    (sage.geometry.fan.Cone_of_fan
                                                                                                                                                                                                             method),
simplicity()(sage.geometry.polyhedron.combinatorial_polyhedron4&dse.CombinatorialPolyhedron
                  method), 268
                                                                                                                 star_generators()
                                                                                                                                                                (sage.geometry.fan.Cone_of_fan
six_hundred_cell() (sage.geometry.polyhedron.library.Polytopes method), 421
                                                                                                                 stereographic() (sage.geometry.polyhedron.plot.Projection
                  method), 90
skeleton() (sage.geometry.lattice_polytope.LatticePolytopeClass method), 140
                  method), 192
                                                                                                                 stratify() (sage.geometry.polyhedral_complex.PolyhedralComplex
skeleton_points() (sage.geometry.lattice_polytope.LatticePolytopenCelthroxd), 332
                                                                                                                 strict_quotient() (sage.geometry.cone.ConvexRationalPolyhedralCone
                  method), 192
skeleton_show() (sage.geometry.lattice_polytope.LatticePolytopeChasthod), 398
                   method), 193
                                                                                                                 sub_polytope_generator()
skip_palp_matrix()
                                                                   (in
                                                                                               module
                                                                                                                                    (sage.geometry.polyhedron.ppl_lattice_polytope.LatticePolytope_
                  sage.geometry.lattice_polytope), 211
                                                                                                                                    method), 233
slack_matrix() (sage.geometry.polyhedron.base3.Polyhedruhn_balkylopes() (sage.geometry.polyhedron.ppl_lattice_polygon.Lattice
                  method), 552
                                                                                                                                    method), 218
slopes() (sage.geometry.newton_polygon.NewtonPolygon_salkon_reeflexive_polygons()
                                                                                                                                                                                                                module
                                                                                                                                                                                           (in
                  method), 720
                                                                                                                                    sage.geometry.polyhedron.ppl lattice polygon),
small_rhombicuboctahedron()
                                                                                                                                    219
                   (sage.geometry.polyhedron.library.Polytopes
                                                                                                                 subdirect_sum() (sage.geometry.polyhedron.base5.Polyhedron_base5
                  method), 91
                                                                                                                                    method), 584
snub_cube() (sage.geometry.polyhedron.library.Polytopes subdivide() (sage.geometry.fan.RationalPolyhedralFan
                  method), 92
                                                                                                                                    method), 445
snub_dodecahedron()
                                                                                                                 subdivide() (sage.geometry.polyhedral complex.PolyhedralComplex
                  (sage.geometry.polyhedron.library.Polytopes
                                                                                                                                    method), 332
                                                                                                                 \verb|sublattice()| (sage.geometry.cone.ConvexRationalPolyhedralCone|)|
                  method), 93
                                                                                                                                    method), 398
solid_restriction()
                  (sage.geometry.cone.ConvexRationalPolyhedralConvblattice_complement()
                  method), 397
                                                                                                                                    (sage.geometry.cone.ConvexRationalPolyhedralCone
some_elements() (sage.geometry.convex_set.ConvexSet_base
                                                                                                                                    method), 399
                                                                                                                 sublattice_quotient()
                   method), 710
\verb|some_elements()| (sage.geometry.polyhedron.parent.Polyhedra\_bas \& sage.geometry.cone.Convex Rational Polyhedral Cone)| (sage.geometry.polyhedron.parent.Polyhedra\_bas \& sage.geometry.cone.Convex Rational Polyhedral Cone)| (sage.geometry.polyhedron.parent.Polyhedra\_bas \& sage.geometry.cone)| (sage.geometry.polyhedron.parent.Polyhedra\_bas \& sage.geometry.cone)| (sage.geometry.polyhedron.parent.Polyhedra\_bas \& sage.geometry.cone)| (sage.geometry.cone)| (sage
                  method), 119
                                                                                                                                    method), 400
span()
                           (sage.geometry.cone.IntegralRayCollection subpolygons_of_polar_P1xP1()
                                                                                                                                                                                                (in
                                                                                                                                                                                                                module
                  method), 407
                                                                                                                                    sage.geometry.polyhedron.ppl lattice polygon),
```

220	<pre>translation() (sage.geometry.polyhedron.base5.Polyhedron_base5</pre>
<pre>subpolygons_of_polar_P2()</pre>	method), 585
sage.geometry.polyhedron.ppl_lattice_polygon), 220	translation() (sage.geometry.relative_interior.RelativeInterior method), 727
<pre>subpolygons_of_polar_P2_112() (in module</pre>	transpositions() (sage.geometry.pseudolines.PseudolineArrangement
sage.geometry.polyhedron.ppl_lattice_polygon),	method), 743
220	<pre>traverse_boundary()</pre>
<pre>support_contains() (sage.geometry.fan.RationalPolyhea method), 446</pre>	lralFan (sage.geometry.lattice_polytope.LatticePolytopeClass method), 193
	triangulate() (sage.geometry.polyhedron.base7.Polyhedron_base7
(sage.geometry.integral_points.InequalityCollecti	on method), 605
	$\verb triangulate()  (sage.geometry.triangulation.point\_configuration.PointCollege (sage.geometry.triangulation.point\_configuration.point\_config$
<pre>symmetric_edge_polytope()</pre>	method), 681
(sage.geometry.polyhedron.library.Polytopes	Triangulation (class in
static method), 93	sage.geometry.triangulation.element), 693
${\tt symmetric\_space()} \ (sage.geometry.hyperplane\_arranger)$	nterit.dnygatpoltnionAmbiodeYeAdhSpace (in module
method), 48	sage.geometry.triangulation.element), 700
<b>T</b>	triangulation_render_3d() (in module
T	sage.geometry.triangulation.element), 700
tetrahedron() (sage.geometry.polyhedron.library.Polytop	$\textbf{griangulations()} \ (sage.geometry.triangulation.point\_configuration.Point\_configu$
method), 95	method), 682
$\verb+tikz()+ (sage.geometry.polyhedron.base 6. Polyhedron\_base)$	∱riangulations_list()
method), 601	(sage.geometry.triangulation.point_configuration.PointConfigura
tikz() (sage.geometry.polyhedron.plot.Projection	method), 683
method), 140	trivial() (in module sage.geometry.cone_catalog), 416
to_linear_program()	tropical_basis()(sage.rings.polynomial.groebner_fan.GroebnerFan
(sage.geometry.polyhedron.base.Polyhedron_base	method), 488
method), 618	tropical_intersection()
to_RationalPolyhedralFan()	(sage.rings.polynomial.groebner_fan.GroebnerFan
(sage.rings.polynomial.groebner_fan.PolyhedralF	Tan method), 488
method), 494	TropicalPrevariety (class in
to_symmetric_space()	sage.rings.polynomial.groebner_fan), 495
method), 53	ж <b>ын</b> с <b>ры pst<sub>aku</sub>be()</b> (sage.geometry.polyhedron.library.Polytopes method), 96
$\verb"toric_variety"() (sage. geometry. fan. Rational Polyhedral Interpretation of the property $	rtmuncated_dodecahedron()
method), 446	(sage.geometry.polyhedron.library.Polytopes
ToricLattice_ambient (class in	method), 96
sage.geometry.toric_lattice), 339	truncated_icosidodecahedron()
ToricLattice_generic (class in	(sage.geometry.polyhedron.library.Polytopes
sage.geometry.toric_lattice), 341	method), 97
Tot Tellace Equocities (crass in	truncated_octahedron()
sage.geometry.toric_lattice), 345	(sage.geometry.polyhedron.library.Polytopes
ToricLattice_quotient_element (class in	method), 98
sage.geometry.toric_lattice), 348	truncated_one_hundred_twenty_cell()
ToricLattice_sublattice (class in	(sage.geometry.polyhedron.library.Polytopes
sage.geometry.toric_lattice), 349	method), 99
	truncated_six_hundred_cell()
sage.geometry.toric_lattice), 349	(sage.geometry.polyhedron.library.Polytopes
ToricLatticeFactory (class in	method), 99
sage.geometry.toric_lattice), 338	truncated_tetrahedron()
ToricPlotter (class in sage.geometry.toric_plotter), 473	(sage.geometry.polyhedron.library.Polytopes method), 99
translation() (sage.geometry.convex_set.ConvexSet_base method), 710	truncation() (sage.geometry.polyhedron.base5.Polyhedron_base5 method), 585

```
twenty_four_cell() (sage.geometry.polyhedron.library.Rodytopxs_facet_graph()
                                    method), 100
                                                                                                                                                                                                                                                          (sage.geometry.polyhedron.combinatorial polyhedron.base.Comb
                                                                                                                                                                                                                                                        method), 269
type() (sage.geometry.polyhedron.representation.Equation
                                    method), 121
                                                                                                                                                                                                                     vertex_facet_pairing_matrix()
type() (sage.geometry.polyhedron.representation.Inequality
                                                                                                                                                                                                                                                          (sage.geometry.lattice_polytope.LatticePolytopeClass
                                   method), 126
                                                                                                                                                                                                                                                         method), 193
                                   (sage.geometry.polyhedron.representation.Line
                                                                                                                                                                                                                  vertex_generator() (sage.geometry.polyhedron.base0.Polyhedron base
type()
                                    method), 127
                                                                                                                                                                                                                                                         method), 509
                                      (sage.geometry.polyhedron.representation.Ray
                                                                                                                                                                                                                     vertex_generator() (sage.geometry.polyhedron.face.PolyhedronFace
type()
                                    method), 130
                                                                                                                                                                                                                                                         method), 155
type() (sage.geometry.polyhedron.representation.Vertex
                                                                                                                                                                                                                     vertex_graph() (sage.geometry.fan.RationalPolyhedralFan
                                    method), 131
                                                                                                                                                                                                                                                         method), 446
                                                                                                                                                                                                                     vertex_graph() (sage.geometry.polyhedron.base4.Polyhedron_base4
U
                                                                                                                                                                                                                                                         method), 569
                                                                                                                                                                                                                     vertex_graph() (sage.geometry.polyhedron.combinatorial_polyhedron.be
unbounded_regions()
                                    (sage.geometry.hyperplane_arrangement.arrangement.HyperplaneArrangementElement
                                                                                                                                                                                                                     vertices() (sage.geometry.hyperplane_arrangement.arrangement.Hyperp
                                   method), 34
union() (sage.geometry.hyperplane_arrangement.arrangement.HyperplateArrangementElement
                                                                                                                                                                                                                     vertices() (sage.geometry.lattice_polytope.LatticePolytopeClass
                                    method), 35
                                                                                                                                                                                                                                                         method), 194
union() (sage.geometry.polyhedral_complex.PolyhedralComplex
                                                                                                                                                                                                                     vertices() (sage.geometry.newton_polygon.NewtonPolygon_element
                                   method), 333
                                                                                                                                                                                                                                                         method), 721
union_as_polyhedron()
                                    (sage.geometry.polyhedral_complex.PolyhedralComplexces() (sage.geometry.polyhedron.base0.Polyhedron_base0
                                                                                                                                                                                                                                                         method), 510
                                   method), 334
\verb"universe()" (sage.geometry.polyhedron.parent.Polyhedra\_\textit{Nexe} \texttt{tices()}" (sage.geometry.polyhedron.combinatorial\_polyhedron.base. Combinatorial\_polyhedron.base. Combinatorial\_polyh
                                                                                                                                                                                                                                                          method), 270
                                    method), 119
                                                                                                                                                                                                                     vertices() (sage.geometry.polyhedron.face.PolyhedronFace
 V
                                                                                                                                                                                                                                                          method), 155
varchenko_matrix() (sage.geometry.hyperplane_arrangement.arrangement.flyperplaneArrangementElement
                                                                                                                                                                                                                                                          method), 23
                                   method), 35
\verb|vector()| (sage.geometry.polyhedron.representation.PolyhedronRepresentation]| (sage.geometry.polyhedron.base0.Polyhedron\_base0)| (sage.geometry.polyhedron.base0.Polyhedron\_base0)| (sage.geometry.polyhedron.base0)| (sage.geometry.base0)| (sage.geometry.polyhedron.base0)| (sage.geometry.polyhedron.base0)| (sage.geometry.polyhedron.base0)| (sage.geometry.polyhedron.base0)| (sage.geometry.polyhedron.base0)| (sage.geometry.base0)| (sage.geometry.polyhedron.base0)| (sage.geometry.polyhedron.base0)| (sage.geometry.polyhedron.base0)| (sage.geometry.polyhedron.base0)| (sage.geometry.polyhedron.base0)| (sage.geometry
                                                                                                                                                                                                                                                         method), 511
                                    method), 128
{\tt verify()} \ (sage.geometry.polyhedron.double\_description.DoubleDescriptionPair} \ (sage.geometry.polyhedron.base 0.Polyhedron\_base 0.
                                    method), 656
verify()(sage.geometry.polyhedron.double_description_inhomogeneous.Hrep2Vieb
                                                                                                                                                                                                                                                          (sage.geometry.polyhedron.ppl_lattice_polytope.LatticePolytope_
                                    method), 661
verify()(sage.geometry.polyhedron.double_description_inhomogeneous.Vrep2Hrep_method) 663 verts_for_normal()
                                                                                                                                                                                                                                                                                                                                                                                                       module
                                    method), 663
                                                                                                                                                                                                                                                          sage.rings.polynomial.groebner fan), 497
Vertex\ (class\ in\ sage.geometry.polyhedron.representation),
                                                                                                                                                                                                                       virtual_rays()(sage.geometry.fan.RationalPolyhedralFan
                                                                                                                                                                                                                                                         method), 447
vertex() (sage.geometry.lattice_polytope.LatticePolytopeClass
                                                                                                                                                                                                                      volume() (sage.geometry.polyhedron.base7.Polyhedron base7
                                    method), 193
                                                                                                                                                                                                                                                         method), 607
vertex_adjacency_matrix()
                                    (sage. geometry. polyhedron. base 3. Polyhedron\_base 3. Polyhedron\_b
                                                                                                                                                                                                                                                         method), 683
                                   method), 553
                                                                                                                                                                                                                     VoronoiDiagram
                                                                                                                                                                                                                                                                                                                                               (class
                                                                                                                                                                                                                                                                                                                                                                                                                           in
vertex_adjacency_matrix()
                                    (sage.geometry.polyhedron.combinatorial_polyhedron.base.CombinatorialPolyhedron), 744

wethod) 268

Vrep2Hrep (class in sage.geometry.polyhedron.double_description_inhomo
                                   method), 268
vertex_digraph() (sage.geometry.polyhedron.base4.Polyhedron base4
                                                                                                                                                                                                                         Trep_generator() (sage.geometry.polyhedron.base0.Polyhedron_base0
                                    method), 568
                                                                                                                                                                                                                                                         method), 499
vertex_facet_graph()
                                   (sage.geometry.polyhedron.base 4. Polyhedron\_base 4. Polyhedron\_base
                                                                                                                                                                                                                                                                                                                                                 (class
                                                                                                                                                                                                                                                          sage.geometry.polyhedron.representation),
                                   method), 568
                                                                                                                                                                                                                                                          131
```

```
Vrepresentation() (sage.geometry.polyhedron.backend_ppl.Polyhedron_ppl
        method), 652
Vrepresentation() (sage.geometry.polyhedron.base0.Polyhedron base0
        method), 500
Vrepresentation() (sage.geometry.polyhedron.combinatorial_polyhedron.base.CombinatorialPolyhedron
        method), 239
Vrepresentation_space()
         (sage.geometry.polyhedron.base1.Polyhedron_base1
        method), 513
Vrepresentation_space()
         (sage.geometry.polyhedron.parent.Polyhedra_base
        method), 116
W
wedge() (sage.geometry.polyhedral_complex.PolyhedralComplex
        method), 334
{\tt wedge()} \ (sage.geometry.polyhedron.base 5. Polyhedron\_base 5
         method), 585
\verb|weight_vectors()| (sage.rings.polynomial.groebner\_fan.GroebnerFan|) |
        method), 489
whitney_data() (sage.geometry.hyperplane arrangement.arrangement.HyperplaneArrangementElement
         method), 37
whitney_number() (sage.geometry.hyperplane_arrangement.arrangement.HyperplaneArrangementElement
        method), 37
write_cdd_Hrepresentation()
         (sage.geometry.polyhedron.base0.Polyhedron_base0
        method), 512
write_cdd_Vrepresentation()
         (sage.geometry.polyhedron.base0.Polyhedron_base0
         method), 512
write_for_palp() (sage.geometry.point_collection.PointCollection
        method), 471
write_palp_matrix()
                                (in
                                             module
        sage.geometry.lattice_polytope), 212
Ζ
Z_operators_gens() (sage.geometry.cone.ConvexRationalPolyhedralCone
         method), 361
zero() (sage.geometry.polyhedron.parent.Polyhedra_base
        method), 119
zero_set() (sage.geometry.polyhedron.double_description.DoubleDescriptionPair
        method), 657
zero_sum_projection()
                                             module
         sage.geometry.polyhedron.library), 106
zonotope() (sage.geometry.polyhedron.library.Polytopes
        method), 100
```