Schemes

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CONTENTS

1 Scheme implementation overview 1

2 Schemes 5

3 The Spec functor 21

4 Scheme obtained by gluing two other schemes 23

5 Points on schemes 25

6 Ambient spaces 27

7 Algebraic schemes 33

8 Hypersurfaces in affine and projective space 71

9 Set of homomorphisms between two schemes 75

10 Scheme morphism 83

11 Divisors on schemes 109

12 Divisor groups 115

13 Affine Schemes 119

14 Projective Schemes 195

15 Products of Projective Spaces 353

16 Toric Varieties 401

17 Cyclic Covers 681

18 Berkovich Analytic Space 703

19 Indices and Tables 747

Python Module Index 749

Index 751

CHAPTER

ONE

SCHEME IMPLEMENTATION OVERVIEW

Various parts of schemes were implemented by different authors. This document aims to give an overview of the different classes of schemes working together coherently.

1.1 Generic

- **Scheme:** A scheme whose datatype might not be defined in terms of algebraic equations: e.g. the Jacobian of a curve may be represented by means of a Scheme.
- **AlgebraicScheme:** A scheme defined by means of polynomial equations, which may be reducible or defined over a ring other than a field. In particular, the defining ideal need not be a radical ideal, and an algebraic scheme may be defined over Spec(R).
- **AmbientSpaces:** Most effective models of algebraic scheme will be defined not by generic gluings, but by embeddings in some fixed ambient space.

1.2 Ambients

- **AffineSpace:** Affine spaces and their affine subschemes form the most important universal objects from which algebraic schemes are built. The affine spaces form universal objects in the sense that a morphism is uniquely determined by the images of its coordinate functions and any such images determine a well-defined morphism.

  By default affine spaces will embed in some ordinary projective space, unless it is created as an affine patch of another object.
- **ProjectiveSpace:** Projective spaces are the most natural ambient spaces for most projective objects. They are locally universal objects.
- **ProjectiveSpace_ordinary (not implemented):** The ordinary projective spaces have the standard weights $[1, .., 1]$ on their coefficients.
- **ProjectiveSpace_weighted (not implemented):** A special subtype for non-standard weights.
- **ToricVariety:** Toric varieties are (partial) compactifications of algebraic tori $(\mathbf{C}^*)^n$ compatible with torus action. Affine and projective spaces are examples of toric varieties, but it is not envisioned that these special cases should inherit from `ToricVariety`.

1.3 Subschemes

- **AlgebraicScheme_subscheme_affine:** An algebraic scheme defined by means of an embedding in a fixed ambient affine space.
- **AlgebraicScheme_subscheme_projective:** An algebraic scheme defined by means of an embedding in a fixed ambient projective space.

- **QuasiAffineScheme (not yet implemented):** An open subset $U = X \setminus Z$ of a closed subset X of affine space; note that this is mathematically a quasi-projective scheme, but its ambient space is an affine space and its points are represented by affine rather than projective points.

  Note

  AlgebraicScheme_quasi is implemented, as a base class for this.

- **QuasiProjectiveScheme (not yet implemented):** An open subset of a closed subset of projective space; this datatype stores the defining polynomial, polynomials, or ideal defining the projective closure X plus the closed subscheme Z of X whose complement $U = X \setminus Z$ is the quasi-projective scheme.

  Note

  The quasi-affine and quasi-projective datatype lets one create schemes like the multiplicative group scheme $\mathbb{G}_m = \mathbb{A}^1 \setminus \{(0)\}$ and the non-affine scheme $\mathbb{A}^2 \setminus \{(0,0)\}$. The latter is not affine and is not of the form $\mathrm{Spec}(R)$.

1.4 Point sets

- **PointSets and points over a ring (to do):** For algebraic schemes X/S and T/S over S, one can form the point set $X(T)$ of morphisms from $T \to X$ over S.

  A projective space object in the category of schemes is a locally free object – the images of the generator functions *locally* determine a point. Over a field, one can choose one of the standard affine patches by the condition that a coordinate function $X_i \neq 0$.

```
sage: PP.<X,Y,Z> = ProjectiveSpace(2, QQ)
sage: PP
Projective Space of dimension 2 over Rational Field
sage: PP(QQ)
Set of rational points of Projective Space
of dimension 2 over Rational Field
sage: PP(QQ)([-2, 3, 5])
(-2/5 : 3/5 : 1)
```

```
>>> from sage.all import *
>>> PP = ProjectiveSpace(Integer(2), QQ, names=('X', 'Y', 'Z',)); (X, Y, Z,) = PP.
↪_first_ngens(3)
>>> PP
Projective Space of dimension 2 over Rational Field
>>> PP(QQ)
Set of rational points of Projective Space
of dimension 2 over Rational Field
>>> PP(QQ)([-Integer(2), Integer(3), Integer(5)])
(-2/5 : 3/5 : 1)
```

  Over a ring, this is not true anymore. For example, even over an integral domain which is not a PID, there may be no *single* affine patch which covers a point.

```
sage: R.<x> = ZZ[]
sage: S.<t> = R.quo(x^2 + 5)
sage: P.<X,Y,Z> = ProjectiveSpace(2, S)
sage: P(S)
Set of rational points of Projective Space of dimension 2 over
Univariate Quotient Polynomial Ring in t over Integer Ring with
modulus x^2 + 5
```

```
>>> from sage.all import *
>>> R = ZZ['x']; (x,) = R._first_ngens(1)
>>> S = R.quo(x**Integer(2) + Integer(5), names=('t',)); (t,) = S._first_ngens(1)
>>> P = ProjectiveSpace(Integer(2), S, names=('X', 'Y', 'Z',)); (X, Y, Z,) = P._
↪first_ngens(3)
>>> P(S)
Set of rational points of Projective Space of dimension 2 over
Univariate Quotient Polynomial Ring in t over Integer Ring with
modulus x^2 + 5
```

In order to represent the projective point $(2 : 1 + t) = (1 - t : 3)$ we note that the first representative is not well-defined at the prime $p = (2, 1 + t)$ and the second element is not well-defined at the prime $q = (1 - t, 3)$, but that $p + q = (1)$, so globally the pair of coordinate representatives is well-defined.

```
sage: P([2, 1 + t])
(2 : t + 1 : 1)
```

```
>>> from sage.all import *
>>> P([Integer(2), Integer(1) + t])
(2 : t + 1 : 1)
```

In fact, we need a test `R.ideal([2, 1 + t]) == R.ideal([1])` in order to make this meaningful.

1.5 Berkovich Analytic Spaces

- **Berkovich Analytic Space (not yet implemented)** The construction of analytic spaces from schemes due to Berkovich. Any Berkovich space should inherit from `Berkovich`
- **Berkovich Analytic Space over Cp** A special case of the general Berkovich analytic space construction. Affine Berkovich space over $\mathbf{C}_p$ is the set of seminorms on the polynomial ring $\mathbf{C}_p[x]$, while projective Berkovich space over $\mathbf{C}_p$ is the one-point compactification of affine Berkovich space $\mathbf{C}_p$. Points are represented using the classification (due to Berkovich) of a corresponding decreasing sequence of disks in $\mathbf{C}_p$.

AUTHORS:

- David Kohel, William Stein (2006-01-03): initial version
- Andrey Novoseltsev (2010-09-24): updated due to addition of toric varieties

CHAPTER

TWO

SCHEMES

AUTHORS:

- William Stein, David Kohel, Kiran Kedlaya (2008): added zeta_series
- Volker Braun (2011-08-11): documenting, improving, refactoring.

class sage.schemes.generic.scheme.**AffineScheme**(*R*, *S=None*, *category=None*)

Bases: UniqueRepresentation, *Scheme*

Class for general affine schemes.

See also

For affine spaces over a base ring and subschemes thereof, see sage.schemes.generic.algebraic_scheme.AffineSpace.

Element

alias of *SchemeTopologicalPoint_prime_ideal*

base_extend(*R*)

Extend the base ring/scheme.

INPUT:

- R – an affine scheme or a commutative ring

EXAMPLES:

```
sage: Spec_ZZ = Spec(ZZ);  Spec_ZZ
Spectrum of Integer Ring
sage: Spec_ZZ.base_extend(QQ)
Spectrum of Rational Field

sage: Spec(ZZ['x']).base_extend(Spec(QQ))
Spectrum of Univariate Polynomial Ring in x over Rational Field
```

```
>>> from sage.all import *
>>> Spec_ZZ = Spec(ZZ);  Spec_ZZ
Spectrum of Integer Ring
>>> Spec_ZZ.base_extend(QQ)
Spectrum of Rational Field
```

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```
>>> Spec(ZZ['x']).base_extend(Spec(QQ))
Spectrum of Univariate Polynomial Ring in x over Rational Field
```

coordinate_ring()

Return the underlying ring of this scheme.

OUTPUT: a commutative ring

EXAMPLES:

```
sage: Spec(QQ).coordinate_ring()
Rational Field
sage: Spec(PolynomialRing(QQ, 3, 'x')).coordinate_ring()
Multivariate Polynomial Ring in x0, x1, x2 over Rational Field
```

```
>>> from sage.all import *
>>> Spec(QQ).coordinate_ring()
Rational Field
>>> Spec(PolynomialRing(QQ, Integer(3), 'x')).coordinate_ring()
Multivariate Polynomial Ring in x0, x1, x2 over Rational Field
```

dimension()

Return the absolute dimension of this scheme.

OUTPUT: integer

EXAMPLES:

```
sage: S = Spec(ZZ)
sage: S.dimension_absolute()
1
sage: S.dimension()
1
```

```
>>> from sage.all import *
>>> S = Spec(ZZ)
>>> S.dimension_absolute()
1
>>> S.dimension()
1
```

dimension_absolute()

Return the absolute dimension of this scheme.

OUTPUT: integer

EXAMPLES:

```
sage: S = Spec(ZZ)
sage: S.dimension_absolute()
1
sage: S.dimension()
1
```

```
>>> from sage.all import *
>>> S = Spec(ZZ)
>>> S.dimension_absolute()
1
>>> S.dimension()
1
```

dimension_relative()

Return the relative dimension of this scheme over its base.

OUTPUT: integer

EXAMPLES:

```
sage: S = Spec(ZZ)
sage: S.dimension_relative()
0
```

```
>>> from sage.all import *
>>> S = Spec(ZZ)
>>> S.dimension_relative()
0
```

hom(*x*, *Y=None*)

Return the scheme morphism from `self` to `Y` defined by `x`.

INPUT:

- `x` – anything that determines a scheme morphism; if `x` is a scheme, try to determine a natural map to `x`
- `Y` – the codomain scheme (optional); if `Y` is not given, try to determine `Y` from context
- `check` – boolean (default: `True`); whether to check the defining data for consistency

OUTPUT: the scheme morphism from `self` to `Y` defined by `x`

EXAMPLES:

We construct the inclusion from $\mathrm{Spec}(\mathbf{Q})$ into $\mathrm{Spec}(\mathbf{Z})$ induced by the inclusion from $\mathbf{Z}$ into $\mathbf{Q}$:

```
sage: X = Spec(QQ)
sage: X.hom(ZZ.hom(QQ))
Affine Scheme morphism:
  From: Spectrum of Rational Field
  To:   Spectrum of Integer Ring
  Defn: Natural morphism:
          From: Integer Ring
          To:   Rational Field
```

```
>>> from sage.all import *
>>> X = Spec(QQ)
>>> X.hom(ZZ.hom(QQ))
Affine Scheme morphism:
  From: Spectrum of Rational Field
  To:   Spectrum of Integer Ring
  Defn: Natural morphism:
```

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```
        From: Integer Ring
        To:   Rational Field
```

is_noetherian()

Return `True` if `self` is Noetherian, `False` otherwise.

EXAMPLES:

```
sage: Spec(ZZ).is_noetherian()
True
```

```
>>> from sage.all import *
>>> Spec(ZZ).is_noetherian()
True
```

class sage.schemes.generic.scheme.**Scheme**(*X=None*, *category=None*)

Bases: `Parent`

The base class for all schemes.

INPUT:

- `X` – a scheme, scheme morphism, commutative ring, commutative ring morphism, or `None` (optional). Determines the base scheme. If a commutative ring is passed, the spectrum of the ring will be used as base.
- `category` – the category (optional); will be automatically constructed by default

EXAMPLES:

```
sage: from sage.schemes.generic.scheme import Scheme
sage: Scheme(ZZ)
<sage.schemes.generic.scheme.Scheme_with_category object at ...>
```

```
>>> from sage.all import *
>>> from sage.schemes.generic.scheme import Scheme
>>> Scheme(ZZ)
<sage.schemes.generic.scheme.Scheme_with_category object at ...>
```

A scheme is in the category of all schemes over its base:

```
sage: ProjectiveSpace(4, QQ).category()
Category of schemes over Rational Field
```

```
>>> from sage.all import *
>>> ProjectiveSpace(Integer(4), QQ).category()
Category of schemes over Rational Field
```

There is a special and unique $\mathrm{Spec}(\mathbf{Z})$ that is the default base scheme:

```
sage: Spec(ZZ).base_scheme() is Spec(QQ).base_scheme()
True
```

```
>>> from sage.all import *
>>> Spec(ZZ).base_scheme() is Spec(QQ).base_scheme()
True
```

base_extend(*Y*)

Extend the base of the scheme.

Derived classes must override this method.

EXAMPLES:

```
sage: from sage.schemes.generic.scheme import Scheme
sage: X = Scheme(ZZ)
sage: X.base_scheme()
Spectrum of Integer Ring
sage: X.base_extend(QQ)
Traceback (most recent call last):
...
NotImplementedError
```

```
>>> from sage.all import *
>>> from sage.schemes.generic.scheme import Scheme
>>> X = Scheme(ZZ)
>>> X.base_scheme()
Spectrum of Integer Ring
>>> X.base_extend(QQ)
Traceback (most recent call last):
...
NotImplementedError
```

base_morphism()

Return the structure morphism from `self` to its base scheme.

OUTPUT: a scheme morphism

EXAMPLES:

```
sage: A = AffineSpace(4, QQ)
sage: A.base_morphism()
Scheme morphism:
  From: Affine Space of dimension 4 over Rational Field
  To:   Spectrum of Rational Field
  Defn: Structure map

sage: X = Spec(QQ)
sage: X.base_morphism()
Scheme morphism:
  From: Spectrum of Rational Field
  To:   Spectrum of Integer Ring
  Defn: Structure map
```

```
>>> from sage.all import *
>>> A = AffineSpace(Integer(4), QQ)
>>> A.base_morphism()
Scheme morphism:
  From: Affine Space of dimension 4 over Rational Field
  To:   Spectrum of Rational Field
  Defn: Structure map
```

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```
>>> X = Spec(QQ)
>>> X.base_morphism()
Scheme morphism:
  From: Spectrum of Rational Field
  To:   Spectrum of Integer Ring
  Defn: Structure map
```

base_ring()

Return the base ring of the scheme `self`.

OUTPUT: a commutative ring

EXAMPLES:

```
sage: A = AffineSpace(4, QQ)
sage: A.base_ring()
Rational Field

sage: X = Spec(QQ)
sage: X.base_ring()
Integer Ring
```

```
>>> from sage.all import *
>>> A = AffineSpace(Integer(4), QQ)
>>> A.base_ring()
Rational Field

>>> X = Spec(QQ)
>>> X.base_ring()
Integer Ring
```

base_scheme()

Return the base scheme.

OUTPUT: a scheme

EXAMPLES:

```
sage: A = AffineSpace(4, QQ)
sage: A.base_scheme()
Spectrum of Rational Field

sage: X = Spec(QQ)
sage: X.base_scheme()
Spectrum of Integer Ring
```

```
>>> from sage.all import *
>>> A = AffineSpace(Integer(4), QQ)
>>> A.base_scheme()
Spectrum of Rational Field

>>> X = Spec(QQ)
>>> X.base_scheme()
Spectrum of Integer Ring
```

coordinate_ring()

Return the coordinate ring.

OUTPUT:

The global coordinate ring of this scheme, if defined. Otherwise this raises a ValueError.

EXAMPLES:

```
sage: R.<x, y> = QQ[]
sage: I = (x^2 - y^2)*R
sage: X = Spec(R.quotient(I))
sage: X.coordinate_ring()
Quotient of Multivariate Polynomial Ring in x, y over Rational Field
 by the ideal (x^2 - y^2)
```

```
>>> from sage.all import *
>>> R = QQ['x, y']; (x, y,) = R._first_ngens(2)
>>> I = (x**Integer(2) - y**Integer(2))*R
>>> X = Spec(R.quotient(I))
>>> X.coordinate_ring()
Quotient of Multivariate Polynomial Ring in x, y over Rational Field
 by the ideal (x^2 - y^2)
```

count_points(*n*)

Count points over finite fields.

INPUT:

- n – integer

OUTPUT:

An integer. The number of points over $\mathbf{F}_q, \ldots, \mathbf{F}_{q^n}$ on a scheme over a finite field $\mathbf{F}_q$.

EXAMPLES:

```
sage: # needs sage.schemes
sage: P.<x> = PolynomialRing(GF(3))
sage: C = HyperellipticCurve(x^3 + x^2 + 1)
sage: C.count_points(4)
[6, 12, 18, 96]
sage: C.base_extend(GF(9,'a')).count_points(2)                                  #␣
↪needs sage.rings.finite_rings
[12, 96]
```

```
>>> from sage.all import *
>>> # needs sage.schemes
>>> P = PolynomialRing(GF(Integer(3)), names=('x',)); (x,) = P._first_ngens(1)
>>> C = HyperellipticCurve(x**Integer(3) + x**Integer(2) + Integer(1))
>>> C.count_points(Integer(4))
[6, 12, 18, 96]
>>> C.base_extend(GF(Integer(9),'a')).count_points(Integer(2))                  ␣
↪              # needs sage.rings.finite_rings
[12, 96]
```

```
sage: P.<x,y,z> = ProjectiveSpace(GF(4, 't'), 2)                                #␣
↪needs sage.rings.finite_rings
sage: X = P.subscheme([y^2*z - x^3 - z^3])                                      #␣
↪needs sage.rings.finite_rings
sage: X.count_points(2)                                                         #␣
↪needs sage.libs.singular sage.rings.finite_rings
[5, 17]
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(GF(Integer(4), 't'), Integer(2), names=('x', 'y', 'z',
↪)); (x, y, z,) = P._first_ngens(3)# needs sage.rings.finite_rings
>>> X = P.subscheme([y**Integer(2)*z - x**Integer(3) - z**Integer(3)])       ␣
↪                           # needs sage.rings.finite_rings
>>> X.count_points(Integer(2))                                               ␣
↪     # needs sage.libs.singular sage.rings.finite_rings
[5, 17]
```

dimension()

Return the absolute dimension of this scheme.

OUTPUT: integer

EXAMPLES:

```
sage: R.<x, y> = QQ[]
sage: I = (x^2 - y^2)*R
sage: X = Spec(R.quotient(I))
sage: X.dimension_absolute()
Traceback (most recent call last):
...
NotImplementedError
sage: X.dimension()
Traceback (most recent call last):
...
NotImplementedError
```

```
>>> from sage.all import *
>>> R = QQ['x, y']; (x, y,) = R._first_ngens(2)
>>> I = (x**Integer(2) - y**Integer(2))*R
>>> X = Spec(R.quotient(I))
>>> X.dimension_absolute()
Traceback (most recent call last):
...
NotImplementedError
>>> X.dimension()
Traceback (most recent call last):
...
NotImplementedError
```

dimension_absolute()

Return the absolute dimension of this scheme.

OUTPUT: integer

EXAMPLES:

```
sage: R.<x, y> = QQ[]
sage: I = (x^2 - y^2)*R
sage: X = Spec(R.quotient(I))
sage: X.dimension_absolute()
Traceback (most recent call last):
...
NotImplementedError
sage: X.dimension()
Traceback (most recent call last):
...
NotImplementedError
```

```
>>> from sage.all import *
>>> R = QQ['x, y']; (x, y,) = R._first_ngens(2)
>>> I = (x**Integer(2) - y**Integer(2))*R
>>> X = Spec(R.quotient(I))
>>> X.dimension_absolute()
Traceback (most recent call last):
...
NotImplementedError
>>> X.dimension()
Traceback (most recent call last):
...
NotImplementedError
```

dimension_relative()

Return the relative dimension of this scheme over its base.

OUTPUT: integer

EXAMPLES:

```
sage: R.<x, y> = QQ[]
sage: I = (x^2 - y^2)*R
sage: X = Spec(R.quotient(I))
sage: X.dimension_relative()
Traceback (most recent call last):
...
NotImplementedError
```

```
>>> from sage.all import *
>>> R = QQ['x, y']; (x, y,) = R._first_ngens(2)
>>> I = (x**Integer(2) - y**Integer(2))*R
>>> X = Spec(R.quotient(I))
>>> X.dimension_relative()
Traceback (most recent call last):
...
NotImplementedError
```

hom(*x*, *Y=None*, *check=True*)

Return the scheme morphism from `self` to `Y` defined by `x`.

INPUT:

- `x` – anything that determines a scheme morphism; if `x` is a scheme, try to determine a natural map to `x`

- `Y` – the codomain scheme (optional); if `Y` is not given, try to determine `Y` from context
- `check` – boolean (default: `True`); whether to check the defining data for consistency

OUTPUT: the scheme morphism from `self` to `Y` defined by `x`

EXAMPLES:

```
sage: P = ProjectiveSpace(ZZ, 3)
sage: P.hom(Spec(ZZ))
Scheme morphism:
  From: Projective Space of dimension 3 over Integer Ring
  To:   Spectrum of Integer Ring
  Defn: Structure map
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(ZZ, Integer(3))
>>> P.hom(Spec(ZZ))
Scheme morphism:
  From: Projective Space of dimension 3 over Integer Ring
  To:   Spectrum of Integer Ring
  Defn: Structure map
```

identity_morphism()

Return the identity morphism.

OUTPUT: the identity morphism of the scheme `self`

EXAMPLES:

```
sage: X = Spec(QQ)
sage: X.identity_morphism()
Scheme endomorphism of Spectrum of Rational Field
  Defn: Identity map
```

```
>>> from sage.all import *
>>> X = Spec(QQ)
>>> X.identity_morphism()
Scheme endomorphism of Spectrum of Rational Field
  Defn: Identity map
```

point(*v*, *check=True*)

Create a point.

INPUT:

- `v` – anything that defines a point
- `check` – boolean (default: `True`); whether to check the defining data for consistency

OUTPUT: a point of the scheme

EXAMPLES:

```
sage: A2 = AffineSpace(QQ, 2)
sage: A2.point([4, 5])
(4, 5)
```

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```
sage: R.<t> = PolynomialRing(QQ)
sage: E = EllipticCurve([t + 1, t, t, 0, 0])                                #␣
↪needs sage.schemes
sage: E.point([0, 0])                                                       #␣
↪needs sage.schemes
(0 : 0 : 1)
```

```
>>> from sage.all import *
>>> A2 = AffineSpace(QQ, Integer(2))
>>> A2.point([Integer(4), Integer(5)])
(4, 5)

>>> R = PolynomialRing(QQ, names=('t',)); (t,) = R._first_ngens(1)
>>> E = EllipticCurve([t + Integer(1), t, t, Integer(0), Integer(0)])        ␣
↪                          # needs sage.schemes
>>> E.point([Integer(0), Integer(0)])                                        ␣
↪               # needs sage.schemes
(0 : 0 : 1)
```

point_homset(*S=None*)

Return the set of S-valued points of this scheme.

INPUT:

- `S` – a commutative ring

OUTPUT: the set of morphisms $\mathrm{Spec}(S) \to X$

EXAMPLES:

```
sage: P = ProjectiveSpace(ZZ, 3)
sage: P.point_homset(ZZ)
Set of rational points of Projective Space of dimension 3 over Integer Ring
sage: P.point_homset(QQ)
Set of rational points of Projective Space of dimension 3 over Rational Field
sage: P.point_homset(GF(11))
Set of rational points of Projective Space of dimension 3 over
 Finite Field of size 11
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(ZZ, Integer(3))
>>> P.point_homset(ZZ)
Set of rational points of Projective Space of dimension 3 over Integer Ring
>>> P.point_homset(QQ)
Set of rational points of Projective Space of dimension 3 over Rational Field
>>> P.point_homset(GF(Integer(11)))
Set of rational points of Projective Space of dimension 3 over
 Finite Field of size 11
```

point_set(*S=None*)

Return the set of S-valued points of this scheme.

INPUT:

- `S` – a commutative ring

OUTPUT: the set of morphisms $\mathrm{Spec}(S) \to X$

EXAMPLES:

```
sage: P = ProjectiveSpace(ZZ, 3)
sage: P.point_homset(ZZ)
Set of rational points of Projective Space of dimension 3 over Integer Ring
sage: P.point_homset(QQ)
Set of rational points of Projective Space of dimension 3 over Rational Field
sage: P.point_homset(GF(11))
Set of rational points of Projective Space of dimension 3 over
 Finite Field of size 11
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(ZZ, Integer(3))
>>> P.point_homset(ZZ)
Set of rational points of Projective Space of dimension 3 over Integer Ring
>>> P.point_homset(QQ)
Set of rational points of Projective Space of dimension 3 over Rational Field
>>> P.point_homset(GF(Integer(11)))
Set of rational points of Projective Space of dimension 3 over
 Finite Field of size 11
```

structure_morphism()

Return the structure morphism from `self` to its base scheme.

OUTPUT: a scheme morphism

EXAMPLES:

```
sage: A = AffineSpace(4, QQ)
sage: A.base_morphism()
Scheme morphism:
  From: Affine Space of dimension 4 over Rational Field
  To:   Spectrum of Rational Field
  Defn: Structure map

sage: X = Spec(QQ)
sage: X.base_morphism()
Scheme morphism:
  From: Spectrum of Rational Field
  To:   Spectrum of Integer Ring
  Defn: Structure map
```

```
>>> from sage.all import *
>>> A = AffineSpace(Integer(4), QQ)
>>> A.base_morphism()
Scheme morphism:
  From: Affine Space of dimension 4 over Rational Field
  To:   Spectrum of Rational Field
  Defn: Structure map

>>> X = Spec(QQ)
>>> X.base_morphism()
```

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```
Scheme morphism:
  From: Spectrum of Rational Field
  To:   Spectrum of Integer Ring
  Defn: Structure map
```

union(*X*)

Return the disjoint union of the schemes `self` and `X`.

EXAMPLES:

```
sage: S = Spec(QQ)
sage: X = AffineSpace(1, QQ)
sage: S.union(X)
Traceback (most recent call last):
...
NotImplementedError
```

```
>>> from sage.all import *
>>> S = Spec(QQ)
>>> X = AffineSpace(Integer(1), QQ)
>>> S.union(X)
Traceback (most recent call last):
...
NotImplementedError
```

zeta_function()

Compute the zeta function of a generic scheme.

Derived classes should override this method.

OUTPUT: rational function in one variable

EXAMPLES:

```
sage: P.<x,y,z> = ProjectiveSpace(GF(4, 't'), 2)                              #␣
↪needs sage.rings.finite_rings
sage: X = P.subscheme([y^2*z - x^3 - z^3])                                    #␣
↪needs sage.rings.finite_rings
sage: X.zeta_function()                                                       #␣
↪needs sage.rings.finite_rings
Traceback (most recent call last):
...
NotImplementedError
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(GF(Integer(4), 't'), Integer(2), names=('x', 'y', 'z',
↪)); (x, y, z,) = P._first_ngens(3)# needs sage.rings.finite_rings
>>> X = P.subscheme([y**Integer(2)*z - x**Integer(3) - z**Integer(3)])       ␣
↪                          # needs sage.rings.finite_rings
>>> X.zeta_function()                                                        #␣
↪needs sage.rings.finite_rings
Traceback (most recent call last):
...
NotImplementedError
```

zeta_series(*n*, *t*)

Return the zeta series.

Compute a power series approximation to the zeta function of a scheme over a finite field.

INPUT:

- `n` – the number of terms of the power series to compute
- `t` – the variable which the series should be returned

OUTPUT: a power series approximating the zeta function of `self`

EXAMPLES:

```
sage: P.<x> = PolynomialRing(GF(3))
sage: C = HyperellipticCurve(x^3 + x^2 + 1)                                    #␣
↪needs sage.schemes
sage: R.<t> = PowerSeriesRing(Integers())
sage: C.zeta_series(4, t)                                                      #␣
↪needs sage.schemes
1 + 6*t + 24*t^2 + 78*t^3 + 240*t^4 + O(t^5)
sage: (1+2*t+3*t^2)/(1-t)/(1-3*t) + O(t^5)
1 + 6*t + 24*t^2 + 78*t^3 + 240*t^4 + O(t^5)
```

```
>>> from sage.all import *
>>> P = PolynomialRing(GF(Integer(3)), names=('x',)); (x,) = P._first_ngens(1)
>>> C = HyperellipticCurve(x**Integer(3) + x**Integer(2) + Integer(1))       ␣
↪                          # needs sage.schemes
>>> R = PowerSeriesRing(Integers(), names=('t',)); (t,) = R._first_ngens(1)
>>> C.zeta_series(Integer(4), t)                                             ␣
↪     # needs sage.schemes
1 + 6*t + 24*t^2 + 78*t^3 + 240*t^4 + O(t^5)
>>> (Integer(1)+Integer(2)*t+Integer(3)*t**Integer(2))/(Integer(1)-t)/
↪(Integer(1)-Integer(3)*t) + O(t**Integer(5))
1 + 6*t + 24*t^2 + 78*t^3 + 240*t^4 + O(t^5)
```

If the scheme has a method `zeta_function`, this is used to provide the required approximation. Otherwise this function depends on `count_points`, which is only defined for prime order fields for general schemes. Nonetheless, since Issue #15108 and Issue #15148, it supports hyperelliptic curves over non-prime fields:

```
sage: C.base_extend(GF(9, 'a')).zeta_series(4, t)                              #␣
↪needs sage.rings.finite_rings sage.schemes
1 + 12*t + 120*t^2 + 1092*t^3 + 9840*t^4 + O(t^5)
```

```
>>> from sage.all import *
>>> C.base_extend(GF(Integer(9), 'a')).zeta_series(Integer(4), t)            ␣
↪              # needs sage.rings.finite_rings sage.schemes
1 + 12*t + 120*t^2 + 1092*t^3 + 9840*t^4 + O(t^5)
```

```
sage: P.<x,y,z> = ProjectiveSpace(GF(4, 't'), 2)                               #␣
↪needs sage.rings.finite_rings
sage: X = P.subscheme([y^2*z - x^3 - z^3])                                     #␣
↪needs sage.rings.finite_rings
```

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```
sage: R.<t> = PowerSeriesRing(Integers())
sage: X.zeta_series(2, t)                                                   #␣
↪needs sage.libs.singular sage.rings.finite_rings
1 + 5*t + 21*t^2 + O(t^3)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(GF(Integer(4), 't'), Integer(2), names=('x', 'y', 'z',
↪)); (x, y, z,) = P._first_ngens(3)# needs sage.rings.finite_rings
>>> X = P.subscheme([y**Integer(2)*z - x**Integer(3) - z**Integer(3)])       ␣
↪                            # needs sage.rings.finite_rings

>>> R = PowerSeriesRing(Integers(), names=('t',)); (t,) = R._first_ngens(1)
>>> X.zeta_series(Integer(2), t)                                             ␣
↪     # needs sage.libs.singular sage.rings.finite_rings
1 + 5*t + 21*t^2 + O(t^3)
```

sage.schemes.generic.scheme.**is_AffineScheme**(*x*)

Return `True` if *x* is an affine scheme.

EXAMPLES:

```
sage: from sage.schemes.generic.scheme import is_AffineScheme
sage: is_AffineScheme(5)
doctest:warning...
DeprecationWarning: The function is_AffineScheme is deprecated; use 'isinstance(..
↪., AffineScheme)' instead.
See https://github.com/sagemath/sage/issues/38022 for details.
False
sage: E = Spec(QQ)
sage: is_AffineScheme(E)
True
```

```
>>> from sage.all import *
>>> from sage.schemes.generic.scheme import is_AffineScheme
>>> is_AffineScheme(Integer(5))
doctest:warning...
DeprecationWarning: The function is_AffineScheme is deprecated; use 'isinstance(..
↪., AffineScheme)' instead.
See https://github.com/sagemath/sage/issues/38022 for details.
False
>>> E = Spec(QQ)
>>> is_AffineScheme(E)
True
```

sage.schemes.generic.scheme.**is_Scheme**(*x*)

Test whether `x` is a scheme.

INPUT:

- `x` – anything

OUTPUT: boolean; whether `x` derives from *Scheme*

EXAMPLES:

```
sage: from sage.schemes.generic.scheme import is_Scheme
sage: is_Scheme(5)
doctest:warning...
DeprecationWarning: The function is_Scheme is deprecated; use 'isinstance(...,␣
↪Scheme)' or categories instead.
See https://github.com/sagemath/sage/issues/38022 for details.
False
sage: X = Spec(QQ)
sage: is_Scheme(X)
True
```

```
>>> from sage.all import *
>>> from sage.schemes.generic.scheme import is_Scheme
>>> is_Scheme(Integer(5))
doctest:warning...
DeprecationWarning: The function is_Scheme is deprecated; use 'isinstance(...,␣
↪Scheme)' or categories instead.
See https://github.com/sagemath/sage/issues/38022 for details.
False
>>> X = Spec(QQ)
>>> is_Scheme(X)
True
```

CHAPTER

THREE

THE SPEC FUNCTOR

AUTHORS:

- William Stein (2006): initial implementation
- Peter Bruin (2014): rewrite Spec as a functor

sage.schemes.generic.spec.**Spec**(*R*, *S=None*)

Apply the Spec functor to R.

INPUT:

- `R` – either a commutative ring or a ring homomorphism
- `S` – a commutative ring (optional), the base ring

OUTPUT:

- `AffineScheme` – the affine scheme $\mathrm{Spec}(R)$

EXAMPLES:

```
sage: Spec(QQ)
Spectrum of Rational Field
sage: Spec(PolynomialRing(QQ, 'x'))
Spectrum of Univariate Polynomial Ring in x over Rational Field
sage: Spec(PolynomialRing(QQ, 'x', 3))
Spectrum of Multivariate Polynomial Ring in x0, x1, x2 over Rational Field
sage: X = Spec(PolynomialRing(GF(49,'a'), 3, 'x')); X                          #␣
↪needs sage.rings.finite_rings
Spectrum of Multivariate Polynomial Ring in x0, x1, x2
 over Finite Field in a of size 7^2
sage: TestSuite(X).run()                                                       #␣
↪needs sage.rings.finite_rings
```

```
>>> from sage.all import *
>>> Spec(QQ)
Spectrum of Rational Field
>>> Spec(PolynomialRing(QQ, 'x'))
Spectrum of Univariate Polynomial Ring in x over Rational Field
>>> Spec(PolynomialRing(QQ, 'x', Integer(3)))
Spectrum of Multivariate Polynomial Ring in x0, x1, x2 over Rational Field
>>> X = Spec(PolynomialRing(GF(Integer(49),'a'), Integer(3), 'x')); X           ␣
↪              # needs sage.rings.finite_rings
Spectrum of Multivariate Polynomial Ring in x0, x1, x2
```

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```
 over Finite Field in a of size 7^2
>>> TestSuite(X).run()                                                    #␣
↪needs sage.rings.finite_rings
```

Applying `Spec` twice to the same ring gives identical output (see Issue #17008):

```
sage: A = Spec(ZZ); B = Spec(ZZ)
sage: A is B
True
```

```
>>> from sage.all import *
>>> A = Spec(ZZ); B = Spec(ZZ)
>>> A is B
True
```

A `TypeError` is raised if the input is not a commutative ring:

```
sage: Spec(5)
Traceback (most recent call last):
...
TypeError: x (=5) is not in Category of commutative rings
sage: Spec(FreeAlgebra(QQ, 2, 'x'))                                        #␣
↪needs sage.combinat sage.modules
Traceback (most recent call last):
...
TypeError: x (=Free Algebra on 2 generators (x0, x1) over Rational Field)
is not in Category of commutative rings
```

```
>>> from sage.all import *
>>> Spec(Integer(5))
Traceback (most recent call last):
...
TypeError: x (=5) is not in Category of commutative rings
>>> Spec(FreeAlgebra(QQ, Integer(2), 'x'))                                 ␣
↪     # needs sage.combinat sage.modules
Traceback (most recent call last):
...
TypeError: x (=Free Algebra on 2 generators (x0, x1) over Rational Field)
is not in Category of commutative rings
```

class sage.schemes.generic.spec.**SpecFunctor**(*base_ring=None*)

Bases: `Functor`, `UniqueRepresentation`

The Spec functor.

CHAPTER

FOUR

SCHEME OBTAINED BY GLUING TWO OTHER SCHEMES

class sage.schemes.generic.glue.**GluedScheme**(*f*, *g*, *check=True*)

Bases: *Scheme*

INPUT:

- `f` – open immersion from a scheme U to a scheme X
- `g` – open immersion from U to a scheme Y

OUTPUT: the scheme obtained by gluing X and Y along the open set U

Note

Checking that f and g are open immersions is not implemented.

EXAMPLES:

```
sage: R.<x, y> = QQ[]
sage: S.<xbar, ybar> = R.quotient(x * y - 1)
sage: Rx = QQ["x"]
sage: Ry = QQ["y"]
sage: phi_x = Rx.hom([xbar])
sage: phi_y = Ry.hom([ybar])
sage: Sx = Schemes()(phi_x)
sage: Sy = Schemes()(phi_y)
sage: Sx.glue_along_domains(Sy)
Scheme obtained by gluing X and Y along U, where
  X: Spectrum of Univariate Polynomial Ring in x over Rational Field
  Y: Spectrum of Univariate Polynomial Ring in y over Rational Field
  U: Spectrum of Quotient of Multivariate Polynomial Ring in x, y over Rational␣
↪Field by the ideal (x*y - 1)
```

```
>>> from sage.all import *
>>> R = QQ['x, y']; (x, y,) = R._first_ngens(2)
>>> S = R.quotient(x * y - Integer(1), names=('xbar', 'ybar',)); (xbar, ybar,) =␣
↪S._first_ngens(2)
>>> Rx = QQ["x"]
>>> Ry = QQ["y"]
>>> phi_x = Rx.hom([xbar])
>>> phi_y = Ry.hom([ybar])
>>> Sx = Schemes()(phi_x)
```

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```
>>> Sy = Schemes()(phi_y)
>>> Sx.glue_along_domains(Sy)
Scheme obtained by gluing X and Y along U, where
  X: Spectrum of Univariate Polynomial Ring in x over Rational Field
  Y: Spectrum of Univariate Polynomial Ring in y over Rational Field
  U: Spectrum of Quotient of Multivariate Polynomial Ring in x, y over Rational␣
↪Field by the ideal (x*y - 1)
```

gluing_maps()

Return the gluing maps of this glued scheme, i.e. the maps f and g.

EXAMPLES:

```
sage: R.<x, y> = QQ[]
sage: S.<xbar, ybar> = R.quotient(x * y - 1)
sage: Rx = QQ["x"]
sage: Ry = QQ["y"]
sage: phi_x = Rx.hom([xbar])
sage: phi_y = Ry.hom([ybar])
sage: Sx = Schemes()(phi_x)
sage: Sy = Schemes()(phi_y)
sage: Sxy = Sx.glue_along_domains(Sy)
sage: Sxy.gluing_maps() == (Sx, Sy)
True
```

```
>>> from sage.all import *
>>> R = QQ['x, y']; (x, y,) = R._first_ngens(2)
>>> S = R.quotient(x * y - Integer(1), names=('xbar', 'ybar',)); (xbar, ybar,
↪) = S._first_ngens(2)
>>> Rx = QQ["x"]
>>> Ry = QQ["y"]
>>> phi_x = Rx.hom([xbar])
>>> phi_y = Ry.hom([ybar])
>>> Sx = Schemes()(phi_x)
>>> Sy = Schemes()(phi_y)
>>> Sxy = Sx.glue_along_domains(Sy)
>>> Sxy.gluing_maps() == (Sx, Sy)
True
```

CHAPTER

FIVE

POINTS ON SCHEMES

class sage.schemes.generic.point.**SchemePoint**(*S*, *parent=None*)

Bases: Element

Base class for points on a scheme, either topological or defined by a morphism.

scheme()

Return the scheme on which self is a point.

EXAMPLES:

```
sage: from sage.schemes.generic.point import SchemePoint
sage: S = Spec(ZZ)
sage: P = SchemePoint(S)
sage: P.scheme()
Spectrum of Integer Ring
```

```
>>> from sage.all import *
>>> from sage.schemes.generic.point import SchemePoint
>>> S = Spec(ZZ)
>>> P = SchemePoint(S)
>>> P.scheme()
Spectrum of Integer Ring
```

class sage.schemes.generic.point.**SchemeTopologicalPoint**(*S*)

Bases: *SchemePoint*

Base class for topological points on schemes.

class sage.schemes.generic.point.**SchemeTopologicalPoint_affine_open**(*u*, *x*)

Bases: *SchemeTopologicalPoint*

INPUT:

- u – morphism with domain an affine scheme U
- x – topological point on U

affine_open()

Return the affine open subset U.

embedding_of_affine_open()

Return the embedding from the affine open subset U into this scheme.

point_on_affine()

Return the scheme point on the affine open U.

class sage.schemes.generic.point.**SchemeTopologicalPoint_prime_ideal**(S, P, *check=False*)

Bases: *SchemeTopologicalPoint*

INPUT:

- S – an affine scheme
- P – a prime ideal of the coordinate ring of S, or anything that can be converted into such an ideal

prime_ideal()

Return the prime ideal that defines this scheme point.

EXAMPLES:

```
sage: from sage.schemes.generic.point import SchemeTopologicalPoint_prime_
↪ideal
sage: P2.<x, y, z> = ProjectiveSpace(2, QQ)
sage: pt = SchemeTopologicalPoint_prime_ideal(P2, y*z - x^2)
sage: pt.prime_ideal()
Ideal (-x^2 + y*z) of Multivariate Polynomial Ring in x, y, z over Rational␣
↪Field
```

```
>>> from sage.all import *
>>> from sage.schemes.generic.point import SchemeTopologicalPoint_prime_ideal
>>> P2 = ProjectiveSpace(Integer(2), QQ, names=('x', 'y', 'z',)); (x, y, z,)␣
↪= P2._first_ngens(3)
>>> pt = SchemeTopologicalPoint_prime_ideal(P2, y*z - x**Integer(2))
>>> pt.prime_ideal()
Ideal (-x^2 + y*z) of Multivariate Polynomial Ring in x, y, z over Rational␣
↪Field
```

sage.schemes.generic.point.**is_SchemeTopologicalPoint**(x)

CHAPTER

SIX

AMBIENT SPACES

class sage.schemes.generic.ambient_space.**AmbientSpace**(*n*, *R=Integer Ring*)

Bases: *Scheme*

Base class for ambient spaces over a ring.

INPUT:

- `n` – dimension
- `R` – ring

ambient_space()

Return the ambient space of the scheme self, in this case self itself.

EXAMPLES:

```
sage: P = ProjectiveSpace(4, ZZ)
sage: P.ambient_space() is P
True

sage: A = AffineSpace(2, GF(3))
sage: A.ambient_space()
Affine Space of dimension 2 over Finite Field of size 3
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(Integer(4), ZZ)
>>> P.ambient_space() is P
True

>>> A = AffineSpace(Integer(2), GF(Integer(3)))
>>> A.ambient_space()
Affine Space of dimension 2 over Finite Field of size 3
```

base_extend(*R*)

Return the natural extension of `self` over `R`.

INPUT:

- `R` – a commutative ring, such that there is a natural map from the base ring of `self` to `R`

OUTPUT: an ambient space over `R` of the same structure as `self`

Note

A `ValueError` is raised if there is no such natural map. If you need to drop this condition, use `self.change_ring(R)`.

EXAMPLES:

```
sage: P.<x, y, z> = ProjectiveSpace(2, ZZ)
sage: PQ = P.base_extend(QQ); PQ
Projective Space of dimension 2 over Rational Field
sage: PQ.base_extend(GF(5))
Traceback (most recent call last):
...
ValueError: no natural map from the base ring (=Rational Field)
to R (=Finite Field of size 5)!
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(Integer(2), ZZ, names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> PQ = P.base_extend(QQ); PQ
Projective Space of dimension 2 over Rational Field
>>> PQ.base_extend(GF(Integer(5)))
Traceback (most recent call last):
...
ValueError: no natural map from the base ring (=Rational Field)
to R (=Finite Field of size 5)!
```

change_ring(*R*)

Return an ambient space over ring R and otherwise the same as `self`.

INPUT:

- `R` – commutative ring

OUTPUT: ambient space over `R`

Note

There is no need to have any relation between R and the base ring of self, if you want to have such a relation, use `self.base_extend(R)` instead.

defining_polynomials()

Return the defining polynomials of the scheme `self`. Since `self` is an ambient space, this is an empty list.

EXAMPLES:

```
sage: ProjectiveSpace(2, QQ).defining_polynomials()
()
sage: AffineSpace(0, ZZ).defining_polynomials()
()
```

```
>>> from sage.all import *
>>> ProjectiveSpace(Integer(2), QQ).defining_polynomials()
()
>>> AffineSpace(Integer(0), ZZ).defining_polynomials()
()
```

dimension()

Return the absolute dimension of this scheme.

EXAMPLES:

```
sage: A2Q = AffineSpace(2, QQ)
sage: A2Q.dimension_absolute()
2
sage: A2Q.dimension()
2
sage: A2Z = AffineSpace(2, ZZ)
sage: A2Z.dimension_absolute()
3
sage: A2Z.dimension()
3
```

```
>>> from sage.all import *
>>> A2Q = AffineSpace(Integer(2), QQ)
>>> A2Q.dimension_absolute()
2
>>> A2Q.dimension()
2
>>> A2Z = AffineSpace(Integer(2), ZZ)
>>> A2Z.dimension_absolute()
3
>>> A2Z.dimension()
3
```

dimension_absolute()

Return the absolute dimension of this scheme.

EXAMPLES:

```
sage: A2Q = AffineSpace(2, QQ)
sage: A2Q.dimension_absolute()
2
sage: A2Q.dimension()
2
sage: A2Z = AffineSpace(2, ZZ)
sage: A2Z.dimension_absolute()
3
sage: A2Z.dimension()
3
```

```
>>> from sage.all import *
>>> A2Q = AffineSpace(Integer(2), QQ)
>>> A2Q.dimension_absolute()
```

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```
2
>>> A2Q.dimension()
2
>>> A2Z = AffineSpace(Integer(2), ZZ)
>>> A2Z.dimension_absolute()
3
>>> A2Z.dimension()
3
```

dimension_relative()

Return the relative dimension of this scheme over its base.

EXAMPLES:

```
sage: A2Q = AffineSpace(2, QQ)
sage: A2Q.dimension_relative()
2
sage: A2Z = AffineSpace(2, ZZ)
sage: A2Z.dimension_relative()
2
```

```
>>> from sage.all import *
>>> A2Q = AffineSpace(Integer(2), QQ)
>>> A2Q.dimension_relative()
2
>>> A2Z = AffineSpace(Integer(2), ZZ)
>>> A2Z.dimension_relative()
2
```

gen(*n=0*)

Return the n-th generator of the coordinate ring of the scheme `self`.

EXAMPLES:

```
sage: P.<x, y, z> = ProjectiveSpace(2, ZZ)
sage: P.gen(1)
y
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(Integer(2), ZZ, names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> P.gen(Integer(1))
y
```

gens()

Return the generators of the coordinate ring of the scheme `self`.

EXAMPLES:

```
sage: AffineSpace(0, QQ).gens()
()

sage: P.<x, y, z> = ProjectiveSpace(2, GF(5))
```

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```
sage: P.gens()
(x, y, z)
```

```
>>> from sage.all import *
>>> AffineSpace(Integer(0), QQ).gens()
()

>>> P = ProjectiveSpace(Integer(2), GF(Integer(5)), names=('x', 'y', 'z',));␣
↪(x, y, z,) = P._first_ngens(3)
>>> P.gens()
(x, y, z)
```

identity_morphism()

Return the identity morphism.

OUTPUT: the identity morphism of the scheme `self`

EXAMPLES:

```
sage: A = AffineSpace(2, GF(3))
sage: A.identity_morphism()
Scheme endomorphism of Affine Space of dimension 2 over Finite Field of size 3
  Defn: Identity map

sage: P = ProjectiveSpace(3, ZZ)
sage: P.identity_morphism()
Scheme endomorphism of Projective Space of dimension 3 over Integer Ring
  Defn: Identity map
```

```
>>> from sage.all import *
>>> A = AffineSpace(Integer(2), GF(Integer(3)))
>>> A.identity_morphism()
Scheme endomorphism of Affine Space of dimension 2 over Finite Field of size 3
  Defn: Identity map

>>> P = ProjectiveSpace(Integer(3), ZZ)
>>> P.identity_morphism()
Scheme endomorphism of Projective Space of dimension 3 over Integer Ring
  Defn: Identity map
```

is_projective()

Return whether this ambient space is projective n-space.

EXAMPLES:

```
sage: AffineSpace(3, QQ).is_projective()
False
sage: ProjectiveSpace(3, QQ).is_projective()
True
```

```
>>> from sage.all import *
>>> AffineSpace(Integer(3), QQ).is_projective()
False
```

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```
>>> ProjectiveSpace(Integer(3), QQ).is_projective()
True
```

ngens()

Return the number of generators of the coordinate ring of the scheme `self`.

EXAMPLES:

```
sage: AffineSpace(0, QQ).ngens()
0

sage: ProjectiveSpace(50, ZZ).ngens()
51
```

```
>>> from sage.all import *
>>> AffineSpace(Integer(0), QQ).ngens()
0

>>> ProjectiveSpace(Integer(50), ZZ).ngens()
51
```

sage.schemes.generic.ambient_space.**is_AmbientSpace**(x)

Return `True` if x is an ambient space.

EXAMPLES:

```
sage: from sage.schemes.generic.ambient_space import is_AmbientSpace
sage: is_AmbientSpace(ProjectiveSpace(3, ZZ))
doctest:warning...
DeprecationWarning: The function is_AmbientSpace is deprecated; use 'isinstance(..
↪., AmbientSpace)' instead.
See https://github.com/sagemath/sage/issues/38022 for details.
True
sage: is_AmbientSpace(AffineSpace(2, QQ))
True
sage: P.<x, y, z> = ProjectiveSpace(2, ZZ)
sage: is_AmbientSpace(P.subscheme([x + y + z]))
False
```

```
>>> from sage.all import *
>>> from sage.schemes.generic.ambient_space import is_AmbientSpace
>>> is_AmbientSpace(ProjectiveSpace(Integer(3), ZZ))
doctest:warning...
DeprecationWarning: The function is_AmbientSpace is deprecated; use 'isinstance(..
↪., AmbientSpace)' instead.
See https://github.com/sagemath/sage/issues/38022 for details.
True
>>> is_AmbientSpace(AffineSpace(Integer(2), QQ))
True
>>> P = ProjectiveSpace(Integer(2), ZZ, names=('x', 'y', 'z',)); (x, y, z,) = P._
↪first_ngens(3)
>>> is_AmbientSpace(P.subscheme([x + y + z]))
False
```

CHAPTER

SEVEN

ALGEBRAIC SCHEMES

An algebraic scheme is defined by a set of polynomials in some suitable affine or projective coordinates. Possible ambient spaces are

- Affine spaces (*AffineSpace*),
- Projective spaces (*ProjectiveSpace*), or
- Toric varieties (*ToricVariety*).

Note that while projective spaces are of course toric varieties themselves, they are implemented differently in Sage due to efficiency considerations. You still can create a projective space as a toric variety if you wish.

In the following, we call the corresponding subschemes affine algebraic schemes, projective algebraic schemes, or toric algebraic schemes. In the future other ambient spaces, perhaps by means of gluing relations, may be introduced.

Generally, polynomials $p_0, p_1, \ldots, p_n$ define an ideal $I = \langle p_0, p_1, \ldots, p_n \rangle$. In the projective and toric case, the polynomials (and, therefore, the ideal) must be homogeneous. The associated subscheme $V(I)$ of the ambient space is, roughly speaking, the subset of the ambient space on which all polynomials vanish simultaneously.

Warning

You should not construct algebraic scheme objects directly. Instead, use `.subscheme()` methods of ambient spaces. See below for examples.

EXAMPLES:

We first construct the ambient space, here the affine space $\mathbf{Q}^2$:

```
sage: A2 = AffineSpace(2, QQ, 'x, y')
sage: A2.coordinate_ring().inject_variables()
Defining x, y
```

```
>>> from sage.all import *
>>> A2 = AffineSpace(Integer(2), QQ, 'x, y')
>>> A2.coordinate_ring().inject_variables()
Defining x, y
```

Now we can write polynomial equations in the variables x and y. For example, one equation cuts out a curve (a one-dimensional subscheme):

```
sage: V = A2.subscheme([x^2 + y^2 - 1]); V
Closed subscheme of Affine Space of dimension 2 over Rational Field defined by:
  x^2 + y^2 - 1
```

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```
sage: V.dimension()                                                          #␣
↪needs sage.libs.singular
1
```

```
>>> from sage.all import *
>>> V = A2.subscheme([x**Integer(2) + y**Integer(2) - Integer(1)]); V
Closed subscheme of Affine Space of dimension 2 over Rational Field defined by:
  x^2 + y^2 - 1
>>> V.dimension()                                                            #␣
↪needs sage.libs.singular
1
```

Here is a more complicated example in a projective space:

```
sage: P3 = ProjectiveSpace(3, QQ, 'x')
sage: P3.inject_variables()
Defining x0, x1, x2, x3
sage: Q = matrix([[x0, x1, x2], [x1, x2, x3]]).minors(2); Q                  #␣
↪needs sage.modules
[-x1^2 + x0*x2, -x1*x2 + x0*x3, -x2^2 + x1*x3]
sage: twisted_cubic = P3.subscheme(Q); twisted_cubic                         #␣
↪needs sage.libs.singular sage.modules
Closed subscheme of Projective Space of dimension 3 over Rational Field defined by:
  -x1^2 + x0*x2,
  -x1*x2 + x0*x3,
  -x2^2 + x1*x3
sage: twisted_cubic.dimension()                                              #␣
↪needs sage.libs.singular sage.modules
1
```

```
>>> from sage.all import *
>>> P3 = ProjectiveSpace(Integer(3), QQ, 'x')
>>> P3.inject_variables()
Defining x0, x1, x2, x3
>>> Q = matrix([[x0, x1, x2], [x1, x2, x3]]).minors(Integer(2)); Q              ␣
↪     # needs sage.modules
[-x1^2 + x0*x2, -x1*x2 + x0*x3, -x2^2 + x1*x3]
>>> twisted_cubic = P3.subscheme(Q); twisted_cubic                           #␣
↪needs sage.libs.singular sage.modules
Closed subscheme of Projective Space of dimension 3 over Rational Field defined by:
  -x1^2 + x0*x2,
  -x1*x2 + x0*x3,
  -x2^2 + x1*x3
>>> twisted_cubic.dimension()                                                #␣
↪needs sage.libs.singular sage.modules
1
```

Note that there are 3 equations in the 3-dimensional ambient space, yet the subscheme is 1-dimensional. One can show that it is not possible to eliminate any of the equations, that is, the twisted cubic is **not** a complete intersection of two polynomial equations.

Let us look at one affine patch, for example the one where $x_0 = 1$

```
sage: patch = twisted_cubic.affine_patch(0); patch                              #␣
↪needs sage.libs.singular sage.modules
Closed subscheme of Affine Space of dimension 3 over Rational Field defined by:
  -x1^2 + x2,
  -x1*x2 + x3,
  -x2^2 + x1*x3
sage: patch.embedding_morphism()                                                #␣
↪needs sage.libs.singular sage.modules
Scheme morphism:
  From: Closed subscheme of Affine Space of dimension 3 over Rational Field
        defined by: -x1^2 + x2, -x1*x2 + x3, -x2^2 + x1*x3
  To:   Closed subscheme of Projective Space of dimension 3 over Rational Field
        defined by: x1^2 - x0*x2, x1*x2 - x0*x3, x2^2 - x1*x3
  Defn: Defined on coordinates by sending (x1, x2, x3) to (1 : x1 : x2 : x3)
```

```
>>> from sage.all import *
>>> patch = twisted_cubic.affine_patch(Integer(0)); patch                       ␣
↪     # needs sage.libs.singular sage.modules
Closed subscheme of Affine Space of dimension 3 over Rational Field defined by:
  -x1^2 + x2,
  -x1*x2 + x3,
  -x2^2 + x1*x3
>>> patch.embedding_morphism()                                                  #␣
↪needs sage.libs.singular sage.modules
Scheme morphism:
  From: Closed subscheme of Affine Space of dimension 3 over Rational Field
        defined by: -x1^2 + x2, -x1*x2 + x3, -x2^2 + x1*x3
  To:   Closed subscheme of Projective Space of dimension 3 over Rational Field
        defined by: x1^2 - x0*x2, x1*x2 - x0*x3, x2^2 - x1*x3
  Defn: Defined on coordinates by sending (x1, x2, x3) to (1 : x1 : x2 : x3)
```

AUTHORS:

- David Kohel, William Stein (2005): initial version
- Andrey Novoseltsev (2010-05-17): subschemes of toric varieties
- Volker Braun (2010-12-24): documentation of schemes and refactoring; added coordinate neighborhoods and is_smooth()
- Ben Hutz (2014): subschemes of Cartesian products of projective space
- Ben Hutz (2017): split subschemes types into respective folders

class sage.schemes.generic.algebraic_scheme.**AlgebraicScheme**(*A*, *category=None*)

Bases: *Scheme*

An algebraic scheme presented as a subscheme in an ambient space.

This is the base class for all algebraic schemes, that is, schemes defined by equations in affine, projective, or toric ambient spaces.

ambient_space()

Return the ambient space of this algebraic scheme.

EXAMPLES:

```
sage: A.<x, y> = AffineSpace(2, GF(5))
sage: S = A.subscheme([])
sage: S.ambient_space()
Affine Space of dimension 2 over Finite Field of size 5

sage: P.<x, y, z> = ProjectiveSpace(2, ZZ)
sage: S = P.subscheme([x - y, x - z])
sage: S.ambient_space() is P
True
```

```
>>> from sage.all import *
>>> A = AffineSpace(Integer(2), GF(Integer(5)), names=('x', 'y',)); (x, y,) =␣
↪A._first_ngens(2)
>>> S = A.subscheme([])
>>> S.ambient_space()
Affine Space of dimension 2 over Finite Field of size 5

>>> P = ProjectiveSpace(Integer(2), ZZ, names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> S = P.subscheme([x - y, x - z])
>>> S.ambient_space() is P
True
```

coordinate_ring()

Return the coordinate ring of this algebraic scheme. The result is cached.

OUTPUT:

The coordinate ring. Usually a polynomial ring, or a quotient thereof.

EXAMPLES:

```
sage: P.<x, y, z> = ProjectiveSpace(2, ZZ)
sage: S = P.subscheme([x - y, x - z])
sage: S.coordinate_ring()
Quotient of Multivariate Polynomial Ring in x, y, z over Integer Ring
 by the ideal (x - y, x - z)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(Integer(2), ZZ, names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> S = P.subscheme([x - y, x - z])
>>> S.coordinate_ring()
Quotient of Multivariate Polynomial Ring in x, y, z over Integer Ring
 by the ideal (x - y, x - z)
```

embedding_center()

Return the distinguished point, if there is any.

If the scheme Y was constructed as a neighbourhood of a point $p \in X$, then *embedding_morphism()* returns a local isomorphism $f : Y \to X$ around the preimage point $f^{-1}(p)$. The latter is returned by *embedding_center()*.

OUTPUT:

A point of `self`. This raises `AttributeError` if there is no distinguished point, depending on how `self` was constructed.

EXAMPLES:

```
sage: P3.<w,x,y,z> = ProjectiveSpace(QQ, 3)
sage: X = P3.subscheme( (w^2-x^2)*(y^2-z^2) )
sage: p = [1,-1,3,4]
sage: nbhd = X.neighborhood(p); nbhd
Closed subscheme of Affine Space of dimension 3 over Rational Field defined␣
↪by:
  w^2*y^2 - x^2*y^2 + 6*w^2*y - 6*x^2*y + 2*w*y^2 +
  2*x*y^2 - 7*w^2 + 7*x^2 + 12*w*y + 12*x*y - 14*w - 14*x
sage: nbhd.embedding_center()
(0, 0, 0)
sage: nbhd.embedding_morphism()(nbhd.embedding_center())
(1/4 : -1/4 : 3/4 : 1)
sage: nbhd.embedding_morphism()
Scheme morphism:
  From: Closed subscheme of Affine Space of dimension 3 over Rational Field
        defined by: w^2*y^2 - x^2*y^2 + 6*w^2*y - 6*x^2*y + 2*w*y^2 + 2*x*y^2
                    - 7*w^2 + 7*x^2 + 12*w*y + 12*x*y - 14*w - 14*x
  To:   Closed subscheme of Projective Space of dimension 3 over Rational␣
↪Field
        defined by: w^2*y^2 - x^2*y^2 - w^2*z^2 + x^2*z^2
  Defn: Defined on coordinates by sending (w, x, y) to
        (w + 1 : x - 1 : y + 3 : 4)
```

```
>>> from sage.all import *
>>> P3 = ProjectiveSpace(QQ, Integer(3), names=('w', 'x', 'y', 'z',)); (w, x,␣
↪y, z,) = P3._first_ngens(4)
>>> X = P3.subscheme( (w**Integer(2)-x**Integer(2))*(y**Integer(2)-
↪z**Integer(2)) )
>>> p = [Integer(1),-Integer(1),Integer(3),Integer(4)]
>>> nbhd = X.neighborhood(p); nbhd
Closed subscheme of Affine Space of dimension 3 over Rational Field defined␣
↪by:
  w^2*y^2 - x^2*y^2 + 6*w^2*y - 6*x^2*y + 2*w*y^2 +
  2*x*y^2 - 7*w^2 + 7*x^2 + 12*w*y + 12*x*y - 14*w - 14*x
>>> nbhd.embedding_center()
(0, 0, 0)
>>> nbhd.embedding_morphism()(nbhd.embedding_center())
(1/4 : -1/4 : 3/4 : 1)
>>> nbhd.embedding_morphism()
Scheme morphism:
  From: Closed subscheme of Affine Space of dimension 3 over Rational Field
        defined by: w^2*y^2 - x^2*y^2 + 6*w^2*y - 6*x^2*y + 2*w*y^2 + 2*x*y^2
                    - 7*w^2 + 7*x^2 + 12*w*y + 12*x*y - 14*w - 14*x
  To:   Closed subscheme of Projective Space of dimension 3 over Rational␣
↪Field
        defined by: w^2*y^2 - x^2*y^2 - w^2*z^2 + x^2*z^2
  Defn: Defined on coordinates by sending (w, x, y) to
        (w + 1 : x - 1 : y + 3 : 4)
```

embedding_morphism()

Return the default embedding morphism of `self`.

If the scheme Y was constructed as a neighbourhood of a point $p \in X$, then *embedding_morphism()* returns a local isomorphism $f : Y \to X$ around the preimage point $f^{-1}(p)$. The latter is returned by *embedding_center()*.

If the algebraic scheme Y was not constructed as a neighbourhood of a point, then the embedding in its *ambient_space()* is returned.

OUTPUT:

A scheme morphism whose `domain()` is `self`.

- By default, it is the tautological embedding into its own ambient space *ambient_space()*.
- If the algebraic scheme (which itself is a subscheme of an auxiliary *ambient_space()*) was constructed as a patch or neighborhood of a point then the embedding is the embedding into the original scheme.
- A `NotImplementedError` is raised if the construction of the embedding morphism is not implemented yet.

EXAMPLES:

```
sage: A2.<x,y> = AffineSpace(QQ, 2)
sage: C = A2.subscheme(x^2 + y^2 - 1)
sage: C.embedding_morphism()                                                #␣
↪needs sage.libs.singular
  Scheme morphism:
  From: Closed subscheme of Affine Space of dimension 2 over Rational Field
        defined by: x^2 + y^2 - 1
  To:   Affine Space of dimension 2 over Rational Field
  Defn: Defined on coordinates by sending (x, y) to (x, y)

sage: # needs sage.geometry.polyhedron sage.graphs sage.libs.singular
sage: P1xP1.<x,y,u,v> = toric_varieties.P1xP1()
sage: P1 = P1xP1.subscheme(x - y)
sage: P1.embedding_morphism()
Scheme morphism:
  From: Closed subscheme of 2-d CPR-Fano toric variety covered
        by 4 affine patches defined by: x - y
  To:   2-d CPR-Fano toric variety covered by 4 affine patches
  Defn: Defined on coordinates by sending [x : y : u : v] to [y : y : u : v]
```

```
>>> from sage.all import *
>>> A2 = AffineSpace(QQ, Integer(2), names=('x', 'y',)); (x, y,) = A2._first_
↪ngens(2)
>>> C = A2.subscheme(x**Integer(2) + y**Integer(2) - Integer(1))
>>> C.embedding_morphism()                                                  #␣
↪needs sage.libs.singular
  Scheme morphism:
  From: Closed subscheme of Affine Space of dimension 2 over Rational Field
        defined by: x^2 + y^2 - 1
  To:   Affine Space of dimension 2 over Rational Field
  Defn: Defined on coordinates by sending (x, y) to (x, y)

>>> # needs sage.geometry.polyhedron sage.graphs sage.libs.singular
```

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```
>>> P1xP1 = toric_varieties.P1xP1(names=('x', 'y', 'u', 'v',)); (x, y, u, v,)␣
↪= P1xP1._first_ngens(4)
>>> P1 = P1xP1.subscheme(x - y)
>>> P1.embedding_morphism()
Scheme morphism:
  From: Closed subscheme of 2-d CPR-Fano toric variety covered
        by 4 affine patches defined by: x - y
  To:   2-d CPR-Fano toric variety covered by 4 affine patches
  Defn: Defined on coordinates by sending [x : y : u : v] to [y : y : u : v]
```

So far, the embedding was just in the own ambient space. Now a bit more interesting examples:

```
sage: P2.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: X = P2.subscheme((x^2-y^2)*z)
sage: p = (1,1,0)
sage: nbhd = X.neighborhood(p); nbhd
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  -y^2*z - 2*y*z
```

```
>>> from sage.all import *
>>> P2 = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,)␣
↪= P2._first_ngens(3)
>>> X = P2.subscheme((x**Integer(2)-y**Integer(2))*z)
>>> p = (Integer(1),Integer(1),Integer(0))
>>> nbhd = X.neighborhood(p); nbhd
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  -y^2*z - 2*y*z
```

Note that $p = (1, 1, 0)$ is a singular point of X. So the neighborhood of p is not just affine space. The `neighborhood()` method returns a presentation of the neighborhood as a subscheme of an auxiliary 2-dimensional affine space:

```
sage: nbhd.ambient_space()
Affine Space of dimension 2 over Rational Field
```

```
>>> from sage.all import *
>>> nbhd.ambient_space()
Affine Space of dimension 2 over Rational Field
```

But its *embedding_morphism()* is not into this auxiliary affine space, but the original subscheme X:

```
sage: nbhd.embedding_morphism()
Scheme morphism:
  From: Closed subscheme of Affine Space of dimension 2 over Rational Field
        defined by: -y^2*z - 2*y*z
  To:   Closed subscheme of Projective Space of dimension 2 over Rational␣
↪Field
        defined by: x^2*z - y^2*z
  Defn: Defined on coordinates by sending (y, z) to (1 : y + 1 : z)
```

```
>>> from sage.all import *
>>> nbhd.embedding_morphism()
Scheme morphism:
  From: Closed subscheme of Affine Space of dimension 2 over Rational Field
        defined by: -y^2*z - 2*y*z
  To:   Closed subscheme of Projective Space of dimension 2 over Rational␣
↪Field
        defined by: x^2*z - y^2*z
  Defn: Defined on coordinates by sending (y, z) to (1 : y + 1 : z)
```

A couple more examples:

```
sage: # needs sage.geometry.polyhedron sage.graphs sage.libs.singular
sage: patch1 = P1xP1.affine_patch(1); patch1
2-d affine toric variety
sage: patch1.embedding_morphism()
Scheme morphism:
  From: 2-d affine toric variety
  To:   2-d CPR-Fano toric variety covered by 4 affine patches
  Defn: Defined on coordinates by sending [y : u] to [1 : y : u : 1]
sage: subpatch = P1.affine_patch(1); subpatch
Closed subscheme of 2-d affine toric variety defined by:
  -y + 1
sage: subpatch.embedding_morphism()
Scheme morphism:
  From: Closed subscheme of 2-d affine toric variety defined by: -y + 1
  To:   Closed subscheme of 2-d CPR-Fano toric variety covered
        by 4 affine patches defined by: x - y
  Defn: Defined on coordinates by sending [y : u] to [1 : y : u : 1]
```

```
>>> from sage.all import *
>>> # needs sage.geometry.polyhedron sage.graphs sage.libs.singular
>>> patch1 = P1xP1.affine_patch(Integer(1)); patch1
2-d affine toric variety
>>> patch1.embedding_morphism()
Scheme morphism:
  From: 2-d affine toric variety
  To:   2-d CPR-Fano toric variety covered by 4 affine patches
  Defn: Defined on coordinates by sending [y : u] to [1 : y : u : 1]
>>> subpatch = P1.affine_patch(Integer(1)); subpatch
Closed subscheme of 2-d affine toric variety defined by:
  -y + 1
>>> subpatch.embedding_morphism()
Scheme morphism:
  From: Closed subscheme of 2-d affine toric variety defined by: -y + 1
  To:   Closed subscheme of 2-d CPR-Fano toric variety covered
        by 4 affine patches defined by: x - y
  Defn: Defined on coordinates by sending [y : u] to [1 : y : u : 1]
```

identity_morphism()

Return the identity morphism.

OUTPUT: the identity morphism of the scheme `self`

EXAMPLES:

```
sage: X = Spec(QQ)
sage: X.identity_morphism()
Scheme endomorphism of Spectrum of Rational Field
  Defn: Identity map
```

```
>>> from sage.all import *
>>> X = Spec(QQ)
>>> X.identity_morphism()
Scheme endomorphism of Spectrum of Rational Field
  Defn: Identity map
```

is_projective()

Return `True` if `self` is presented as a subscheme of an ambient projective space.

OUTPUT: boolean

EXAMPLES:

```
sage: PP.<x,y,z,w> = ProjectiveSpace(3, QQ)
sage: f = x^3 + y^3 + z^3 + w^3
sage: R = f.parent()
sage: I = [f] + [f.derivative(zz) for zz in PP.gens()]
sage: V = PP.subscheme(I)
sage: V.is_projective()
True
sage: AA.<x,y,z,w> = AffineSpace(4, QQ)
sage: V = AA.subscheme(I)
sage: V.is_projective()
False
```

```
>>> from sage.all import *
>>> PP = ProjectiveSpace(Integer(3), QQ, names=('x', 'y', 'z', 'w',)); (x, y,␣
↪z, w,) = PP._first_ngens(4)
>>> f = x**Integer(3) + y**Integer(3) + z**Integer(3) + w**Integer(3)
>>> R = f.parent()
>>> I = [f] + [f.derivative(zz) for zz in PP.gens()]
>>> V = PP.subscheme(I)
>>> V.is_projective()
True
>>> AA = AffineSpace(Integer(4), QQ, names=('x', 'y', 'z', 'w',)); (x, y, z,␣
↪w,) = AA._first_ngens(4)
>>> V = AA.subscheme(I)
>>> V.is_projective()
False
```

Note that toric varieties are implemented differently than projective spaces. This is why this method returns `False` for toric varieties:

```
sage: # needs sage.geometry.polyhedron sage.graphs
sage: PP.<x,y,z,w> = toric_varieties.P(3)
sage: V = PP.subscheme(x^3 + y^3 + z^3 + w^3)
```

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```
sage: V.is_projective()
False
```

```
>>> from sage.all import *
>>> # needs sage.geometry.polyhedron sage.graphs
>>> PP = toric_varieties.P(Integer(3), names=('x', 'y', 'z', 'w',)); (x, y, z,
↪ w,) = PP._first_ngens(4)
>>> V = PP.subscheme(x**Integer(3) + y**Integer(3) + z**Integer(3) +␣
↪w**Integer(3))
>>> V.is_projective()
False
```

ngens()

Return the number of generators of the ambient space of this algebraic scheme.

EXAMPLES:

```
sage: A.<x, y> = AffineSpace(2, GF(5))
sage: S = A.subscheme([])
sage: S.ngens()
2
sage: P.<x, y, z> = ProjectiveSpace(2, ZZ)
sage: S = P.subscheme([x - y, x - z])
sage: P.ngens()
3
```

```
>>> from sage.all import *
>>> A = AffineSpace(Integer(2), GF(Integer(5)), names=('x', 'y',)); (x, y,) =␣
↪A._first_ngens(2)
>>> S = A.subscheme([])
>>> S.ngens()
2
>>> P = ProjectiveSpace(Integer(2), ZZ, names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> S = P.subscheme([x - y, x - z])
>>> P.ngens()
3
```

class sage.schemes.generic.algebraic_scheme.**AlgebraicScheme_quasi**(X, Y)

Bases: *AlgebraicScheme*

The quasi-affine or quasi-projective scheme $X - Y$, where X and Y are both closed subschemes of a common ambient affine or projective space.

Warning

You should not create objects of this class directly. The preferred method to construct such subschemes is to use `complement()` method of algebraic schemes.

OUTPUT: an instance of *AlgebraicScheme_quasi*

EXAMPLES:

```
sage: P.<x, y, z> = ProjectiveSpace(2, ZZ)
sage: S = P.subscheme([])
sage: T = P.subscheme([x - y])
sage: T.complement(S)
Quasi-projective subscheme X - Y
 of Projective Space of dimension 2 over Integer Ring,
 where X is defined by:
   (no polynomials)
 and Y is defined by:
   x - y
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(Integer(2), ZZ, names=('x', 'y', 'z',)); (x, y, z,) = P._
↪first_ngens(3)
>>> S = P.subscheme([])
>>> T = P.subscheme([x - y])
>>> T.complement(S)
Quasi-projective subscheme X - Y
 of Projective Space of dimension 2 over Integer Ring,
 where X is defined by:
   (no polynomials)
 and Y is defined by:
   x - y
```

X()

Return the scheme X such that `self` is represented as $X - Y$.

EXAMPLES:

```
sage: P.<x, y, z> = ProjectiveSpace(2, ZZ)
sage: S = P.subscheme([])
sage: T = P.subscheme([x - y])
sage: U = T.complement(S)
sage: U.X() is S
True
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(Integer(2), ZZ, names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> S = P.subscheme([])
>>> T = P.subscheme([x - y])
>>> U = T.complement(S)
>>> U.X() is S
True
```

Y()

Return the scheme Y such that `self` is represented as $X - Y$.

EXAMPLES:

```
sage: P.<x, y, z> = ProjectiveSpace(2, ZZ)
sage: S = P.subscheme([])
sage: T = P.subscheme([x - y])
```

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```
sage: U = T.complement(S)
sage: U.Y() is T
True
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(Integer(2), ZZ, names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> S = P.subscheme([])
>>> T = P.subscheme([x - y])
>>> U = T.complement(S)
>>> U.Y() is T
True
```

rational_points(***kwds*)

Return the set of rational points on this algebraic scheme over the field F.

INPUT: keyword arguments:

- `bound` – integer (default: 0); the bound for the coordinates for subschemes with dimension at least 1
- `F` – field (default: base ring); the field to compute the rational points over

EXAMPLES:

```
sage: A.<x, y> = AffineSpace(2, GF(7))
sage: S = A.subscheme([x^2 - y])
sage: T = A.subscheme([x - y])
sage: U = T.complement(S)
sage: U.rational_points()
[(2, 4), (3, 2), (4, 2), (5, 4), (6, 1)]
sage: U.rational_points(F=GF(7^2, 'b'))                                    #␣
↪needs sage.rings.finite_rings
[(2, 4), (3, 2), (4, 2), (5, 4), (6, 1), (b, b + 4), (b + 1, 3*b + 5),
 (b + 2, 5*b + 1), (b + 3, 6), (b + 4, 2*b + 6), (b + 5, 4*b + 1),
 (b + 6, 6*b + 5), (2*b, 4*b + 2), (2*b + 1, b + 3), (2*b + 2, 5*b + 6),
 (2*b + 3, 2*b + 4), (2*b + 4, 6*b + 4), (2*b + 5, 3*b + 6), (2*b + 6, 3),
 (3*b, 2*b + 1), (3*b + 1, b + 2), (3*b + 2, 5), (3*b + 3, 6*b + 3),
 (3*b + 4, 5*b + 3), (3*b + 5, 4*b + 5), (3*b + 6, 3*b + 2),
 (4*b, 2*b + 1), (4*b + 1, 3*b + 2), (4*b + 2, 4*b + 5),
 (4*b + 3, 5*b + 3), (4*b + 4, 6*b + 3), (4*b + 5, 5), (4*b + 6, b + 2),
 (5*b, 4*b + 2), (5*b + 1, 3), (5*b + 2, 3*b + 6), (5*b + 3, 6*b + 4),
 (5*b + 4, 2*b + 4), (5*b + 5, 5*b + 6), (5*b + 6, b + 3), (6*b, b + 4),
 (6*b + 1, 6*b + 5), (6*b + 2, 4*b + 1), (6*b + 3, 2*b + 6), (6*b + 4, 6),
 (6*b + 5, 5*b + 1), (6*b + 6, 3*b + 5)]
```

```
>>> from sage.all import *
>>> A = AffineSpace(Integer(2), GF(Integer(7)), names=('x', 'y',)); (x, y,) =␣
↪A._first_ngens(2)
>>> S = A.subscheme([x**Integer(2) - y])
>>> T = A.subscheme([x - y])
>>> U = T.complement(S)
>>> U.rational_points()
[(2, 4), (3, 2), (4, 2), (5, 4), (6, 1)]
```

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```
>>> U.rational_points(F=GF(Integer(7)**Integer(2), 'b'))
↪               # needs sage.rings.finite_rings
[(2, 4), (3, 2), (4, 2), (5, 4), (6, 1), (b, b + 4), (b + 1, 3*b + 5),
 (b + 2, 5*b + 1), (b + 3, 6), (b + 4, 2*b + 6), (b + 5, 4*b + 1),
 (b + 6, 6*b + 5), (2*b, 4*b + 2), (2*b + 1, b + 3), (2*b + 2, 5*b + 6),
 (2*b + 3, 2*b + 4), (2*b + 4, 6*b + 4), (2*b + 5, 3*b + 6), (2*b + 6, 3),
 (3*b, 2*b + 1), (3*b + 1, b + 2), (3*b + 2, 5), (3*b + 3, 6*b + 3),
 (3*b + 4, 5*b + 3), (3*b + 5, 4*b + 5), (3*b + 6, 3*b + 2),
 (4*b, 2*b + 1), (4*b + 1, 3*b + 2), (4*b + 2, 4*b + 5),
 (4*b + 3, 5*b + 3), (4*b + 4, 6*b + 3), (4*b + 5, 5), (4*b + 6, b + 2),
 (5*b, 4*b + 2), (5*b + 1, 3), (5*b + 2, 3*b + 6), (5*b + 3, 6*b + 4),
 (5*b + 4, 2*b + 4), (5*b + 5, 5*b + 6), (5*b + 6, b + 3), (6*b, b + 4),
 (6*b + 1, 6*b + 5), (6*b + 2, 4*b + 1), (6*b + 3, 2*b + 6), (6*b + 4, 6),
 (6*b + 5, 5*b + 1), (6*b + 6, 3*b + 5)]
```

class sage.schemes.generic.algebraic_scheme.**AlgebraicScheme_subscheme**(*A*, *polynomials*, *category=None*)

Bases: *AlgebraicScheme*

An algebraic scheme presented as a closed subscheme is defined by explicit polynomial equations. This is as opposed to a general scheme, which could, e.g., be the Neron model of some object, and for which we do not want to give explicit equations.

INPUT:

- `A` – ambient space (e.g. affine or projective n-space)
- `polynomials` – single polynomial, ideal or iterable of defining polynomials; in any case polynomials must belong to the coordinate ring of the ambient space and define valid polynomial functions (e.g. they should be homogeneous in the case of a projective space)

OUTPUT: algebraic scheme

EXAMPLES:

```
sage: from sage.schemes.generic.algebraic_scheme import AlgebraicScheme_subscheme
sage: P.<x, y, z> = ProjectiveSpace(2, QQ)
sage: P.subscheme([x^2 - y*z])
Closed subscheme of Projective Space of dimension 2 over Rational Field defined␣
↪by:
  x^2 - y*z
sage: AlgebraicScheme_subscheme(P, [x^2 - y*z])
Closed subscheme of Projective Space of dimension 2 over Rational Field defined␣
↪by:
  x^2 - y*z
```

```
>>> from sage.all import *
>>> from sage.schemes.generic.algebraic_scheme import AlgebraicScheme_subscheme
>>> P = ProjectiveSpace(Integer(2), QQ, names=('x', 'y', 'z',)); (x, y, z,) = P._
↪first_ngens(3)
>>> P.subscheme([x**Integer(2) - y*z])
Closed subscheme of Projective Space of dimension 2 over Rational Field defined␣
↪by:
  x^2 - y*z
>>> AlgebraicScheme_subscheme(P, [x**Integer(2) - y*z])
```

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```
Closed subscheme of Projective Space of dimension 2 over Rational Field defined␣
↪by:
  x^2 - y*z
```

Jacobian()

Return the Jacobian ideal.

This is the ideal generated by

- the $d \times d$ minors of the Jacobian matrix, where d is the *codimension()* of the algebraic scheme, and
- the defining polynomials of the algebraic scheme. Note that some authors do not include these in the definition of the Jacobian ideal. An example of a reference that does include the defining equations is [Laz2004], p. 181.

OUTPUT: an ideal in the coordinate ring of the ambient space

EXAMPLES:

```
sage: P3.<w,x,y,z> = ProjectiveSpace(3, QQ)
sage: twisted_cubic = P3.subscheme(matrix([[w, x, y],                          #␣
↪needs sage.libs.singular
....:                                      [x, y, z]]).minors(2))
sage: twisted_cubic.Jacobian()                                                 #␣
↪needs sage.libs.singular
Ideal (-x^2 + w*y, -x*y + w*z, -y^2 + x*z, x*z, -2*w*z, w*y, 3*w*y,
       -2*w*x, w^2, y*z, -2*x*z, w*z, 3*w*z, -2*w*y, w*x, z^2, -2*y*z,
       x*z, 3*x*z, -2*w*z, w*y)
 of Multivariate Polynomial Ring in w, x, y, z over Rational Field
sage: twisted_cubic.defining_ideal()                                           #␣
↪needs sage.libs.singular
Ideal (-x^2 + w*y, -x*y + w*z, -y^2 + x*z)
 of Multivariate Polynomial Ring in w, x, y, z over Rational Field
```

```
>>> from sage.all import *
>>> P3 = ProjectiveSpace(Integer(3), QQ, names=('w', 'x', 'y', 'z',)); (w, x,␣
↪y, z,) = P3._first_ngens(4)
>>> twisted_cubic = P3.subscheme(matrix([[w, x, y],                           #␣
↪needs sage.libs.singular
...                                       [x, y, z]]).minors(Integer(2)))
>>> twisted_cubic.Jacobian()                                                  #␣
↪needs sage.libs.singular
Ideal (-x^2 + w*y, -x*y + w*z, -y^2 + x*z, x*z, -2*w*z, w*y, 3*w*y,
       -2*w*x, w^2, y*z, -2*x*z, w*z, 3*w*z, -2*w*y, w*x, z^2, -2*y*z,
       x*z, 3*x*z, -2*w*z, w*y)
 of Multivariate Polynomial Ring in w, x, y, z over Rational Field
>>> twisted_cubic.defining_ideal()                                            #␣
↪needs sage.libs.singular
Ideal (-x^2 + w*y, -x*y + w*z, -y^2 + x*z)
 of Multivariate Polynomial Ring in w, x, y, z over Rational Field
```

This example addresses issue Issue #20512:

```
sage: X = P3.subscheme([])
sage: X.Jacobian() == P3.coordinate_ring().unit_ideal()                    #␣
↪needs sage.libs.singular
True
```

```
>>> from sage.all import *
>>> X = P3.subscheme([])
>>> X.Jacobian() == P3.coordinate_ring().unit_ideal()                      #␣
↪needs sage.libs.singular
True
```

Jacobian_matrix()

Return the matrix $\frac{\partial f_i}{\partial x_j}$ of (formal) partial derivatives.

OUTPUT: a matrix of polynomials

EXAMPLES:

```
sage: P3.<w,x,y,z> = ProjectiveSpace(3, QQ)
sage: twisted_cubic = P3.subscheme(matrix([[w, x, y],                      #␣
↪needs sage.libs.singular
....:                                      [x, y, z]]).minors(2))
sage: twisted_cubic.Jacobian_matrix()                                      #␣
↪needs sage.libs.singular
[   y -2*x    w    0]
[   z   -y   -x    w]
[   0    z -2*y    x]
```

```
>>> from sage.all import *
>>> P3 = ProjectiveSpace(Integer(3), QQ, names=('w', 'x', 'y', 'z',)); (w, x,␣
↪y, z,) = P3._first_ngens(4)
>>> twisted_cubic = P3.subscheme(matrix([[w, x, y],                        #␣
↪needs sage.libs.singular
...                                      [x, y, z]]).minors(Integer(2)))
>>> twisted_cubic.Jacobian_matrix()                                        #␣
↪needs sage.libs.singular
[   y -2*x    w    0]
[   z   -y   -x    w]
[   0    z -2*y    x]
```

This example addresses issue Issue #20512:

```
sage: X = P3.subscheme([])
sage: X.Jacobian_matrix().base_ring() == P3.coordinate_ring()              #␣
↪needs sage.libs.singular
True
```

```
>>> from sage.all import *
>>> X = P3.subscheme([])
>>> X.Jacobian_matrix().base_ring() == P3.coordinate_ring()                #␣
↪needs sage.libs.singular
True
```

base_extend(R)

Return the base change to the ring R of this scheme.

EXAMPLES:

```
sage: P.<x, y, z> = ProjectiveSpace(2, GF(11))
sage: S = P.subscheme([x^2 - y*z])
sage: S.base_extend(GF(11^2, 'b'))                                          #␣
↪needs sage.rings.finite_rings
Closed subscheme of Projective Space of dimension 2
 over Finite Field in b of size 11^2
 defined by: x^2 - y*z
sage: S.base_extend(ZZ)
Traceback (most recent call last):
...
ValueError: no natural map from the base ring (=Finite Field of size 11)
to R (=Integer Ring)!
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(Integer(2), GF(Integer(11)), names=('x', 'y', 'z',));␣
↪(x, y, z,) = P._first_ngens(3)
>>> S = P.subscheme([x**Integer(2) - y*z])
>>> S.base_extend(GF(Integer(11)**Integer(2), 'b'))                         ␣
↪               # needs sage.rings.finite_rings
Closed subscheme of Projective Space of dimension 2
 over Finite Field in b of size 11^2
 defined by: x^2 - y*z
>>> S.base_extend(ZZ)
Traceback (most recent call last):
...
ValueError: no natural map from the base ring (=Finite Field of size 11)
to R (=Integer Ring)!
```

change_ring(R)

Return a new algebraic subscheme which is this subscheme coerced to `R`.

INPUT:

- `R` – ring or morphism

OUTPUT: a new algebraic subscheme which is this subscheme coerced to `R`

EXAMPLES:

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: X = P.subscheme([3*x^2 - y^2])
sage: H = Hom(X, X)
sage: X.change_ring(GF(3))
Closed subscheme of Projective Space of dimension 1
 over Finite Field of size 3 defined by: -y^2
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> X = P.subscheme([Integer(3)*x**Integer(2) - y**Integer(2)])
```

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```
>>> H = Hom(X, X)
>>> X.change_ring(GF(Integer(3)))
Closed subscheme of Projective Space of dimension 1
 over Finite Field of size 3 defined by: -y^2
```

```
sage: # needs sage.rings.number_field
sage: K.<w> = QuadraticField(2)
sage: R.<z> = K[]
sage: L.<v> = K.extension(z^3 - 5)
sage: P.<x,y> = ProjectiveSpace(K, 1)
sage: X = P.subscheme(x - w*y)                                              #␣
↪needs sage.libs.singular
sage: X.change_ring(L)                                                      #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 1 over
 Number Field in v with defining polynomial z^3 - 5 over its base field
 defined by: x + (-w)*y
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> K = QuadraticField(Integer(2), names=('w',)); (w,) = K._first_ngens(1)
>>> R = K['z']; (z,) = R._first_ngens(1)
>>> L = K.extension(z**Integer(3) - Integer(5), names=('v',)); (v,) = L._
↪first_ngens(1)
>>> P = ProjectiveSpace(K, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> X = P.subscheme(x - w*y)                                                #␣
↪needs sage.libs.singular
>>> X.change_ring(L)                                                        #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 1 over
 Number Field in v with defining polynomial z^3 - 5 over its base field
 defined by: x + (-w)*y
```

```
sage: # needs sage.rings.number_field
sage: K.<w> = QuadraticField(2)
sage: R.<z> = K[]
sage: L.<v> = K.extension(z^3 - 5)
sage: P.<x,y,z> = AffineSpace(L, 3)
sage: X = P.subscheme([x - w*y, z^2 - v*x])                                 #␣
↪needs sage.libs.singular
sage: emb = L.embeddings(QQbar)                                             #␣
↪needs sage.libs.singular
sage: X.change_ring(emb[0])                                                 #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 3 over Algebraic Field
 defined by:
  x + (-1.414213562373095? + 0.?e-16*I)*y,
  z^2 + (0.8549879733383485? + 1.480882609682365?*I)*x
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> K = QuadraticField(Integer(2), names=('w',)); (w,) = K._first_ngens(1)
>>> R = K['z']; (z,) = R._first_ngens(1)
>>> L = K.extension(z**Integer(3) - Integer(5), names=('v',)); (v,) = L._
↪first_ngens(1)
>>> P = AffineSpace(L, Integer(3), names=('x', 'y', 'z',)); (x, y, z,) = P._
↪first_ngens(3)
>>> X = P.subscheme([x - w*y, z**Integer(2) - v*x])                          ␣
↪      # needs sage.libs.singular
>>> emb = L.embeddings(QQbar)                                               #␣
↪needs sage.libs.singular
>>> X.change_ring(emb[Integer(0)])                                           ␣
↪     # needs sage.libs.singular
Closed subscheme of Affine Space of dimension 3 over Algebraic Field
 defined by:
  x + (-1.414213562373095? + 0.?e-16*I)*y,
  z^2 + (0.8549879733383485? + 1.480882609682365?*I)*x
```

```
sage: # needs sage.rings.number_field
sage: K.<w> = QuadraticField(2)
sage: R.<z> = K[]
sage: L.<v> = K.extension(z^3 - 5)
sage: P.<x,y,z> = AffineSpace(L, 3)
sage: X = P.subscheme([x - w*y, z^2 - v*x])                                #␣
↪needs sage.libs.singular
sage: emb = L.embeddings(QQbar)                                            #␣
↪needs sage.libs.singular
sage: X.change_ring(emb[1])                                                #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 3 over Algebraic Field
 defined by:
  x + (-1.414213562373095? + 0.?e-16*I)*y,
  z^2 + (0.8549879733383485? - 1.480882609682365?*I)*x
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> K = QuadraticField(Integer(2), names=('w',)); (w,) = K._first_ngens(1)
>>> R = K['z']; (z,) = R._first_ngens(1)
>>> L = K.extension(z**Integer(3) - Integer(5), names=('v',)); (v,) = L._
↪first_ngens(1)
>>> P = AffineSpace(L, Integer(3), names=('x', 'y', 'z',)); (x, y, z,) = P._
↪first_ngens(3)
>>> X = P.subscheme([x - w*y, z**Integer(2) - v*x])                          ␣
↪      # needs sage.libs.singular
>>> emb = L.embeddings(QQbar)                                               #␣
↪needs sage.libs.singular
>>> X.change_ring(emb[Integer(1)])                                           ␣
↪     # needs sage.libs.singular
Closed subscheme of Affine Space of dimension 3 over Algebraic Field
 defined by:
  x + (-1.414213562373095? + 0.?e-16*I)*y,
```

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```
  z^2 + (0.8549879733383485? - 1.480882609682365?*I)*x
```

```
sage: # needs sage.rings.number_field
sage: K.<w> = QuadraticField(-3)
sage: P.<x,y> = ProjectiveSpace(K, 1)
sage: X = P.subscheme(x - w*y)                                              #␣
↪needs sage.libs.singular
sage: X.change_ring(CC)                                                     #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 1
 over Complex Field with 53 bits of precision defined by:
  x + (-1.73205080756888*I)*y
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> K = QuadraticField(-Integer(3), names=('w',)); (w,) = K._first_ngens(1)
>>> P = ProjectiveSpace(K, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> X = P.subscheme(x - w*y)                                                #␣
↪needs sage.libs.singular
>>> X.change_ring(CC)                                                       #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 1
 over Complex Field with 53 bits of precision defined by:
  x + (-1.73205080756888*I)*y
```

```
sage: # needs sage.rings.number_field
sage: K.<w> = QuadraticField(3)
sage: P.<x,y> = ProjectiveSpace(K, 1)
sage: X = P.subscheme(x - w*y)                                              #␣
↪needs sage.libs.singular
sage: X.change_ring(RR)                                                     #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 1
 over Real Field with 53 bits of precision defined by:
  x - 1.73205080756888*y
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> K = QuadraticField(Integer(3), names=('w',)); (w,) = K._first_ngens(1)
>>> P = ProjectiveSpace(K, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> X = P.subscheme(x - w*y)                                                #␣
↪needs sage.libs.singular
>>> X.change_ring(RR)                                                       #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 1
 over Real Field with 53 bits of precision defined by:
  x - 1.73205080756888*y
```

```
sage: # needs sage.rings.number_field
sage: K.<v> = CyclotomicField(7)
sage: O = K.maximal_order()
sage: P.<x,y> = ProjectiveSpace(O, 1)
sage: X = P.subscheme([x^2 + O(v)*y^2])                                    #␣
↪needs sage.libs.singular
sage: X.change_ring(CC)                                                    #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 1
 over Complex Field with 53 bits of precision defined by:
  x^2 + (0.623489801858734 + 0.781831482468030*I)*y^2
sage: X.change_ring(K).change_ring(K.embeddings(QQbar)[3])                 #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 1
 over Algebraic Field defined by:
  x^2 + (-0.9009688679024191? - 0.4338837391175581?*I)*y^2
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> K = CyclotomicField(Integer(7), names=('v',)); (v,) = K._first_ngens(1)
>>> O = K.maximal_order()
>>> P = ProjectiveSpace(O, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> X = P.subscheme([x**Integer(2) + O(v)*y**Integer(2)])                  ␣
↪                # needs sage.libs.singular
>>> X.change_ring(CC)                                                     #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 1
 over Complex Field with 53 bits of precision defined by:
  x^2 + (0.623489801858734 + 0.781831482468030*I)*y^2
>>> X.change_ring(K).change_ring(K.embeddings(QQbar)[Integer(3)])          ␣
↪     # needs sage.libs.singular
Closed subscheme of Projective Space of dimension 1
 over Algebraic Field defined by:
  x^2 + (-0.9009688679024191? - 0.4338837391175581?*I)*y^2
```

```
sage: # needs sage.rings.number_field
sage: R.<x> = QQ[]
sage: f = x^6 - 2
sage: L.<b> = NumberField(f, embedding=f.roots(CC)[2][0])
sage: A.<x,y> = AffineSpace(L, 2)
sage: H = Hom(A, A)
sage: X = A.subscheme([b*x^2, y^2])                                        #␣
↪needs sage.libs.singular
sage: X.change_ring(CC)                                                    #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 2
 over Complex Field with 53 bits of precision defined by:
  (-0.561231024154687 - 0.972080648619833*I)*x^2,
  y^2
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> f = x**Integer(6) - Integer(2)
>>> L = NumberField(f, embedding=f.roots(CC)[Integer(2)][Integer(0)], names=(
↪'b',)); (b,) = L._first_ngens(1)
>>> A = AffineSpace(L, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> H = Hom(A, A)
>>> X = A.subscheme([b*x**Integer(2), y**Integer(2)])                    ␣
↪                # needs sage.libs.singular
>>> X.change_ring(CC)                                                    #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 2
 over Complex Field with 53 bits of precision defined by:
  (-0.561231024154687 - 0.972080648619833*I)*x^2,
  y^2
```

codimension()

Return the codimension of the algebraic subscheme.

OUTPUT: integer

EXAMPLES:

```
sage: PP.<x,y,z,w,v> = ProjectiveSpace(4, QQ)
sage: V = PP.subscheme(x*y)
sage: V.codimension()                                                    #␣
↪needs sage.libs.singular
1
sage: V.dimension()                                                      #␣
↪needs sage.libs.singular
3
```

```
>>> from sage.all import *
>>> PP = ProjectiveSpace(Integer(4), QQ, names=('x', 'y', 'z', 'w', 'v',));␣
↪(x, y, z, w, v,) = PP._first_ngens(5)
>>> V = PP.subscheme(x*y)
>>> V.codimension()                                                      #␣
↪needs sage.libs.singular
1
>>> V.dimension()                                                        #␣
↪needs sage.libs.singular
3
```

complement(*other=None*)

Return the scheme-theoretic complement `other - self`, where `self` and `other` are both closed algebraic subschemes of the same ambient space.

If `other` is unspecified, it is taken to be the ambient space of `self`.

EXAMPLES:

```
sage: A.<x, y, z> = AffineSpace(3, ZZ)
sage: X = A.subscheme([x + y - z])
sage: Y = A.subscheme([x - y + z])
sage: Y.complement(X)
Quasi-affine subscheme X - Y of
 Affine Space of dimension 3 over Integer Ring,
 where X is defined by:
   x + y - z
 and Y is defined by:
   x - y + z
sage: Y.complement()
Quasi-affine subscheme X - Y of
 Affine Space of dimension 3 over Integer Ring,
 where X is defined by:
   (no polynomials)
 and Y is defined by:
   x - y + z
sage: P.<x, y, z> = ProjectiveSpace(2, QQ)
sage: X = P.subscheme([x^2 + y^2 + z^2])
sage: Y = P.subscheme([x*y + y*z + z*x])
sage: Y.complement(X)
Quasi-projective subscheme X - Y of
 Projective Space of dimension 2 over Rational Field,
 where X is defined by:
   x^2 + y^2 + z^2
 and Y is defined by:
   x*y + x*z + y*z
sage: Y.complement(P)
Quasi-projective subscheme X - Y of
 Projective Space of dimension 2 over Rational Field,
 where X is defined by:
   (no polynomials)
 and Y is defined by:
   x*y + x*z + y*z
```

```
>>> from sage.all import *
>>> A = AffineSpace(Integer(3), ZZ, names=('x', 'y', 'z',)); (x, y, z,) = A._
↪first_ngens(3)
>>> X = A.subscheme([x + y - z])
>>> Y = A.subscheme([x - y + z])
>>> Y.complement(X)
Quasi-affine subscheme X - Y of
 Affine Space of dimension 3 over Integer Ring,
 where X is defined by:
   x + y - z
 and Y is defined by:
   x - y + z
>>> Y.complement()
Quasi-affine subscheme X - Y of
 Affine Space of dimension 3 over Integer Ring,
 where X is defined by:
   (no polynomials)
```

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```
 and Y is defined by:
   x - y + z
>>> P = ProjectiveSpace(Integer(2), QQ, names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> X = P.subscheme([x**Integer(2) + y**Integer(2) + z**Integer(2)])
>>> Y = P.subscheme([x*y + y*z + z*x])
>>> Y.complement(X)
Quasi-projective subscheme X - Y of
 Projective Space of dimension 2 over Rational Field,
 where X is defined by:
   x^2 + y^2 + z^2
 and Y is defined by:
   x*y + x*z + y*z
>>> Y.complement(P)
Quasi-projective subscheme X - Y of
 Projective Space of dimension 2 over Rational Field,
 where X is defined by:
   (no polynomials)
 and Y is defined by:
   x*y + x*z + y*z
```

defining_ideal()

Return the ideal that defines this scheme as a subscheme of its ambient space.

OUTPUT: an ideal in the coordinate ring of the ambient space

EXAMPLES:

```
sage: P.<x, y, z> = ProjectiveSpace(2, ZZ)
sage: S = P.subscheme([x^2 - y*z, x^3 + z^3])
sage: S.defining_ideal()
Ideal (x^2 - y*z, x^3 + z^3) of Multivariate Polynomial Ring in x, y, z
 over Integer Ring
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(Integer(2), ZZ, names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> S = P.subscheme([x**Integer(2) - y*z, x**Integer(3) + z**Integer(3)])
>>> S.defining_ideal()
Ideal (x^2 - y*z, x^3 + z^3) of Multivariate Polynomial Ring in x, y, z
 over Integer Ring
```

defining_polynomials()

Return the polynomials that define this scheme as a subscheme of its ambient space.

OUTPUT:

A tuple of polynomials in the coordinate ring of the ambient space.

EXAMPLES:

```
sage: P.<x, y, z> = ProjectiveSpace(2, ZZ)
sage: S = P.subscheme([x^2 - y*z, x^3 + z^3])
sage: S.defining_polynomials()
(x^2 - y*z, x^3 + z^3)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(Integer(2), ZZ, names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> S = P.subscheme([x**Integer(2) - y*z, x**Integer(3) + z**Integer(3)])
>>> S.defining_polynomials()
(x^2 - y*z, x^3 + z^3)
```

intersection(*other*)

Return the scheme-theoretic intersection of `self` and `other` in their common ambient space.

EXAMPLES:

```
sage: A.<x, y> = AffineSpace(2, ZZ)
sage: X = A.subscheme([x^2 - y])
sage: Y = A.subscheme([y])
sage: X.intersection(Y)
Closed subscheme of Affine Space of dimension 2 over Integer Ring defined by:
  x^2 - y,
  y
```

```
>>> from sage.all import *
>>> A = AffineSpace(Integer(2), ZZ, names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> X = A.subscheme([x**Integer(2) - y])
>>> Y = A.subscheme([y])
>>> X.intersection(Y)
Closed subscheme of Affine Space of dimension 2 over Integer Ring defined by:
  x^2 - y,
  y
```

irreducible_components()

Return the irreducible components of this algebraic scheme, as subschemes of the same ambient space.

OUTPUT:

an immutable sequence of irreducible subschemes of the ambient space of this scheme

The components are cached.

EXAMPLES:

We define what is clearly a union of four hypersurfaces in $\P^4_{\QQ}$ then find the irreducible components:

```
sage: PP.<x,y,z,w,v> = ProjectiveSpace(4, QQ)
sage: V = PP.subscheme((x^2 - y^2 - z^2) * (w^5 - 2*v^2*z^3) * w * (v^3 - x^
↪2*z))
sage: V.irreducible_components()                                              #␣
↪needs sage.libs.singular
[Closed subscheme of Projective Space of dimension 4 over Rational Field␣
↪defined by:
   w,
 Closed subscheme of Projective Space of dimension 4 over Rational Field␣
↪defined by:
   x^2 - y^2 - z^2,
 Closed subscheme of Projective Space of dimension 4 over Rational Field␣
```

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```
↪defined by:
  x^2*z - v^3,
 Closed subscheme of Projective Space of dimension 4 over Rational Field␣
↪defined by:
  w^5 - 2*z^3*v^2]
```

```
>>> from sage.all import *
>>> PP = ProjectiveSpace(Integer(4), QQ, names=('x', 'y', 'z', 'w', 'v',));␣
↪(x, y, z, w, v,) = PP._first_ngens(5)
>>> V = PP.subscheme((x**Integer(2) - y**Integer(2) - z**Integer(2)) *␣
↪(w**Integer(5) - Integer(2)*v**Integer(2)*z**Integer(3)) * w *␣
↪(v**Integer(3) - x**Integer(2)*z))
>>> V.irreducible_components()                                              #␣
↪needs sage.libs.singular
[Closed subscheme of Projective Space of dimension 4 over Rational Field␣
↪defined by:
  w,
 Closed subscheme of Projective Space of dimension 4 over Rational Field␣
↪defined by:
  x^2 - y^2 - z^2,
 Closed subscheme of Projective Space of dimension 4 over Rational Field␣
↪defined by:
  x^2*z - v^3,
 Closed subscheme of Projective Space of dimension 4 over Rational Field␣
↪defined by:
  w^5 - 2*z^3*v^2]
```

We verify that the irrelevant ideal is not accidentally returned (see Issue #6920):

```
sage: PP.<x,y,z,w> = ProjectiveSpace(3, QQ)
sage: f = x^3 + y^3 + z^3 + w^3
sage: R = f.parent()
sage: I = [f] + [f.derivative(zz) for zz in PP.gens()]
sage: V = PP.subscheme(I)
sage: V.irreducible_components()                                            #␣
↪needs sage.libs.singular
[]
```

```
>>> from sage.all import *
>>> PP = ProjectiveSpace(Integer(3), QQ, names=('x', 'y', 'z', 'w',)); (x, y,␣
↪z, w,) = PP._first_ngens(4)
>>> f = x**Integer(3) + y**Integer(3) + z**Integer(3) + w**Integer(3)
>>> R = f.parent()
>>> I = [f] + [f.derivative(zz) for zz in PP.gens()]
>>> V = PP.subscheme(I)
>>> V.irreducible_components()                                              #␣
↪needs sage.libs.singular
[]
```

The same polynomial as above defines a scheme with a nontrivial irreducible component in affine space (instead of the empty scheme as above):

```
sage: AA.<x,y,z,w> = AffineSpace(4, QQ)
sage: V = AA.subscheme(I)
sage: V.irreducible_components()                                                #␣
↪needs sage.libs.singular
[Closed subscheme of Affine Space of dimension 4 over Rational Field defined␣
↪by:
   w,
   z,
   y,
   x]
```

```
>>> from sage.all import *
>>> AA = AffineSpace(Integer(4), QQ, names=('x', 'y', 'z', 'w',)); (x, y, z,␣
↪w,) = AA._first_ngens(4)
>>> V = AA.subscheme(I)
>>> V.irreducible_components()                                                  #␣
↪needs sage.libs.singular
[Closed subscheme of Affine Space of dimension 4 over Rational Field defined␣
↪by:
   w,
   z,
   y,
   x]
```

is_irreducible()

Return whether this subscheme is or is not irreducible.

OUTPUT: boolean

EXAMPLES:

```
sage: # needs sage.rings.number_field
sage: K = QuadraticField(-3)
sage: P.<x,y,z,w,t,u> = ProjectiveSpace(K, 5)
sage: X = P.subscheme([x*y - z^2 - K.0*t^2, t*w*x + y*z^2 - u^3])
sage: X.is_irreducible()                                                        #␣
↪needs sage.libs.singular
True
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> K = QuadraticField(-Integer(3))
>>> P = ProjectiveSpace(K, Integer(5), names=('x', 'y', 'z', 'w', 't', 'u',));
↪ (x, y, z, w, t, u,) = P._first_ngens(6)
>>> X = P.subscheme([x*y - z**Integer(2) - K.gen(0)*t**Integer(2), t*w*x +␣
↪y*z**Integer(2) - u**Integer(3)])
>>> X.is_irreducible()                                                          #␣
↪needs sage.libs.singular
True
```

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: X = P.subscheme([(y + x - z)^2])
sage: X.is_irreducible()                                                        #␣
```

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```
↪needs sage.libs.singular
False
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> X = P.subscheme([(y + x - z)**Integer(2)])
>>> X.is_irreducible()                                                    #␣
↪needs sage.libs.singular
False
```

```
sage: A.<x,y,z,w> = AffineSpace(GF(17), 4)
sage: X = A.subscheme([
....:         x*y*z^2 - x*y*z*w - z*w^2 + w^3,
....:         x^3*y*z*w - x*y^3*z - x^2*y*z*w - x^2*w^3 + y^2*w^2 + x*w^3
....:     ])
sage: X.is_irreducible()                                                  #␣
↪needs sage.libs.singular
False
```

```
>>> from sage.all import *
>>> A = AffineSpace(GF(Integer(17)), Integer(4), names=('x', 'y', 'z', 'w',));
↪ (x, y, z, w,) = A._first_ngens(4)
>>> X = A.subscheme([
...         x*y*z**Integer(2) - x*y*z*w - z*w**Integer(2) + w**Integer(3),
...         x**Integer(3)*y*z*w - x*y**Integer(3)*z - x**Integer(2)*y*z*w -␣
↪x**Integer(2)*w**Integer(3) + y**Integer(2)*w**Integer(2) + x*w**Integer(3)
...     ])
>>> X.is_irreducible()                                                    #␣
↪needs sage.libs.singular
False
```

normalize_defining_polynomials()

Function to normalize the coefficients of defining polynomials of given subscheme.

Normalization as in removing denominator from all the coefficients, and then removing any common factor between the coefficients. It takes LCM of denominators and then removes common factor among coefficients, if any.

EXAMPLES:

```
sage: A.<x,y> = AffineSpace(2, QQ)
sage: S = A.subscheme([2*x^2 + 4*x*y, 1/8*x + 1/3*y])
sage: S.normalize_defining_polynomials()
sage: S.defining_polynomials()
(x^2 + 2*x*y, 3*x + 8*y)
```

```
>>> from sage.all import *
>>> A = AffineSpace(Integer(2), QQ, names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> S = A.subscheme([Integer(2)*x**Integer(2) + Integer(4)*x*y, Integer(1)/
↪Integer(8)*x + Integer(1)/Integer(3)*y])
```

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```
>>> S.normalize_defining_polynomials()
>>> S.defining_polynomials()
(x^2 + 2*x*y, 3*x + 8*y)
```

rational_points(***kwds*)

Return the rational points on the algebraic subscheme.

For a dimension 0 subscheme, if the base ring is a numerical field such as the ComplexField the results returned could be very far from correct. If the polynomials defining the subscheme are defined over a number field, you will get better results calling rational points with F defined as the number field and the base ring as the field of definition. If the base ring is a number field, the embedding into `F` must be known.

In the case of numerically approximated points, the points are returned over as points of the ambient space.

For a dimension greater than 0 scheme, depending on bound size, either the points in the ambient space are enumerated or a sieving algorithm lifting points modulo primes is used. See the documentation in homset for the details of the sieving algorithm.

INPUT: keyword arguments:

- `bound` – integer (default: 0); the bound for the coordinates for subschemes with dimension at least 1
- `prec` – integer (default: 53); the precision to use to compute the elements of bounded height for number fields
- `F` – field (default: base ring). The field to compute the rational points over
- `point_tolerance` – positive real number (default: 10^(-10)). For numerically inexact fields, two points are considered the same if their coordinates are within tolerance.
- `zero_tolerance` – positive real number (default: 10^(-10)). For numerically inexact fields, points are on the subscheme if they satisfy the equations to within tolerance.
- `tolerance` – a rational number in (0,1] used in Doyle-Krumm algorithm-4

OUTPUT: list of points in subscheme or ambient space

Warning

For numerically inexact fields such as ComplexField or RealField the list of points returned is very likely to be incomplete at best.

EXAMPLES:

Enumerate over a projective scheme over a number field:

```
sage: # needs sage.rings.number_field
sage: u = QQ['u'].0
sage: K.<v> = NumberField(u^2 + 3)
sage: A.<x,y> = ProjectiveSpace(K, 1)
sage: X = A.subscheme(x^2 - y^2)
sage: X.rational_points(bound=3)                                                #␣
↪needs sage.libs.singular
[(-1 : 1), (1 : 1)]
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> u = QQ['u'].gen(0)
>>> K = NumberField(u**Integer(2) + Integer(3), names=('v',)); (v,) = K._
↪first_ngens(1)
>>> A = ProjectiveSpace(K, Integer(1), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> X = A.subscheme(x**Integer(2) - y**Integer(2))
>>> X.rational_points(bound=Integer(3))                                    ␣
↪     # needs sage.libs.singular
[(-1 : 1), (1 : 1)]
```

One can enumerate points up to a given bound on a projective scheme over the rationals:

```
sage: E = EllipticCurve('37a')                                             #␣
↪needs sage.schemes
sage: E.rational_points(bound=8)                                           #␣
↪needs sage.libs.singular sage.schemes
[(-1 : -1 : 1), (-1 : 0 : 1), (0 : -1 : 1), (0 : 0 : 1), (0 : 1 : 0),
 (1/4 : -5/8 : 1), (1/4 : -3/8 : 1), (1 : -1 : 1), (1 : 0 : 1),
 (2 : -3 : 1), (2 : 2 : 1)]
```

```
>>> from sage.all import *
>>> E = EllipticCurve('37a')                                             #␣
↪needs sage.schemes
>>> E.rational_points(bound=Integer(8))                                    ␣
↪     # needs sage.libs.singular sage.schemes
[(-1 : -1 : 1), (-1 : 0 : 1), (0 : -1 : 1), (0 : 0 : 1), (0 : 1 : 0),
 (1/4 : -5/8 : 1), (1/4 : -3/8 : 1), (1 : -1 : 1), (1 : 0 : 1),
 (2 : -3 : 1), (2 : 2 : 1)]
```

For a small finite field, the complete set of points can be enumerated.

```
sage: Etilde = E.base_extend(GF(3))                                        #␣
↪needs sage.schemes
sage: Etilde.rational_points()                                             #␣
↪needs sage.libs.singular sage.schemes
[(0 : 1 : 0), (0 : 0 : 1), (0 : 2 : 1), (1 : 0 : 1),
 (1 : 2 : 1), (2 : 0 : 1), (2 : 2 : 1)]
```

```
>>> from sage.all import *
>>> Etilde = E.base_extend(GF(Integer(3)))                                 ␣
↪     # needs sage.schemes
>>> Etilde.rational_points()                                             #␣
↪needs sage.libs.singular sage.schemes
[(0 : 1 : 0), (0 : 0 : 1), (0 : 2 : 1), (1 : 0 : 1),
 (1 : 2 : 1), (2 : 0 : 1), (2 : 2 : 1)]
```

The class of hyperelliptic curves does not (yet) support desingularization of the places at infinity into two points:

```
sage: FF = FiniteField(7)
sage: P.<x> = PolynomialRing(FiniteField(7))
```

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```
sage: C = HyperellipticCurve(x^8 + x + 1)                                   #␣
↪needs sage.schemes
sage: C.rational_points()                                                   #␣
↪needs sage.libs.singular sage.schemes
[(0 : 1 : 0), (0 : 1 : 1), (0 : 6 : 1), (2 : 0 : 1),
 (4 : 0 : 1), (6 : 1 : 1), (6 : 6 : 1)]
```

```
>>> from sage.all import *
>>> FF = FiniteField(Integer(7))
>>> P = PolynomialRing(FiniteField(Integer(7)), names=('x',)); (x,) = P._
↪first_ngens(1)
>>> C = HyperellipticCurve(x**Integer(8) + x + Integer(1))                  ␣
↪               # needs sage.schemes
>>> C.rational_points()                                                    #␣
↪needs sage.libs.singular sage.schemes
[(0 : 1 : 0), (0 : 1 : 1), (0 : 6 : 1), (2 : 0 : 1),
 (4 : 0 : 1), (6 : 1 : 1), (6 : 6 : 1)]
```

```
sage: # needs sage.rings.number_field sage.rings.real_mpfr
sage: K.<v> = QuadraticField(-3)
sage: P.<x,y,z> = ProjectiveSpace(K, 2)
sage: X = P.subscheme([x^2 - v^2*x*z, y*x - v*z^2])
sage: X.rational_points(F=CC)                                               #␣
↪needs sage.libs.singular
[(-3.00000000000000 : -0.577350269189626*I : 1.00000000000000),
 (0.000000000000000 : 1.00000000000000 : 0.000000000000000)]
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field sage.rings.real_mpfr
>>> K = QuadraticField(-Integer(3), names=('v',)); (v,) = K._first_ngens(1)
>>> P = ProjectiveSpace(K, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> X = P.subscheme([x**Integer(2) - v**Integer(2)*x*z, y*x -␣
↪v*z**Integer(2)])
>>> X.rational_points(F=CC)                                                 #␣
↪needs sage.libs.singular
[(-3.00000000000000 : -0.577350269189626*I : 1.00000000000000),
 (0.000000000000000 : 1.00000000000000 : 0.000000000000000)]
```

```
sage: # needs sage.rings.number_field sage.rings.real_mpfr
sage: K.<v> = QuadraticField(3)
sage: A.<x,y> = AffineSpace(K, 2)
sage: X = A.subscheme([x^2 - v^2*y, y*x - v])
sage: X.rational_points(F=RR)                                               #␣
↪needs sage.libs.singular
[(1.73205080756888, 1.00000000000000)]
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field sage.rings.real_mpfr
>>> K = QuadraticField(Integer(3), names=('v',)); (v,) = K._first_ngens(1)
>>> A = AffineSpace(K, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
```

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```
↪ngens(2)
>>> X = A.subscheme([x**Integer(2) - v**Integer(2)*y, y*x - v])
>>> X.rational_points(F=RR)                                                #␣
↪needs sage.libs.singular
[(1.73205080756888, 1.00000000000000)]
```

Todo

Implement Stoll's model in weighted projective space to resolve singularities and find two points (1 : 1 : 0) and (-1 : 1 : 0) at infinity.

reduce()

Return the corresponding reduced algebraic space associated to this scheme.

EXAMPLES: First we construct the union of a doubled and tripled line in the affine plane over **Q**

```
sage: A.<x,y> = AffineSpace(2, QQ)
sage: X = A.subscheme([(x-1)^2*(x-y)^3]); X
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  x^5 - 3*x^4*y + 3*x^3*y^2 - x^2*y^3 - 2*x^4 + 6*x^3*y
  - 6*x^2*y^2 + 2*x*y^3 + x^3 - 3*x^2*y + 3*x*y^2 - y^3
sage: X.dimension()                                                       #␣
↪needs sage.libs.singular
1
```

```
>>> from sage.all import *
>>> A = AffineSpace(Integer(2), QQ, names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> X = A.subscheme([(x-Integer(1))**Integer(2)*(x-y)**Integer(3)]); X
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  x^5 - 3*x^4*y + 3*x^3*y^2 - x^2*y^3 - 2*x^4 + 6*x^3*y
  - 6*x^2*y^2 + 2*x*y^3 + x^3 - 3*x^2*y + 3*x*y^2 - y^3
>>> X.dimension()                                                         #␣
↪needs sage.libs.singular
1
```

Then we compute the corresponding reduced scheme:

```
sage: Y = X.reduce(); Y                                                   #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  x^2 - x*y - x + y
```

```
>>> from sage.all import *
>>> Y = X.reduce(); Y                                                     #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
```

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```
↪by:
  x^2 - x*y - x + y
```

Finally, we verify that the reduced scheme Y is the union of those two lines:

```
sage: # needs sage.libs.singular
sage: L1 = A.subscheme([x - 1]); L1
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  x - 1
sage: L2 = A.subscheme([x - y]); L2
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  x - y
sage: W = L1.union(L2); W              # taken in ambient space
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  x^2 - x*y - x + y
sage: Y == W
True
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> L1 = A.subscheme([x - Integer(1)]); L1
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  x - 1
>>> L2 = A.subscheme([x - y]); L2
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  x - y
>>> W = L1.union(L2); W              # taken in ambient space
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  x^2 - x*y - x + y
>>> Y == W
True
```

specialization(*D=None*, *phi=None*)

Specialization of this subscheme.

Given a family of maps defined over a polynomial ring. A specialization is a particular member of that family. The specialization can be specified either by a dictionary or a `SpecializationMorphism`.

INPUT:

- `D` – dictionary (optional)
- `phi` – `SpecializationMorphism` (optional)

OUTPUT: `SchemeMorphism_polynomial`

EXAMPLES:

```
sage: R.<c> = PolynomialRing(QQ)
sage: P.<x,y> = ProjectiveSpace(R, 1)
sage: X = P.subscheme([x^2 + c*y^2])
sage: X.specialization(dict({c:2}))
Closed subscheme of Projective Space of dimension 1 over Rational Field␣
↪defined by:
  x^2 + 2*y^2
```

```
>>> from sage.all import *
>>> R = PolynomialRing(QQ, names=('c',)); (c,) = R._first_ngens(1)
>>> P = ProjectiveSpace(R, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> X = P.subscheme([x**Integer(2) + c*y**Integer(2)])
>>> X.specialization(dict({c:Integer(2)}))
Closed subscheme of Projective Space of dimension 1 over Rational Field␣
↪defined by:
  x^2 + 2*y^2
```

```
sage: R.<c> = PolynomialRing(QQ)
sage: S.<a,b> = R[]
sage: P.<x,y,z> = AffineSpace(S, 3)
sage: X = P.subscheme([x^2 + a*c*y^2 - b*z^2])
sage: from sage.rings.polynomial.flatten import SpecializationMorphism
sage: phi = SpecializationMorphism(P.coordinate_ring(),
....:                              dict({c: 2, a: 1}))
sage: X.specialization(phi=phi)                                              #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 3
 over Univariate Polynomial Ring in b over Rational Field defined by:
  x^2 + 2*y^2 + (-b)*z^2
```

```
>>> from sage.all import *
>>> R = PolynomialRing(QQ, names=('c',)); (c,) = R._first_ngens(1)
>>> S = R['a, b']; (a, b,) = S._first_ngens(2)
>>> P = AffineSpace(S, Integer(3), names=('x', 'y', 'z',)); (x, y, z,) = P._
↪first_ngens(3)
>>> X = P.subscheme([x**Integer(2) + a*c*y**Integer(2) - b*z**Integer(2)])
>>> from sage.rings.polynomial.flatten import SpecializationMorphism
>>> phi = SpecializationMorphism(P.coordinate_ring(),
...                              dict({c: Integer(2), a: Integer(1)}))
>>> X.specialization(phi=phi)                                                #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 3
 over Univariate Polynomial Ring in b over Rational Field defined by:
  x^2 + 2*y^2 + (-b)*z^2
```

union(*other*)

Return the scheme-theoretic union of `self` and `other` in their common ambient space.

EXAMPLES: We construct the union of a line and a tripled-point on the line.

```
sage: A.<x,y> = AffineSpace(2, QQ)
```

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```
sage: I = ideal([x, y])^3
sage: P = A.subscheme(I)
sage: L = A.subscheme([y - 1])
sage: S = L.union(P); S                                                    #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  y^4 - y^3,
  x*y^3 - x*y^2,
  x^2*y^2 - x^2*y,
  x^3*y - x^3
sage: S.dimension()                                                        #␣
↪needs sage.libs.singular
1
sage: S.reduce()                                                           #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  y^2 - y,
  x*y - x
```

```
>>> from sage.all import *
>>> A = AffineSpace(Integer(2), QQ, names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> I = ideal([x, y])**Integer(3)
>>> P = A.subscheme(I)
>>> L = A.subscheme([y - Integer(1)])
>>> S = L.union(P); S                                                      #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  y^4 - y^3,
  x*y^3 - x*y^2,
  x^2*y^2 - x^2*y,
  x^3*y - x^3
>>> S.dimension()                                                          #␣
↪needs sage.libs.singular
1
>>> S.reduce()                                                             #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  y^2 - y,
  x*y - x
```

We can also use the notation "+" for the union:

```
sage: A.subscheme([x]) + A.subscheme([y^2 - (x^3+1)])                      #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  x^4 - x*y^2 + x
```

```
>>> from sage.all import *
>>> A.subscheme([x]) + A.subscheme([y**Integer(2) -␣
↪(x**Integer(3)+Integer(1))])                          # needs sage.libs.
↪singular
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  x^4 - x*y^2 + x
```

Saving and loading:

```
sage: loads(S.dumps()) == S                                                    #␣
↪needs sage.libs.singular
True
```

```
>>> from sage.all import *
>>> loads(S.dumps()) == S                                                      #␣
↪needs sage.libs.singular
True
```

weil_restriction()

Compute the Weil restriction of this variety over some extension field. If the field is a finite field, then this computes the Weil restriction to the prime subfield.

A Weil restriction of scalars - denoted $Res_{L/k}$ - is a functor which, for any finite extension of fields L/k and any algebraic variety X over L, produces another corresponding variety $Res_{L/k}(X)$, defined over k. It is useful for reducing questions about varieties over large fields to questions about more complicated varieties over smaller fields.

This function does not compute this Weil restriction directly but computes on generating sets of polynomial ideals:

Let d be the degree of the field extension L/k, let a a generator of L/k and p the minimal polynomial of L/k. Denote this ideal by I.

Specifically, this function first maps each variable x to its representation over k: $\sum_{i=0}^{d-1} a^i x_i$. Then each generator of I is evaluated over these representations and reduced modulo the minimal polynomial p. The result is interpreted as a univariate polynomial in a and its coefficients are the new generators of the returned ideal.

If the input and the output ideals are radical, this is equivalent to the statement about algebraic varieties above.

OUTPUT: affine subscheme; the Weil restriction of `self`

EXAMPLES:

```
sage: # needs sage.rings.number_field
sage: R.<x> = QQ[]
sage: K.<w> = NumberField(x^5 - 2)
sage: R.<x> = K[]
sage: L.<v> = K.extension(x^2 + 1)
sage: A.<x,y> = AffineSpace(L, 2)
sage: X = A.subscheme([y^2 - L(w)*x^3 - v])                                    #␣
↪needs sage.libs.singular
sage: X.weil_restriction()                                                     #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 4
```

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```
 over Number Field in w with defining polynomial x^5 - 2 defined by:
  (-w)*z0^3 + (3*w)*z0*z1^2 + z2^2 - z3^2,
  (-3*w)*z0^2*z1 + w*z1^3 + 2*z2*z3 - 1
sage: X.weil_restriction().ambient_space() is A.weil_restriction()          #␣
↪needs sage.libs.singular
True
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> K = NumberField(x**Integer(5) - Integer(2), names=('w',)); (w,) = K._
↪first_ngens(1)
>>> R = K['x']; (x,) = R._first_ngens(1)
>>> L = K.extension(x**Integer(2) + Integer(1), names=('v',)); (v,) = L._
↪first_ngens(1)
>>> A = AffineSpace(L, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> X = A.subscheme([y**Integer(2) - L(w)*x**Integer(3) - v])                ␣
↪                # needs sage.libs.singular
>>> X.weil_restriction()                                                    #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 4
 over Number Field in w with defining polynomial x^5 - 2 defined by:
  (-w)*z0^3 + (3*w)*z0*z1^2 + z2^2 - z3^2,
  (-3*w)*z0^2*z1 + w*z1^3 + 2*z2*z3 - 1
>>> X.weil_restriction().ambient_space() is A.weil_restriction()          #␣
↪needs sage.libs.singular
True
```

```
sage: A.<x,y,z> = AffineSpace(GF(5^2, 't'), 3)                             #␣
↪needs sage.rings.finite_rings
sage: X = A.subscheme([y^2 - x*z, z^2 + 2*y])                              #␣
↪needs sage.libs.singular sage.rings.finite_rings
sage: X.weil_restriction()                                                 #␣
↪needs sage.libs.singular sage.rings.finite_rings
Closed subscheme of Affine Space of dimension 6
 over Finite Field of size 5 defined by:
  z2^2 - 2*z3^2 - z0*z4 + 2*z1*z5,
  2*z2*z3 + z3^2 - z1*z4 - z0*z5 - z1*z5,
  z4^2 - 2*z5^2 + 2*z2,
  2*z4*z5 + z5^2 + 2*z3
```

```
>>> from sage.all import *
>>> A = AffineSpace(GF(Integer(5)**Integer(2), 't'), Integer(3), names=('x',
↪'y', 'z',)); (x, y, z,) = A._first_ngens(3)# needs sage.rings.finite_rings
>>> X = A.subscheme([y**Integer(2) - x*z, z**Integer(2) + Integer(2)*y])     ␣
↪                        # needs sage.libs.singular sage.rings.finite_rings
>>> X.weil_restriction()                                                    #␣
↪needs sage.libs.singular sage.rings.finite_rings
Closed subscheme of Affine Space of dimension 6
 over Finite Field of size 5 defined by:
```

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```
  z2^2 - 2*z3^2 - z0*z4 + 2*z1*z5,
  2*z2*z3 + z3^2 - z1*z4 - z0*z5 - z1*z5,
  z4^2 - 2*z5^2 + 2*z2,
  2*z4*z5 + z5^2 + 2*z3
```

sage.schemes.generic.algebraic_scheme.**is_AlgebraicScheme**(*x*)

Test whether `x` is an algebraic scheme.

INPUT:

- `x` – anything

OUTPUT:

boolean; whether `x` is an algebraic scheme, that is, a subscheme of an ambient space over a ring defined by polynomial equations.

EXAMPLES:

```
sage: A2 = AffineSpace(2, QQ, 'x, y')
sage: A2.coordinate_ring().inject_variables()
Defining x, y
sage: V = A2.subscheme([x^2 + y^2]); V
Closed subscheme of Affine Space of dimension 2 over Rational Field defined by:
  x^2 + y^2
sage: from sage.schemes.generic.algebraic_scheme import is_AlgebraicScheme
sage: is_AlgebraicScheme(V)
doctest:warning...
DeprecationWarning: The function is_AlgebraicScheme is deprecated; use
↪'isinstance(..., AlgebraicScheme)' instead.
See https://github.com/sagemath/sage/issues/38022 for details.
True
```

```
>>> from sage.all import *
>>> A2 = AffineSpace(Integer(2), QQ, 'x, y')
>>> A2.coordinate_ring().inject_variables()
Defining x, y
>>> V = A2.subscheme([x**Integer(2) + y**Integer(2)]); V
Closed subscheme of Affine Space of dimension 2 over Rational Field defined by:
  x^2 + y^2
>>> from sage.schemes.generic.algebraic_scheme import is_AlgebraicScheme
>>> is_AlgebraicScheme(V)
doctest:warning...
DeprecationWarning: The function is_AlgebraicScheme is deprecated; use
↪'isinstance(..., AlgebraicScheme)' instead.
See https://github.com/sagemath/sage/issues/38022 for details.
True
```

Affine space is itself not an algebraic scheme, though the closed subscheme defined by no equations is:

```
sage: from sage.schemes.generic.algebraic_scheme import is_AlgebraicScheme
sage: is_AlgebraicScheme(AffineSpace(10, QQ))
False
sage: V = AffineSpace(10, QQ).subscheme([]); V
```

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```
Closed subscheme of Affine Space of dimension 10 over Rational Field defined by:
  (no polynomials)
sage: is_AlgebraicScheme(V)
True
```

```
>>> from sage.all import *
>>> from sage.schemes.generic.algebraic_scheme import is_AlgebraicScheme
>>> is_AlgebraicScheme(AffineSpace(Integer(10), QQ))
False
>>> V = AffineSpace(Integer(10), QQ).subscheme([]); V
Closed subscheme of Affine Space of dimension 10 over Rational Field defined by:
  (no polynomials)
>>> is_AlgebraicScheme(V)
True
```

We create a more complicated closed subscheme:

```
sage: A,x = AffineSpace(10, QQ).objgens()
sage: X = A.subscheme([sum(x)]); X
Closed subscheme of Affine Space of dimension 10 over Rational Field defined by:
  x0 + x1 + x2 + x3 + x4 + x5 + x6 + x7 + x8 + x9
sage: is_AlgebraicScheme(X)
True
```

```
>>> from sage.all import *
>>> A,x = AffineSpace(Integer(10), QQ).objgens()
>>> X = A.subscheme([sum(x)]); X
Closed subscheme of Affine Space of dimension 10 over Rational Field defined by:
  x0 + x1 + x2 + x3 + x4 + x5 + x6 + x7 + x8 + x9
>>> is_AlgebraicScheme(X)
True
```

```
sage: is_AlgebraicScheme(QQ)
False
sage: S = Spec(QQ)
sage: is_AlgebraicScheme(S)
False
```

```
>>> from sage.all import *
>>> is_AlgebraicScheme(QQ)
False
>>> S = Spec(QQ)
>>> is_AlgebraicScheme(S)
False
```

CHAPTER

EIGHT

HYPERSURFACES IN AFFINE AND PROJECTIVE SPACE

AUTHORS:

- William Stein <wstein@gmail.com> (2005-12-08)
- David Kohel <kohel@maths.usyd.edu.au> (2005-12-08)
- Alex Ghitza <aghitza@alum.mit.edu> (2009-04-17)

class sage.schemes.generic.hypersurface.**AffineHypersurface**(*poly*, *ambient=None*)

Bases: *AlgebraicScheme_subscheme_affine*

The affine hypersurface defined by the given polynomial.

EXAMPLES:

```
sage: A.<x, y, z> = AffineSpace(ZZ, 3)
sage: AffineHypersurface(x*y - z^3, A)
Affine hypersurface defined by -z^3 + x*y
 in Affine Space of dimension 3 over Integer Ring
```

```
>>> from sage.all import *
>>> A = AffineSpace(ZZ, Integer(3), names=('x', 'y', 'z',)); (x, y, z,) = A._
↪first_ngens(3)
>>> AffineHypersurface(x*y - z**Integer(3), A)
Affine hypersurface defined by -z^3 + x*y
 in Affine Space of dimension 3 over Integer Ring
```

```
sage: A.<x, y, z> = QQ[]
sage: AffineHypersurface(x*y - z^3)
Affine hypersurface defined by -z^3 + x*y
 in Affine Space of dimension 3 over Rational Field
```

```
>>> from sage.all import *
>>> A = QQ['x, y, z']; (x, y, z,) = A._first_ngens(3)
>>> AffineHypersurface(x*y - z**Integer(3))
Affine hypersurface defined by -z^3 + x*y
 in Affine Space of dimension 3 over Rational Field
```

defining_polynomial()

Return the polynomial equation that cuts out this affine hypersurface.

EXAMPLES:

```
sage: R.<x, y, z> = ZZ[]
sage: H = AffineHypersurface(x*z + y^2)
sage: H.defining_polynomial()
y^2 + x*z
```

```
>>> from sage.all import *
>>> R = ZZ['x, y, z']; (x, y, z,) = R._first_ngens(3)
>>> H = AffineHypersurface(x*z + y**Integer(2))
>>> H.defining_polynomial()
y^2 + x*z
```

class sage.schemes.generic.hypersurface.**ProjectiveHypersurface**(*poly*, *ambient=None*)

Bases: *AlgebraicScheme_subscheme_projective*

The projective hypersurface defined by the given polynomial.

EXAMPLES:

```
sage: P.<x, y, z> = ProjectiveSpace(ZZ, 2)
sage: ProjectiveHypersurface(x - y, P)
Projective hypersurface defined by x - y
 in Projective Space of dimension 2 over Integer Ring
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(ZZ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) = P._
↪first_ngens(3)
>>> ProjectiveHypersurface(x - y, P)
Projective hypersurface defined by x - y
 in Projective Space of dimension 2 over Integer Ring
```

```
sage: R.<x, y, z> = QQ[]
sage: ProjectiveHypersurface(x - y)
Projective hypersurface defined by x - y
 in Projective Space of dimension 2 over Rational Field
```

```
>>> from sage.all import *
>>> R = QQ['x, y, z']; (x, y, z,) = R._first_ngens(3)
>>> ProjectiveHypersurface(x - y)
Projective hypersurface defined by x - y
 in Projective Space of dimension 2 over Rational Field
```

defining_polynomial()

Return the polynomial equation that cuts out this projective hypersurface.

EXAMPLES:

```
sage: R.<x, y, z> = ZZ[]
sage: H = ProjectiveHypersurface(x*z + y^2)
sage: H.defining_polynomial()
y^2 + x*z
```

```
>>> from sage.all import *
>>> R = ZZ['x, y, z']; (x, y, z,) = R._first_ngens(3)
```

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```
>>> H = ProjectiveHypersurface(x*z + y**Integer(2))
>>> H.defining_polynomial()
y^2 + x*z
```

sage.schemes.generic.hypersurface.**is_Hypersurface**(*self*)

Return `True` if `self` is a hypersurface, i.e. an object of the type *ProjectiveHypersurface* or *AffineHypersurface*.

EXAMPLES:

```
sage: from sage.schemes.generic.hypersurface import is_Hypersurface
sage: R.<x, y, z> = ZZ[]
sage: H = ProjectiveHypersurface(x*z + y^2)
sage: is_Hypersurface(H)
doctest:warning...
DeprecationWarning: The function is_Hypersurface is deprecated; use 'isinstance(..
↪., (ProjectiveHypersurface, AffineHypersurface))' instead.
See https://github.com/sagemath/sage/issues/38022 for details.
True
```

```
>>> from sage.all import *
>>> from sage.schemes.generic.hypersurface import is_Hypersurface
>>> R = ZZ['x, y, z']; (x, y, z,) = R._first_ngens(3)
>>> H = ProjectiveHypersurface(x*z + y**Integer(2))
>>> is_Hypersurface(H)
doctest:warning...
DeprecationWarning: The function is_Hypersurface is deprecated; use 'isinstance(..
↪., (ProjectiveHypersurface, AffineHypersurface))' instead.
See https://github.com/sagemath/sage/issues/38022 for details.
True
```

```
sage: H = AffineHypersurface(x*z + y^2)
sage: is_Hypersurface(H)
True
```

```
>>> from sage.all import *
>>> H = AffineHypersurface(x*z + y**Integer(2))
>>> is_Hypersurface(H)
True
```

```
sage: H = ProjectiveSpace(QQ, 5)
sage: is_Hypersurface(H)
False
```

```
>>> from sage.all import *
>>> H = ProjectiveSpace(QQ, Integer(5))
>>> is_Hypersurface(H)
False
```

CHAPTER

NINE

SET OF HOMOMORPHISMS BETWEEN TWO SCHEMES

For schemes X and Y, this module implements the set of morphisms $\mathrm{Hom}(X, Y)$. This is done by *SchemeHomset_generic*.

As a special case, the Hom-sets can also represent the points of a scheme. Recall that the K-rational points of a scheme X over k can be identified with the set of morphisms $\mathrm{Spec}(K) \to X$. In Sage the rational points are implemented by such scheme morphisms. This is done by *SchemeHomset_points* and its subclasses.

Note

You should not create the Hom-sets manually. Instead, use the `Hom()` method that is inherited by all schemes.

AUTHORS:

- William Stein (2006): initial version.
- Volker Braun (2011-08-11): significant improvement and refactoring.
- Ben Hutz (June 2012): added support for projective ring

class sage.schemes.generic.homset.**SchemeHomsetFactory**

Bases: `UniqueFactory`

Factory for Hom-sets of schemes.

EXAMPLES:

```
sage: A2 = AffineSpace(QQ, 2)
sage: A3 = AffineSpace(QQ, 3)
sage: Hom = A3.Hom(A2)
```

```
>>> from sage.all import *
>>> A2 = AffineSpace(QQ, Integer(2))
>>> A3 = AffineSpace(QQ, Integer(3))
>>> Hom = A3.Hom(A2)
```

The Hom-sets are uniquely determined by domain and codomain:

```
sage: Hom is copy(Hom)
True
sage: Hom is A3.Hom(A2)
True
```

```
>>> from sage.all import *
>>> Hom is copy(Hom)
True
>>> Hom is A3.Hom(A2)
True
```

The Hom-sets are identical if the domains and codomains are identical:

```
sage: loads(Hom.dumps()) is Hom
True
sage: A3_iso = AffineSpace(QQ, 3)
sage: A3_iso is A3
True
sage: Hom_iso = A3_iso.Hom(A2)
sage: Hom_iso is Hom
True
```

```
>>> from sage.all import *
>>> loads(Hom.dumps()) is Hom
True
>>> A3_iso = AffineSpace(QQ, Integer(3))
>>> A3_iso is A3
True
>>> Hom_iso = A3_iso.Hom(A2)
>>> Hom_iso is Hom
True
```

create_key_and_extra_args(*X*, *Y*, *category=None*, *base=None*, *check=True*, *as_point_homset=False*)

Create a key that uniquely determines the Hom-set.

INPUT:

- `X` – a scheme; the domain of the morphisms
- `Y` – a scheme; the codomain of the morphisms
- `category` – a category for the Hom-sets (default: schemes over given base)
- `base` – a scheme or a ring; the base scheme of domain and codomain schemes. If a ring is specified, the spectrum of that ring will be used as base scheme.
- `check` – boolean (default: `True`)

EXAMPLES:

```
sage: A2 = AffineSpace(QQ, 2)
sage: A3 = AffineSpace(QQ, 3)
sage: A3.Hom(A2)    # indirect doctest
Set of morphisms
  From: Affine Space of dimension 3 over Rational Field
  To:   Affine Space of dimension 2 over Rational Field
sage: from sage.schemes.generic.homset import SchemeHomsetFactory
sage: SHOMfactory = SchemeHomsetFactory('test')
sage: key, extra = SHOMfactory.create_key_and_extra_args(A3, A2, check=False)
sage: key
(..., ..., Category of schemes over Rational Field, False)
```

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```
sage: extra
{'X': Affine Space of dimension 3 over Rational Field,
 'Y': Affine Space of dimension 2 over Rational Field,
 'base_ring': Rational Field,
 'check': False}
```

```
>>> from sage.all import *
>>> A2 = AffineSpace(QQ, Integer(2))
>>> A3 = AffineSpace(QQ, Integer(3))
>>> A3.Hom(A2)    # indirect doctest
Set of morphisms
  From: Affine Space of dimension 3 over Rational Field
  To:   Affine Space of dimension 2 over Rational Field
>>> from sage.schemes.generic.homset import SchemeHomsetFactory
>>> SHOMfactory = SchemeHomsetFactory('test')
>>> key, extra = SHOMfactory.create_key_and_extra_args(A3, A2, check=False)
>>> key
(..., ..., Category of schemes over Rational Field, False)
>>> extra
{'X': Affine Space of dimension 3 over Rational Field,
 'Y': Affine Space of dimension 2 over Rational Field,
 'base_ring': Rational Field,
 'check': False}
```

create_object(*version*, *key*, ***extra_args*)

Create a *SchemeHomset_generic*.

INPUT:

- `version` – object version; currently not used
- `key` – a key created by *create_key_and_extra_args()*
- `extra_args` – dictionary of extra keyword arguments

EXAMPLES:

```
sage: A2 = AffineSpace(QQ, 2)
sage: A3 = AffineSpace(QQ, 3)
sage: A3.Hom(A2) is A3.Hom(A2)    # indirect doctest
True
sage: from sage.schemes.generic.homset import SchemeHomsetFactory
sage: SHOMfactory = SchemeHomsetFactory('test')
sage: SHOMfactory.create_object(0, [id(A3), id(A2), A3.category(), False],
....:                           check=True, X=A3, Y=A2, base_ring=QQ)
Set of morphisms
  From: Affine Space of dimension 3 over Rational Field
  To:   Affine Space of dimension 2 over Rational Field
```

```
>>> from sage.all import *
>>> A2 = AffineSpace(QQ, Integer(2))
>>> A3 = AffineSpace(QQ, Integer(3))
>>> A3.Hom(A2) is A3.Hom(A2)    # indirect doctest
True
```

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```
>>> from sage.schemes.generic.homset import SchemeHomsetFactory
>>> SHOMfactory = SchemeHomsetFactory('test')
>>> SHOMfactory.create_object(Integer(0), [id(A3), id(A2), A3.category(),␣
↪False],
...                            check=True, X=A3, Y=A2, base_ring=QQ)
Set of morphisms
  From: Affine Space of dimension 3 over Rational Field
  To:   Affine Space of dimension 2 over Rational Field
```

class sage.schemes.generic.homset.**SchemeHomset_generic**(*X*, *Y*, *category=None*, *check=True*, *base=None*)

Bases: HomsetWithBase

The base class for Hom-sets of schemes.

INPUT:

- X – a scheme; the domain of the Hom-set
- Y – a scheme; the codomain of the Hom-set
- category – a category (optional); the category of the Hom-set
- check – boolean (default: True); whether to check the defining data for consistency

EXAMPLES:

```
sage: from sage.schemes.generic.homset import SchemeHomset_generic
sage: A2 = AffineSpace(QQ,2)
sage: Hom = SchemeHomset_generic(A2, A2); Hom
Set of morphisms
  From: Affine Space of dimension 2 over Rational Field
  To:   Affine Space of dimension 2 over Rational Field
sage: Hom.category()
Category of endsets of schemes over Rational Field
```

```
>>> from sage.all import *
>>> from sage.schemes.generic.homset import SchemeHomset_generic
>>> A2 = AffineSpace(QQ,Integer(2))
>>> Hom = SchemeHomset_generic(A2, A2); Hom
Set of morphisms
  From: Affine Space of dimension 2 over Rational Field
  To:   Affine Space of dimension 2 over Rational Field
>>> Hom.category()
Category of endsets of schemes over Rational Field
```

Element

alias of *SchemeMorphism*

natural_map()

Return a natural map in the Hom space.

OUTPUT:

A *SchemeMorphism* if there is a natural map from domain to codomain. Otherwise, a NotImplementedError is raised.

EXAMPLES:

```
sage: A = AffineSpace(4, QQ)
sage: A.structure_morphism()   # indirect doctest
Scheme morphism:
  From: Affine Space of dimension 4 over Rational Field
  To:   Spectrum of Rational Field
  Defn: Structure map
```

```
>>> from sage.all import *
>>> A = AffineSpace(Integer(4), QQ)
>>> A.structure_morphism()   # indirect doctest
Scheme morphism:
  From: Affine Space of dimension 4 over Rational Field
  To:   Spectrum of Rational Field
  Defn: Structure map
```

class sage.schemes.generic.homset.**SchemeHomset_points**(*X*, *Y*, *category=None*, *check=True*, *base=Integer Ring*)

Bases: *SchemeHomset_generic*

Set of rational points of the scheme.

Recall that the K-rational points of a scheme X over k can be identified with the set of morphisms $\mathrm{Spec}(K) \to X$. In Sage, the rational points are implemented by such scheme morphisms.

If a scheme has a finite number of points, then the homset is supposed to implement the Python iterator interface. See *SchemeHomset_points_toric_field* for example.

INPUT:

See *SchemeHomset_generic*.

EXAMPLES:

```
sage: from sage.schemes.generic.homset import SchemeHomset_points
sage: SchemeHomset_points(Spec(QQ), AffineSpace(ZZ,2))
Set of rational points of Affine Space of dimension 2 over Rational Field
```

```
>>> from sage.all import *
>>> from sage.schemes.generic.homset import SchemeHomset_points
>>> SchemeHomset_points(Spec(QQ), AffineSpace(ZZ,Integer(2)))
Set of rational points of Affine Space of dimension 2 over Rational Field
```

cardinality()

Return the number of points.

OUTPUT: integer or infinity

EXAMPLES:

```
sage: toric_varieties.P2().point_set().cardinality()                    #␣
↪needs sage.geometry.polyhedron sage.graphs
+Infinity

sage: P2 = toric_varieties.P2(base_ring=GF(3))                          #␣
↪needs sage.geometry.polyhedron sage.graphs
sage: P2.point_set().cardinality()                                      #␣
```

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```
↪needs sage.geometry.polyhedron sage.graphs
13
```

```
>>> from sage.all import *
>>> toric_varieties.P2().point_set().cardinality()                    #␣
↪needs sage.geometry.polyhedron sage.graphs
+Infinity

>>> P2 = toric_varieties.P2(base_ring=GF(Integer(3)))                    ␣
↪     # needs sage.geometry.polyhedron sage.graphs
>>> P2.point_set().cardinality()                                      #␣
↪needs sage.geometry.polyhedron sage.graphs
13
```

extended_codomain()

Return the codomain with extended base, if necessary.

OUTPUT:

The codomain scheme, with its base ring extended to the codomain. That is, the codomain is of the form $\mathrm{Spec}(R)$ and the base ring of the domain is extended to R.

EXAMPLES:

```
sage: # needs sage.rings.number_field
sage: P2 = ProjectiveSpace(QQ, 2)
sage: x = polygen(ZZ, 'x')
sage: K.<a> = NumberField(x^2 + x - (3^3-3))
sage: K_points = P2(K);  K_points
Set of rational points of Projective Space of dimension 2
 over Number Field in a with defining polynomial x^2 + x - 24
sage: K_points.codomain()
Projective Space of dimension 2 over Rational Field
sage: K_points.extended_codomain()
Projective Space of dimension 2
 over Number Field in a with defining polynomial x^2 + x - 24
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> P2 = ProjectiveSpace(QQ, Integer(2))
>>> x = polygen(ZZ, 'x')
>>> K = NumberField(x**Integer(2) + x - (Integer(3)**Integer(3)-Integer(3)),␣
↪names=('a',)); (a,) = K._first_ngens(1)
>>> K_points = P2(K);  K_points
Set of rational points of Projective Space of dimension 2
 over Number Field in a with defining polynomial x^2 + x - 24
>>> K_points.codomain()
Projective Space of dimension 2 over Rational Field
>>> K_points.extended_codomain()
Projective Space of dimension 2
 over Number Field in a with defining polynomial x^2 + x - 24
```

list()

Return a tuple containing all points.

OUTPUT: a tuple containing all points of the toric variety

EXAMPLES:

```
sage: P1 = toric_varieties.P1(base_ring=GF(3))                                #␣
↪needs sage.geometry.polyhedron sage.graphs
sage: P1.point_set().list()                                                   #␣
↪needs sage.geometry.polyhedron sage.graphs
([0 : 1], [1 : 0], [1 : 1], [1 : 2])
```

```
>>> from sage.all import *
>>> P1 = toric_varieties.P1(base_ring=GF(Integer(3)))                         ␣
↪     # needs sage.geometry.polyhedron sage.graphs
>>> P1.point_set().list()                                                    #␣
↪needs sage.geometry.polyhedron sage.graphs
([0 : 1], [1 : 0], [1 : 1], [1 : 2])
```

value_ring()

Return R for a point Hom-set $X(\mathrm{Spec}(R))$.

OUTPUT: a commutative ring

EXAMPLES:

```
sage: P2 = ProjectiveSpace(ZZ, 2)
sage: P2(QQ).value_ring()
Rational Field
```

```
>>> from sage.all import *
>>> P2 = ProjectiveSpace(ZZ, Integer(2))
>>> P2(QQ).value_ring()
Rational Field
```

zero()

Return the identity of the codomain with extended base, if necessary.

sage.schemes.generic.homset.**is_SchemeHomset**(H)

Test whether H is a scheme Hom-set.

EXAMPLES:

```
sage: f = Spec(QQ).identity_morphism();  f
Scheme endomorphism of Spectrum of Rational Field
  Defn: Identity map
sage: from sage.schemes.generic.homset import is_SchemeHomset
sage: is_SchemeHomset(f)
doctest:warning...
DeprecationWarning: The function is_SchemeHomset is deprecated; use 'isinstance(..
↪., SchemeHomset_generic)' instead.
See https://github.com/sagemath/sage/issues/38022 for details.
False
sage: is_SchemeHomset(f.parent())
True
sage: is_SchemeHomset('a string')
False
```

```
>>> from sage.all import *
>>> f = Spec(QQ).identity_morphism();  f
Scheme endomorphism of Spectrum of Rational Field
  Defn: Identity map
>>> from sage.schemes.generic.homset import is_SchemeHomset
>>> is_SchemeHomset(f)
doctest:warning...
DeprecationWarning: The function is_SchemeHomset is deprecated; use 'isinstance(..
↪., SchemeHomset_generic)' instead.
See https://github.com/sagemath/sage/issues/38022 for details.
False
>>> is_SchemeHomset(f.parent())
True
>>> is_SchemeHomset('a string')
False
```

CHAPTER

TEN

SCHEME MORPHISM

Note

You should never create the morphisms directly. Instead, use the `hom()` and `Hom()` methods that are inherited by all schemes.

If you want to extend the Sage library with some new kind of scheme, your new class (say, `MyScheme`) should provide a method

- `MyScheme._morphism(*args, **kwds)` returning a morphism between two schemes in your category, usually defined via polynomials. Your morphism class should derive from *SchemeMorphism_polynomial*. These morphisms will usually be elements of the Hom-set *SchemeHomset_generic*.

Optionally, you can also provide a special Hom-set class for your subcategory of schemes. If you want to do this, you should also provide a method

- `MyScheme._homset(*args, **kwds)` returning a Hom-set, which must be an element of a derived class of *SchemeHomset_generic*. If your new Hom-set class does not use `MyScheme._morphism` then you do not have to provide it.

Note that points on schemes are morphisms $\mathrm{Spec}(K) \to X$, too. But we typically use a different notation, so they are implemented in a different derived class. For this, you should implement a method

- `MyScheme._point(*args, **kwds)` returning a point, that is, a morphism $\mathrm{Spec}(K) \to X$. Your point class should derive from *SchemeMorphism_point*.

Optionally, you can also provide a special Hom-set for the points, for example the point Hom-set can provide a method to enumerate all points. If you want to do this, you should also provide a method

- `MyScheme._point_homset(*args, **kwds)` returning the *homset* of points. The Hom-sets of points are implemented in classes named `SchemeHomset_points_...`. If your new Hom-set class does not use `MyScheme._point` then you do not have to provide it.

AUTHORS:

- David Kohel, William Stein
- William Stein (2006-02-11): fixed bug where P(0,0,0) was allowed as a projective point.
- Volker Braun (2011-08-08): Renamed classes, more documentation, misc cleanups.
- Ben Hutz (June 2012): added support for projective ring
- Simon King (2013-10): copy the changes of `Morphism` that have been introduced in Issue #14711.

class sage.schemes.generic.morphism.**SchemeMorphism**(*parent*, *codomain=None*)

Bases: Element

Base class for scheme morphisms.

INPUT:

- parent – the parent of the morphism

Todo

For historical reasons, *SchemeMorphism* copies code from Map rather than inheriting from it. Proper inheritance should be used instead. See Issue #14711.

EXAMPLES:

```
sage: X = Spec(ZZ)
sage: Hom = X.Hom(X)
sage: from sage.schemes.generic.morphism import SchemeMorphism
sage: f = SchemeMorphism(Hom)
sage: type(f)
<class 'sage.schemes.generic.morphism.SchemeMorphism'>
```

```
>>> from sage.all import *
>>> X = Spec(ZZ)
>>> Hom = X.Hom(X)
>>> from sage.schemes.generic.morphism import SchemeMorphism
>>> f = SchemeMorphism(Hom)
>>> type(f)
<class 'sage.schemes.generic.morphism.SchemeMorphism'>
```

base_ring()

Return the base ring of self, that is, the ring over which the defining polynomials of self are defined.

OUTPUT: ring

EXAMPLES:

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: H = Hom(P, P)
sage: f = H([3/5*x^2, 6*y^2])
sage: f.base_ring()
Rational Field
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> H = Hom(P, P)
>>> f = H([Integer(3)/Integer(5)*x**Integer(2), Integer(6)*y**Integer(2)])
>>> f.base_ring()
Rational Field
```

```
sage: R.<t> = PolynomialRing(ZZ, 1)
sage: P.<x,y> = ProjectiveSpace(R, 1)
```

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```
sage: H = Hom(P, P)
sage: f = H([3*x^2, y^2])
sage: f.base_ring()
Multivariate Polynomial Ring in t over Integer Ring
```

```
>>> from sage.all import *
>>> R = PolynomialRing(ZZ, Integer(1), names=('t',)); (t,) = R._first_ngens(1)
>>> P = ProjectiveSpace(R, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> H = Hom(P, P)
>>> f = H([Integer(3)*x**Integer(2), y**Integer(2)])
>>> f.base_ring()
Multivariate Polynomial Ring in t over Integer Ring
```

Points have correct base rings too (Issue #34336):

```
sage: x = P(t, 5); x
(t : 5)
sage: x.base_ring()
Multivariate Polynomial Ring in t over Integer Ring
```

```
>>> from sage.all import *
>>> x = P(t, Integer(5)); x
(t : 5)
>>> x.base_ring()
Multivariate Polynomial Ring in t over Integer Ring
```

```
sage: # needs sage.rings.finite_rings sage.schemes
sage: E = EllipticCurve(GF((17,2)), [1,2,3,4,5])
sage: P = E.random_point()
sage: P.base_ring()
Finite Field in z2 of size 17^2
```

```
>>> from sage.all import *
>>> # needs sage.rings.finite_rings sage.schemes
>>> E = EllipticCurve(GF((Integer(17),Integer(2))), [Integer(1),Integer(2),
↪Integer(3),Integer(4),Integer(5)])
>>> P = E.random_point()
>>> P.base_ring()
Finite Field in z2 of size 17^2
```

category()

Return the category of the Hom-set.

OUTPUT: a category

EXAMPLES:

```
sage: A2 = AffineSpace(QQ, 2)
sage: A2.structure_morphism().category()
Category of homsets of schemes
```

```
>>> from sage.all import *
>>> A2 = AffineSpace(QQ, Integer(2))
>>> A2.structure_morphism().category()
Category of homsets of schemes
```

category_for()

Return the category which this morphism belongs to.

EXAMPLES:

```
sage: A2 = AffineSpace(QQ, 2)
sage: A2.structure_morphism().category_for()
Category of schemes
```

```
>>> from sage.all import *
>>> A2 = AffineSpace(QQ, Integer(2))
>>> A2.structure_morphism().category_for()
Category of schemes
```

codomain()

The constant function from the codomain.

EXAMPLES:

```
sage: A.<x,y> = AffineSpace(QQ['x,y'])
sage: H = A.Hom(A)
sage: f = H([y, x^2 + y])
sage: f.codomain() is A
True
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ['x,y'], names=('x', 'y',)); (x, y,) = A._first_ngens(2)
>>> H = A.Hom(A)
>>> f = H([y, x**Integer(2) + y])
>>> f.codomain() is A
True
```

domain()

The constant function from the domain.

EXAMPLES:

```
sage: A.<x,y> = AffineSpace(QQ['x,y'])
sage: H = A.Hom(A)
sage: f = H([y, x^2 + y])
sage: f.domain() is A
True
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ['x,y'], names=('x', 'y',)); (x, y,) = A._first_ngens(2)
>>> H = A.Hom(A)
>>> f = H([y, x**Integer(2) + y])
>>> f.domain() is A
True
```

glue_along_domains(*other*)

Glue two morphisms.

INPUT:

- `other` – a scheme morphism with the same domain

OUTPUT:

Assuming that `self` and `other` are open immersions with the same domain, return scheme obtained by gluing along the images.

EXAMPLES:

We construct a scheme isomorphic to the projective line over Spec($\mathbf{Q}$) by gluing two copies of $\mathbb{A}^1$ minus a point:

```
sage: # needs sage.libs.singular
sage: R.<x,y> = PolynomialRing(QQ, 2)
sage: S.<xbar, ybar> = R.quotient(x*y - 1)
sage: Rx = PolynomialRing(QQ, 'x')
sage: i1 = Rx.hom([xbar])
sage: Ry = PolynomialRing(QQ, 'y')
sage: i2 = Ry.hom([ybar])
sage: Sch = Schemes()
sage: f1 = Sch(i1)
sage: f2 = Sch(i2)
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> R = PolynomialRing(QQ, Integer(2), names=('x', 'y',)); (x, y,) = R._first_
↪ngens(2)
>>> S = R.quotient(x*y - Integer(1), names=('xbar', 'ybar',)); (xbar, ybar,)␣
↪= S._first_ngens(2)
>>> Rx = PolynomialRing(QQ, 'x')
>>> i1 = Rx.hom([xbar])
>>> Ry = PolynomialRing(QQ, 'y')
>>> i2 = Ry.hom([ybar])
>>> Sch = Schemes()
>>> f1 = Sch(i1)
>>> f2 = Sch(i2)
```

Now f1 and f2 have the same domain, which is a $\mathbb{A}^1$ minus a point. We glue along the domain:

```
sage: # needs sage.libs.singular
sage: P1 = f1.glue_along_domains(f2); P1
Scheme obtained by gluing X and Y along U, where
  X: Spectrum of Univariate Polynomial Ring in x over Rational Field
  Y: Spectrum of Univariate Polynomial Ring in y over Rational Field
  U: Spectrum of Quotient of Multivariate Polynomial Ring in x, y
     over Rational Field by the ideal (x*y - 1)
sage: a, b = P1.gluing_maps()
sage: a
Affine Scheme morphism:
  From: Spectrum of Quotient of Multivariate Polynomial Ring in x, y
        over Rational Field by the ideal (x*y - 1)
```

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```
  To:   Spectrum of Univariate Polynomial Ring in x over Rational Field
  Defn: Ring morphism:
          From: Univariate Polynomial Ring in x over Rational Field
          To:   Quotient of Multivariate Polynomial Ring in x, y over
                Rational Field by the ideal (x*y - 1)
          Defn: x |--> xbar
sage: b
Affine Scheme morphism:
  From: Spectrum of Quotient of Multivariate Polynomial Ring in x, y
        over Rational Field by the ideal (x*y - 1)
  To:   Spectrum of Univariate Polynomial Ring in y over Rational Field
  Defn: Ring morphism:
          From: Univariate Polynomial Ring in y over Rational Field
          To:   Quotient of Multivariate Polynomial Ring in x, y over
                Rational Field by the ideal (x*y - 1)
          Defn: y |--> ybar
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> P1 = f1.glue_along_domains(f2); P1
Scheme obtained by gluing X and Y along U, where
  X: Spectrum of Univariate Polynomial Ring in x over Rational Field
  Y: Spectrum of Univariate Polynomial Ring in y over Rational Field
  U: Spectrum of Quotient of Multivariate Polynomial Ring in x, y
     over Rational Field by the ideal (x*y - 1)
>>> a, b = P1.gluing_maps()
>>> a
Affine Scheme morphism:
  From: Spectrum of Quotient of Multivariate Polynomial Ring in x, y
        over Rational Field by the ideal (x*y - 1)
  To:   Spectrum of Univariate Polynomial Ring in x over Rational Field
  Defn: Ring morphism:
          From: Univariate Polynomial Ring in x over Rational Field
          To:   Quotient of Multivariate Polynomial Ring in x, y over
                Rational Field by the ideal (x*y - 1)
          Defn: x |--> xbar
>>> b
Affine Scheme morphism:
  From: Spectrum of Quotient of Multivariate Polynomial Ring in x, y
        over Rational Field by the ideal (x*y - 1)
  To:   Spectrum of Univariate Polynomial Ring in y over Rational Field
  Defn: Ring morphism:
          From: Univariate Polynomial Ring in y over Rational Field
          To:   Quotient of Multivariate Polynomial Ring in x, y over
                Rational Field by the ideal (x*y - 1)
          Defn: y |--> ybar
```

is_endomorphism()

Return whether the morphism is an endomorphism.

OUTPUT: boolean; whether the domain and codomain are identical

EXAMPLES:

```
sage: X = AffineSpace(QQ, 2)
sage: X.structure_morphism().is_endomorphism()
False
sage: X.identity_morphism().is_endomorphism()
True
```

```
>>> from sage.all import *
>>> X = AffineSpace(QQ, Integer(2))
>>> X.structure_morphism().is_endomorphism()
False
>>> X.identity_morphism().is_endomorphism()
True
```

class sage.schemes.generic.morphism.**SchemeMorphism_id**(X)

Bases: *SchemeMorphism*

Return the identity morphism from X to itself.

INPUT:

- X – the scheme

EXAMPLES:

```
sage: X = Spec(ZZ)
sage: X.identity_morphism()  # indirect doctest
Scheme endomorphism of Spectrum of Integer Ring
  Defn: Identity map
```

```
>>> from sage.all import *
>>> X = Spec(ZZ)
>>> X.identity_morphism()  # indirect doctest
Scheme endomorphism of Spectrum of Integer Ring
  Defn: Identity map
```

class sage.schemes.generic.morphism.**SchemeMorphism_point**(*parent*, *codomain=None*)

Bases: *SchemeMorphism*

Base class for rational points on schemes.

Recall that the K-rational points of a scheme X over k can be identified with the set of morphisms $\mathrm{Spec}(K) \to X$. In Sage, the rational points are implemented by such scheme morphisms.

EXAMPLES:

```
sage: from sage.schemes.generic.morphism import SchemeMorphism
sage: f = SchemeMorphism(Spec(ZZ).Hom(Spec(ZZ)))
sage: type(f)
<class 'sage.schemes.generic.morphism.SchemeMorphism'>
```

```
>>> from sage.all import *
>>> from sage.schemes.generic.morphism import SchemeMorphism
>>> f = SchemeMorphism(Spec(ZZ).Hom(Spec(ZZ)))
>>> type(f)
<class 'sage.schemes.generic.morphism.SchemeMorphism'>
```

change_ring(*R*, *check=True*)

Return a new *SchemeMorphism_point* which is this point coerced to `R`.

If `check` is true, then the initialization checks are performed.

INPUT:

- `R` – ring or morphism
- `check` – boolean

OUTPUT: *SchemeMorphism_point*

EXAMPLES:

```
sage: P.<x,y,z> = ProjectiveSpace(ZZ, 2)
sage: X = P.subscheme(x^2 - y^2)
sage: X(23,23,1).change_ring(GF(13))
(10 : 10 : 1)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(ZZ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> X = P.subscheme(x**Integer(2) - y**Integer(2))
>>> X(Integer(23),Integer(23),Integer(1)).change_ring(GF(Integer(13)))
(10 : 10 : 1)
```

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: P(-2/3,1).change_ring(CC)                                                 #␣
↪needs sage.rings.real_mpfr
(-0.666666666666667 : 1.00000000000000)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> P(-Integer(2)/Integer(3),Integer(1)).change_ring(CC)                        ␣
↪                        # needs sage.rings.real_mpfr
(-0.666666666666667 : 1.00000000000000)
```

```
sage: P.<x,y> = ProjectiveSpace(ZZ, 1)
sage: P(152,113).change_ring(Zp(5))                                             #␣
↪needs sage.rings.padics
(2 + 5^2 + 5^3 + O(5^20) : 3 + 2*5 + 4*5^2 + O(5^20))
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(ZZ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> P(Integer(152),Integer(113)).change_ring(Zp(Integer(5)))                    ␣
↪                        # needs sage.rings.padics
(2 + 5^2 + 5^3 + O(5^20) : 3 + 2*5 + 4*5^2 + O(5^20))
```

```
sage: # needs sage.rings.number_field
sage: K.<v> = QuadraticField(-7)
sage: O = K.maximal_order()
```

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```
sage: P.<x,y> = ProjectiveSpace(O, 1)
sage: H = End(P)
sage: F = H([x^2 + O(v)*y^2, y^2])
sage: F.change_ring(K).change_ring(K.embeddings(QQbar)[0])
Scheme endomorphism of Projective Space of dimension 1
 over Algebraic Field
  Defn: Defined on coordinates by sending (x : y) to
        (x^2 + (-2.645751311064591?*I)*y^2 : y^2)
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> K = QuadraticField(-Integer(7), names=('v',)); (v,) = K._first_ngens(1)
>>> O = K.maximal_order()
>>> P = ProjectiveSpace(O, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> H = End(P)
>>> F = H([x**Integer(2) + O(v)*y**Integer(2), y**Integer(2)])
>>> F.change_ring(K).change_ring(K.embeddings(QQbar)[Integer(0)])
Scheme endomorphism of Projective Space of dimension 1
 over Algebraic Field
  Defn: Defined on coordinates by sending (x : y) to
        (x^2 + (-2.645751311064591?*I)*y^2 : y^2)
```

```
sage: # needs sage.rings.number_field
sage: R.<x> = PolynomialRing(QQ)
sage: K.<a> = NumberField(x^2 - x + 1)
sage: P.<x,y> = ProjectiveSpace(K, 1)
sage: Q = P([a + 1, 1])
sage: emb = K.embeddings(QQbar)
sage: Q.change_ring(emb[0])
(1.5000000000000000? - 0.866025403784439?*I : 1)
sage: Q.change_ring(emb[1])
(1.5000000000000000? + 0.866025403784439?*I : 1)
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = PolynomialRing(QQ, names=('x',)); (x,) = R._first_ngens(1)
>>> K = NumberField(x**Integer(2) - x + Integer(1), names=('a',)); (a,) = K._
↪first_ngens(1)
>>> P = ProjectiveSpace(K, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> Q = P([a + Integer(1), Integer(1)])
>>> emb = K.embeddings(QQbar)
>>> Q.change_ring(emb[Integer(0)])
(1.5000000000000000? - 0.866025403784439?*I : 1)
>>> Q.change_ring(emb[Integer(1)])
(1.5000000000000000? + 0.866025403784439?*I : 1)
```

```
sage: # needs sage.rings.number_field
sage: K.<v> = QuadraticField(2)
sage: P.<x,y> = ProjectiveSpace(K, 1)
```

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```
sage: Q = P([v,1])
sage: Q.change_ring(K.embeddings(QQbar)[0])
(-1.414213562373095? : 1)
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> K = QuadraticField(Integer(2), names=('v',)); (v,) = K._first_ngens(1)
>>> P = ProjectiveSpace(K, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> Q = P([v,Integer(1)])
>>> Q.change_ring(K.embeddings(QQbar)[Integer(0)])
(-1.414213562373095? : 1)
```

```
sage: # needs sage.rings.number_field
sage: R.<x> = QQ[]
sage: f = x^6 - 2
sage: L.<b> = NumberField(f, embedding=f.roots(QQbar)[1][0])
sage: A.<x,y> = AffineSpace(L, 2)
sage: P = A([b,1])
sage: P.change_ring(QQbar)
(1.122462048309373?, 1)
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> f = x**Integer(6) - Integer(2)
>>> L = NumberField(f, embedding=f.roots(QQbar)[Integer(1)][Integer(0)],␣
↪names=('b',)); (b,) = L._first_ngens(1)
>>> A = AffineSpace(L, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> P = A([b,Integer(1)])
>>> P.change_ring(QQbar)
(1.122462048309373?, 1)
```

scheme()

Return the scheme whose point is represented.

OUTPUT: a scheme

EXAMPLES:

```
sage: A = AffineSpace(2, QQ)
sage: a = A(1,2)
sage: a.scheme()
Affine Space of dimension 2 over Rational Field
```

```
>>> from sage.all import *
>>> A = AffineSpace(Integer(2), QQ)
>>> a = A(Integer(1),Integer(2))
>>> a.scheme()
Affine Space of dimension 2 over Rational Field
```

specialization(*D=None*, *phi=None*, *ambient=None*)

Specialization of this point.

Given a family of points defined over a polynomial ring. A specialization is a particular member of that family. The specialization can be specified either by a dictionary or a `SpecializationMorphism`.

INPUT:

- `D` – dictionary (optional)
- `phi` – SpecializationMorphism (optional)
- `ambient` – ambient space of specialized point (optional)

OUTPUT: *SchemeMorphism_polynomial*

EXAMPLES:

```
sage: R.<c> = PolynomialRing(QQ)
sage: P.<x,y> = ProjectiveSpace(R, 1)
sage: Q = P([c,1])
sage: Q.specialization({c: 1})
(1 : 1)
```

```
>>> from sage.all import *
>>> R = PolynomialRing(QQ, names=('c',)); (c,) = R._first_ngens(1)
>>> P = ProjectiveSpace(R, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> Q = P([c,Integer(1)])
>>> Q.specialization({c: Integer(1)})
(1 : 1)
```

```
sage: R.<a,b> = PolynomialRing(QQ)
sage: P.<x,y> = ProjectiveSpace(R, 1)
sage: Q = P([a^2 + 2*a*b + 34, 1])
sage: from sage.rings.polynomial.flatten import SpecializationMorphism
sage: phi = SpecializationMorphism(P.coordinate_ring(), {a: 2, b: -1})
sage: T = Q.specialization(phi=phi); T
(34 : 1)
sage: Q2 = P([a,1])
sage: T2 = Q2.specialization(phi=phi)
sage: T2.codomain() is T.codomain()
True
sage: T3 = Q2.specialization(phi=phi, ambient=T.codomain())
sage: T3.codomain() is T.codomain()
True
```

```
>>> from sage.all import *
>>> R = PolynomialRing(QQ, names=('a', 'b',)); (a, b,) = R._first_ngens(2)
>>> P = ProjectiveSpace(R, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> Q = P([a**Integer(2) + Integer(2)*a*b + Integer(34), Integer(1)])
>>> from sage.rings.polynomial.flatten import SpecializationMorphism
>>> phi = SpecializationMorphism(P.coordinate_ring(), {a: Integer(2), b: -
↪Integer(1)})
>>> T = Q.specialization(phi=phi); T
```

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```
(34 : 1)
>>> Q2 = P([a,Integer(1)])
>>> T2 = Q2.specialization(phi=phi)
>>> T2.codomain() is T.codomain()
True
>>> T3 = Q2.specialization(phi=phi, ambient=T.codomain())
>>> T3.codomain() is T.codomain()
True
```

```
sage: R.<c> = PolynomialRing(QQ)
sage: P.<x,y> = ProjectiveSpace(R, 1)
sage: X = P.subscheme([x - c*y])
sage: Q = X([c, 1])
sage: Q2 = Q.specialization({c:2}); Q2
(2 : 1)
sage: Q2.codomain()
Closed subscheme of Projective Space of dimension 1 over Rational Field
 defined by: x - 2*y
```

```
>>> from sage.all import *
>>> R = PolynomialRing(QQ, names=('c',)); (c,) = R._first_ngens(1)
>>> P = ProjectiveSpace(R, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> X = P.subscheme([x - c*y])
>>> Q = X([c, Integer(1)])
>>> Q2 = Q.specialization({c:Integer(2)}); Q2
(2 : 1)
>>> Q2.codomain()
Closed subscheme of Projective Space of dimension 1 over Rational Field
 defined by: x - 2*y
```

```
sage: R.<l> = PolynomialRing(QQ)
sage: S.<k,j> = PolynomialRing(R)
sage: K.<a,b,c,d> = S[]
sage: P.<x,y> = ProjectiveSpace(K, 1)
sage: H = End(P)
sage: Q = P([a^2, b^2])
sage: Q.specialization({a: 2})
(4 : b^2)
```

```
>>> from sage.all import *
>>> R = PolynomialRing(QQ, names=('l',)); (l,) = R._first_ngens(1)
>>> S = PolynomialRing(R, names=('k', 'j',)); (k, j,) = S._first_ngens(2)
>>> K = S['a, b, c, d']; (a, b, c, d,) = K._first_ngens(4)
>>> P = ProjectiveSpace(K, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> H = End(P)
>>> Q = P([a**Integer(2), b**Integer(2)])
>>> Q.specialization({a: Integer(2)})
(4 : b^2)
```

class sage.schemes.generic.morphism.**SchemeMorphism_polynomial**(*parent*, *polys*, *check=True*)

Bases: *SchemeMorphism*

A morphism of schemes determined by polynomials that define what the morphism does on points in the ambient space.

INPUT:

- `parent` – Hom-set whose domain and codomain are affine or projective schemes
- `polys` – list/tuple/iterable of polynomials defining the scheme morphism
- `check` – boolean (default: `True`); whether to check the input for consistency

EXAMPLES:

An example involving the affine plane:

```
sage: R.<x,y> = QQ[]
sage: A2 = AffineSpace(R)
sage: H = A2.Hom(A2)
sage: f = H([x - y, x*y])
sage: f([0, 1])
(-1, 0)
```

```
>>> from sage.all import *
>>> R = QQ['x, y']; (x, y,) = R._first_ngens(2)
>>> A2 = AffineSpace(R)
>>> H = A2.Hom(A2)
>>> f = H([x - y, x*y])
>>> f([Integer(0), Integer(1)])
(-1, 0)
```

An example involving the projective line:

```
sage: R.<x,y> = QQ[]
sage: P1 = ProjectiveSpace(R)
sage: H = P1.Hom(P1)
sage: f = H([x^2 + y^2, x*y])
sage: f([0, 1])
(1 : 0)
```

```
>>> from sage.all import *
>>> R = QQ['x, y']; (x, y,) = R._first_ngens(2)
>>> P1 = ProjectiveSpace(R)
>>> H = P1.Hom(P1)
>>> f = H([x**Integer(2) + y**Integer(2), x*y])
>>> f([Integer(0), Integer(1)])
(1 : 0)
```

Some checks are performed to make sure the given polynomials define a morphism:

```
sage: f = H([exp(x),exp(y)])                                                #␣
↪needs sage.symbolic
Traceback (most recent call last):
...
```

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```
TypeError: polys (=[e^x, e^y]) must be elements of Multivariate
Polynomial Ring in x, y over Rational Field
```

```
>>> from sage.all import *
>>> f = H([exp(x),exp(y)])                                                    #␣
↪needs sage.symbolic
Traceback (most recent call last):
...
TypeError: polys (=[e^x, e^y]) must be elements of Multivariate
Polynomial Ring in x, y over Rational Field
```

change_ring(*R*, *check=True*)

Return a new *SchemeMorphism_polynomial* which is this map coerced to `R`.

If `check` is `True`, then the initialization checks are performed.

INPUT:

- `R` – ring or morphism
- `check` – boolean

OUTPUT: a new *SchemeMorphism_polynomial* which is this map coerced to `R`

EXAMPLES:

```
sage: P.<x,y> = ProjectiveSpace(ZZ, 1)
sage: H = Hom(P, P)
sage: f = H([3*x^2, y^2])
sage: f.change_ring(GF(3))
Scheme endomorphism of Projective Space of dimension 1 over Finite Field of␣
↪size 3
  Defn: Defined on coordinates by sending (x : y) to (0 : y^2)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(ZZ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> H = Hom(P, P)
>>> f = H([Integer(3)*x**Integer(2), y**Integer(2)])
>>> f.change_ring(GF(Integer(3)))
Scheme endomorphism of Projective Space of dimension 1 over Finite Field of␣
↪size 3
  Defn: Defined on coordinates by sending (x : y) to (0 : y^2)
```

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: H = Hom(P, P)
sage: f = H([5/2*x^3 + 3*x*y^2 - y^3, 3*z^3 + y*x^2, x^3 - z^3])
sage: f.change_ring(GF(3))
Scheme endomorphism of Projective Space of dimension 2 over Finite Field of␣
↪size 3
  Defn: Defined on coordinates by sending (x : y : z) to
        (x^3 - y^3 : x^2*y : x^3 - z^3)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> H = Hom(P, P)
>>> f = H([Integer(5)/Integer(2)*x**Integer(3) + Integer(3)*x*y**Integer(2) -␣
↪y**Integer(3), Integer(3)*z**Integer(3) + y*x**Integer(2), x**Integer(3) -␣
↪z**Integer(3)])
>>> f.change_ring(GF(Integer(3)))
Scheme endomorphism of Projective Space of dimension 2 over Finite Field of␣
↪size 3
  Defn: Defined on coordinates by sending (x : y : z) to
        (x^3 - y^3 : x^2*y : x^3 - z^3)
```

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: X = P.subscheme([5*x^2 - y^2])
sage: H = Hom(X, X)
sage: f = H([x, y])
sage: f.change_ring(GF(3))
Scheme endomorphism of Closed subscheme of Projective Space of dimension 1
over Finite Field of size 3 defined by: -x^2 - y^2
  Defn: Defined on coordinates by sending (x : y) to (x : y)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> X = P.subscheme([Integer(5)*x**Integer(2) - y**Integer(2)])
>>> H = Hom(X, X)
>>> f = H([x, y])
>>> f.change_ring(GF(Integer(3)))
Scheme endomorphism of Closed subscheme of Projective Space of dimension 1
over Finite Field of size 3 defined by: -x^2 - y^2
  Defn: Defined on coordinates by sending (x : y) to (x : y)
```

Check that Issue #16834 is fixed:

```
sage: # needs sage.rings.real_mpfr
sage: A.<x,y,z> = AffineSpace(RR, 3)
sage: h = Hom(A, A)
sage: f = h([x^2 + 1.5, y^3, z^5 - 2.0])
sage: f.change_ring(CC)
Scheme endomorphism of Affine Space of dimension 3 over
 Complex Field with 53 bits of precision
  Defn: Defined on coordinates by sending (x, y, z) to
        (x^2 + 1.50000000000000, y^3, z^5 - 2.00000000000000)
```

```
>>> from sage.all import *
>>> # needs sage.rings.real_mpfr
>>> A = AffineSpace(RR, Integer(3), names=('x', 'y', 'z',)); (x, y, z,) = A._
↪first_ngens(3)
>>> h = Hom(A, A)
>>> f = h([x**Integer(2) + RealNumber('1.5'), y**Integer(3), z**Integer(5) -␣
↪RealNumber('2.0')])
```

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```
>>> f.change_ring(CC)
Scheme endomorphism of Affine Space of dimension 3 over
 Complex Field with 53 bits of precision
  Defn: Defined on coordinates by sending (x, y, z) to
        (x^2 + 1.50000000000000, y^3, z^5 - 2.00000000000000)
```

```
sage: A.<x,y> = AffineSpace(ZZ, 2)
sage: B.<u,v> = ProjectiveSpace(QQ, 1)
sage: h = Hom(A,B)
sage: f = h([x^2, y^2])
sage: f.change_ring(QQ)
Scheme morphism:
  From: Affine Space of dimension 2 over Rational Field
  To:   Projective Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x, y) to (x^2 : y^2)
```

```
>>> from sage.all import *
>>> A = AffineSpace(ZZ, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> B = ProjectiveSpace(QQ, Integer(1), names=('u', 'v',)); (u, v,) = B._
↪first_ngens(2)
>>> h = Hom(A,B)
>>> f = h([x**Integer(2), y**Integer(2)])
>>> f.change_ring(QQ)
Scheme morphism:
  From: Affine Space of dimension 2 over Rational Field
  To:   Projective Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x, y) to (x^2 : y^2)
```

```
sage: A.<x,y> = AffineSpace(QQ, 2)
sage: H = Hom(A, A)
sage: f = H([3*x^2/y, y^2/x])
sage: f.change_ring(RR)                                                    #␣
↪needs sage.rings.real_mpfr
Scheme endomorphism of Affine Space of dimension 2 over Real Field with
53 bits of precision
  Defn: Defined on coordinates by sending (x, y) to
        (3.00000000000000*x^2/y, y^2/x)
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> H = Hom(A, A)
>>> f = H([Integer(3)*x**Integer(2)/y, y**Integer(2)/x])
>>> f.change_ring(RR)                                                      #␣
↪needs sage.rings.real_mpfr
Scheme endomorphism of Affine Space of dimension 2 over Real Field with
53 bits of precision
  Defn: Defined on coordinates by sending (x, y) to
        (3.00000000000000*x^2/y, y^2/x)
```

```
sage: # needs sage.rings.number_field
sage: R.<x> = PolynomialRing(QQ)
sage: K.<a> = NumberField(x^3 - x + 1)
sage: P.<x,y> = ProjectiveSpace(K, 1)
sage: H = End(P)
sage: f = H([x^2 + a*x*y + a^2*y^2, y^2])
sage: emb = K.embeddings(QQbar)
sage: f.change_ring(emb[0])
Scheme endomorphism of Projective Space of dimension 1
 over Algebraic Field
   Defn: Defined on coordinates by sending (x : y) to
         (x^2 + (-1.324717957244746?)*x*y + 1.754877666246693?*y^2 : y^2)
sage: f.change_ring(emb[1])
Scheme endomorphism of Projective Space of dimension 1
 over Algebraic Field
   Defn: Defined on coordinates by sending (x : y) to
         (x^2 + (0.6623589786223730? - 0.5622795120623013?*I)*x*y
          + (0.1225611668766537? - 0.7448617666197452?*I)*y^2 : y^2)
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = PolynomialRing(QQ, names=('x',)); (x,) = R._first_ngens(1)
>>> K = NumberField(x**Integer(3) - x + Integer(1), names=('a',)); (a,) = K._
↪first_ngens(1)
>>> P = ProjectiveSpace(K, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> H = End(P)
>>> f = H([x**Integer(2) + a*x*y + a**Integer(2)*y**Integer(2),␣
↪y**Integer(2)])
>>> emb = K.embeddings(QQbar)
>>> f.change_ring(emb[Integer(0)])
Scheme endomorphism of Projective Space of dimension 1
 over Algebraic Field
   Defn: Defined on coordinates by sending (x : y) to
         (x^2 + (-1.324717957244746?)*x*y + 1.754877666246693?*y^2 : y^2)
>>> f.change_ring(emb[Integer(1)])
Scheme endomorphism of Projective Space of dimension 1
 over Algebraic Field
   Defn: Defined on coordinates by sending (x : y) to
         (x^2 + (0.6623589786223730? - 0.5622795120623013?*I)*x*y
          + (0.1225611668766537? - 0.7448617666197452?*I)*y^2 : y^2)
```

```
sage: # needs sage.rings.number_field sage.symbolic
sage: K.<v> = QuadraticField(2, embedding=QQbar(sqrt(2)))
sage: P.<x,y> = ProjectiveSpace(K, 1)
sage: H = End(P)
sage: f = H([x^2 + v*y^2, y^2])
sage: f.change_ring(QQbar)
Scheme endomorphism of Projective Space of dimension 1
 over Algebraic Field
  Defn: Defined on coordinates by sending (x : y) to
        (x^2 + 1.414213562373095?*y^2 : y^2)
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field sage.symbolic
>>> K = QuadraticField(Integer(2), embedding=QQbar(sqrt(Integer(2))), names=(
↪'v',)); (v,) = K._first_ngens(1)
>>> P = ProjectiveSpace(K, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> H = End(P)
>>> f = H([x**Integer(2) + v*y**Integer(2), y**Integer(2)])
>>> f.change_ring(QQbar)
Scheme endomorphism of Projective Space of dimension 1
 over Algebraic Field
  Defn: Defined on coordinates by sending (x : y) to
        (x^2 + 1.414213562373095?*y^2 : y^2)
```

```
sage: # needs sage.rings.number_field sage.symbolic
sage: from sage.misc.verbose import set_verbose
sage: set_verbose(-1)
sage: K.<w> = QuadraticField(2, embedding=QQbar(-sqrt(2)))
sage: P.<x,y> = ProjectiveSpace(K, 1)
sage: X = P.subscheme(x - y)
sage: H = End(X)
sage: f = H([6*x^2 + 2*x*y + 16*y^2, -w*x^2 - 4*x*y - 4*y^2])
sage: f.change_ring(QQbar)
Scheme endomorphism of Closed subscheme of Projective Space of dimension 1
 over Algebraic Field defined by: x - y
  Defn: Defined on coordinates by sending (x : y) to
        (6*x^2 + 2*x*y + 16*y^2 : 1.414213562373095?*x^2 + (-4)*x*y + (-4)*y^
↪2)
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field sage.symbolic
>>> from sage.misc.verbose import set_verbose
>>> set_verbose(-Integer(1))
>>> K = QuadraticField(Integer(2), embedding=QQbar(-sqrt(Integer(2))), names=(
↪'w',)); (w,) = K._first_ngens(1)
>>> P = ProjectiveSpace(K, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> X = P.subscheme(x - y)
>>> H = End(X)
>>> f = H([Integer(6)*x**Integer(2) + Integer(2)*x*y +␣
↪Integer(16)*y**Integer(2), -w*x**Integer(2) - Integer(4)*x*y -␣
↪Integer(4)*y**Integer(2)])
>>> f.change_ring(QQbar)
Scheme endomorphism of Closed subscheme of Projective Space of dimension 1
 over Algebraic Field defined by: x - y
  Defn: Defined on coordinates by sending (x : y) to
        (6*x^2 + 2*x*y + 16*y^2 : 1.414213562373095?*x^2 + (-4)*x*y + (-4)*y^
↪2)
```

```
sage: # needs sage.rings.number_field
sage: R.<x> = QQ[]
sage: f = x^6 - 2
```

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```
sage: L.<b> = NumberField(f, embedding=f.roots(QQbar)[1][0])
sage: A.<x,y> = AffineSpace(L, 2)
sage: H = Hom(A, A)
sage: F = H([b*x/y, 1 + y])
sage: F.change_ring(QQbar)
Scheme endomorphism of Affine Space of dimension 2 over Algebraic Field
  Defn: Defined on coordinates by sending (x, y) to
        (1.122462048309373?*x/y, y + 1)
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> f = x**Integer(6) - Integer(2)
>>> L = NumberField(f, embedding=f.roots(QQbar)[Integer(1)][Integer(0)],␣
↪names=('b',)); (b,) = L._first_ngens(1)
>>> A = AffineSpace(L, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> H = Hom(A, A)
>>> F = H([b*x/y, Integer(1) + y])
>>> F.change_ring(QQbar)
Scheme endomorphism of Affine Space of dimension 2 over Algebraic Field
  Defn: Defined on coordinates by sending (x, y) to
        (1.122462048309373?*x/y, y + 1)
```

```
sage: # needs sage.rings.number_field
sage: K.<a> = QuadraticField(-1)
sage: A.<x,y> = AffineSpace(K, 2)
sage: H = End(A)
sage: phi = H([x/y, y])
sage: emb = K.embeddings(QQbar)[0]
sage: phi.change_ring(emb)
Scheme endomorphism of Affine Space of dimension 2 over Algebraic Field
  Defn: Defined on coordinates by sending (x, y) to (x/y, y)
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> K = QuadraticField(-Integer(1), names=('a',)); (a,) = K._first_ngens(1)
>>> A = AffineSpace(K, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> H = End(A)
>>> phi = H([x/y, y])
>>> emb = K.embeddings(QQbar)[Integer(0)]
>>> phi.change_ring(emb)
Scheme endomorphism of Affine Space of dimension 2 over Algebraic Field
  Defn: Defined on coordinates by sending (x, y) to (x/y, y)
```

coordinate_ring()

Return the coordinate ring of the ambient projective space.

OUTPUT: a multivariable polynomial ring over the base ring

EXAMPLES:

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: H = Hom(P, P)
sage: f = H([3/5*x^2, 6*y^2])
sage: f.coordinate_ring()
Multivariate Polynomial Ring in x, y over Rational Field
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> H = Hom(P, P)
>>> f = H([Integer(3)/Integer(5)*x**Integer(2), Integer(6)*y**Integer(2)])
>>> f.coordinate_ring()
Multivariate Polynomial Ring in x, y over Rational Field
```

```
sage: R.<t> = PolynomialRing(ZZ, 1)
sage: P.<x,y> = ProjectiveSpace(R, 1)
sage: H = Hom(P, P)
sage: f = H([3*x^2, y^2])
sage: f.coordinate_ring()
Multivariate Polynomial Ring in x, y over Multivariate Polynomial Ring
in t over Integer Ring
```

```
>>> from sage.all import *
>>> R = PolynomialRing(ZZ, Integer(1), names=('t',)); (t,) = R._first_ngens(1)
>>> P = ProjectiveSpace(R, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> H = Hom(P, P)
>>> f = H([Integer(3)*x**Integer(2), y**Integer(2)])
>>> f.coordinate_ring()
Multivariate Polynomial Ring in x, y over Multivariate Polynomial Ring
in t over Integer Ring
```

defining_polynomials()

Return the defining polynomials.

OUTPUT:

An immutable sequence of polynomials that defines this scheme morphism.

EXAMPLES:

```
sage: R.<x,y> = QQ[]
sage: A.<x,y> = AffineSpace(R)
sage: H = A.Hom(A)
sage: H([x^3 + y, 1 - x - y]).defining_polynomials()
(x^3 + y, -x - y + 1)
```

```
>>> from sage.all import *
>>> R = QQ['x, y']; (x, y,) = R._first_ngens(2)
>>> A = AffineSpace(R, names=('x', 'y',)); (x, y,) = A._first_ngens(2)
>>> H = A.Hom(A)
>>> H([x**Integer(3) + y, Integer(1) - x - y]).defining_polynomials()
(x^3 + y, -x - y + 1)
```

specialization(*D=None*, *phi=None*, *homset=None*)

Specialization of this map.

Given a family of maps defined over a polynomial ring. A specialization is a particular member of that family. The specialization can be specified either by a dictionary or a `SpecializationMorphism`.

INPUT:

- `D` – dictionary (optional)
- `phi` – SpecializationMorphism (optional)
- `homset` – homset of specialized map (optional)

OUTPUT: *SchemeMorphism_polynomial*

EXAMPLES:

```
sage: R.<c> = PolynomialRing(QQ)
sage: P.<x,y> = ProjectiveSpace(R, 1)
sage: H = End(P)
sage: f = H([x^2 + c*y^2, y^2])
sage: f.specialization({c: 1})
Scheme endomorphism of Projective Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x : y) to (x^2 + y^2 : y^2)
```

```
>>> from sage.all import *
>>> R = PolynomialRing(QQ, names=('c',)); (c,) = R._first_ngens(1)
>>> P = ProjectiveSpace(R, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> H = End(P)
>>> f = H([x**Integer(2) + c*y**Integer(2), y**Integer(2)])
>>> f.specialization({c: Integer(1)})
Scheme endomorphism of Projective Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x : y) to (x^2 + y^2 : y^2)
```

```
sage: R.<a,b> = PolynomialRing(QQ)
sage: P.<x,y> = ProjectiveSpace(R, 1)
sage: H = End(P)
sage: f = H([x^3 + a*x*y^2 + b*y^3, y^3])
sage: from sage.rings.polynomial.flatten import SpecializationMorphism
sage: phi = SpecializationMorphism(P.coordinate_ring(), {a: 2, b: -1})
sage: F = f.specialization(phi=phi); F
Scheme endomorphism of Projective Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x : y) to
        (x^3 + 2*x*y^2 - y^3 : y^3)
sage: g = H([x^2 + a*y^2, y^2])
sage: G = g.specialization(phi=phi)
sage: G.parent() is F.parent()
True
sage: G = g.specialization(phi=phi, homset=F.parent())
sage: G.parent() is F.parent()
True
```

```
>>> from sage.all import *
>>> R = PolynomialRing(QQ, names=('a', 'b',)); (a, b,) = R._first_ngens(2)
```

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```
>>> P = ProjectiveSpace(R, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> H = End(P)
>>> f = H([x**Integer(3) + a*x*y**Integer(2) + b*y**Integer(3),␣
↪y**Integer(3)])
>>> from sage.rings.polynomial.flatten import SpecializationMorphism
>>> phi = SpecializationMorphism(P.coordinate_ring(), {a: Integer(2), b: -
↪Integer(1)})
>>> F = f.specialization(phi=phi); F
Scheme endomorphism of Projective Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x : y) to
        (x^3 + 2*x*y^2 - y^3 : y^3)
>>> g = H([x**Integer(2) + a*y**Integer(2), y**Integer(2)])
>>> G = g.specialization(phi=phi)
>>> G.parent() is F.parent()
True
>>> G = g.specialization(phi=phi, homset=F.parent())
>>> G.parent() is F.parent()
True
```

```
sage: R.<c> = PolynomialRing(QQ)
sage: P.<x,y> = ProjectiveSpace(R, 1)
sage: X = P.subscheme([x - c*y])
sage: H = End(X)
sage: f = H([x^2, c*y^2])
sage: f.specialization({c: 2})
Scheme endomorphism of Closed subscheme of Projective Space of dimension 1
 over Rational Field defined by: x - 2*y
      Defn: Defined on coordinates by sending (x : y) to (x^2 : 2*y^2)
```

```
>>> from sage.all import *
>>> R = PolynomialRing(QQ, names=('c',)); (c,) = R._first_ngens(1)
>>> P = ProjectiveSpace(R, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> X = P.subscheme([x - c*y])
>>> H = End(X)
>>> f = H([x**Integer(2), c*y**Integer(2)])
>>> f.specialization({c: Integer(2)})
Scheme endomorphism of Closed subscheme of Projective Space of dimension 1
 over Rational Field defined by: x - 2*y
      Defn: Defined on coordinates by sending (x : y) to (x^2 : 2*y^2)
```

```
sage: R.<c> = QQ[]
sage: P.<x,y> = ProjectiveSpace(R, 1)
sage: f = DynamicalSystem_projective([x^2 + c*y^2, y^2], domain=P)
sage: F = f.dynatomic_polynomial(3)                                    #␣
↪needs sage.libs.pari
sage: g = F.specialization({c: 1}); g
x^6 + x^5*y + 4*x^4*y^2 + 3*x^3*y^3 + 7*x^2*y^4 + 4*x*y^5 + 5*y^6
sage: g == f.specialization({c:1}).dynatomic_polynomial(3)             #␣
↪needs sage.libs.pari
```

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```
True
```

```
>>> from sage.all import *
>>> R = QQ['c']; (c,) = R._first_ngens(1)
>>> P = ProjectiveSpace(R, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> f = DynamicalSystem_projective([x**Integer(2) + c*y**Integer(2),␣
↪y**Integer(2)], domain=P)
>>> F = f.dynatomic_polynomial(Integer(3))                                    ␣
↪     # needs sage.libs.pari
>>> g = F.specialization({c: Integer(1)}); g
x^6 + x^5*y + 4*x^4*y^2 + 3*x^3*y^3 + 7*x^2*y^4 + 4*x*y^5 + 5*y^6
>>> g == f.specialization({c:Integer(1)}).dynatomic_polynomial(Integer(3))   ␣
↪              # needs sage.libs.pari
True
```

```
sage: R1.<alpha, beta> = QQ[]
sage: A.<x> = AffineSpace(Frac(R1), 1)
sage: f = DynamicalSystem_affine([alpha/(x^2 + 1/alpha)/(x - 1/beta^2)])
sage: f.specialization({alpha: 5, beta: 10})
Dynamical System of Affine Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x) to
          (5/(x^3 - 1/100*x^2 + 1/5*x - 1/500))
sage: f_5_10 = f.specialization({alpha: 5}).specialization({beta: 10})
sage: f_5_10 == f.specialization({alpha: 5, beta: 10})
True
```

```
>>> from sage.all import *
>>> R1 = QQ['alpha, beta']; (alpha, beta,) = R1._first_ngens(2)
>>> A = AffineSpace(Frac(R1), Integer(1), names=('x',)); (x,) = A._first_
↪ngens(1)
>>> f = DynamicalSystem_affine([alpha/(x**Integer(2) + Integer(1)/alpha)/(x -␣
↪Integer(1)/beta**Integer(2))])
>>> f.specialization({alpha: Integer(5), beta: Integer(10)})
Dynamical System of Affine Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x) to
          (5/(x^3 - 1/100*x^2 + 1/5*x - 1/500))
>>> f_5_10 = f.specialization({alpha: Integer(5)}).specialization({beta:␣
↪Integer(10)})
>>> f_5_10 == f.specialization({alpha: Integer(5), beta: Integer(10)})
True
```

class sage.schemes.generic.morphism.**SchemeMorphism_polynomial_id**(X)

Bases: *SchemeMorphism_id*, *SchemeMorphism_polynomial*

Return the identity morphism from X to itself.

INPUT:

- `X` – an affine or projective scheme

EXAMPLES:

```
sage: X = Spec(ZZ)
sage: X.identity_morphism()  # indirect doctest
Scheme endomorphism of Spectrum of Integer Ring
  Defn: Identity map
```

```
>>> from sage.all import *
>>> X = Spec(ZZ)
>>> X.identity_morphism()  # indirect doctest
Scheme endomorphism of Spectrum of Integer Ring
  Defn: Identity map
```

class sage.schemes.generic.morphism.**SchemeMorphism_spec**(*parent*, *phi*, *check=True*)

Bases: *SchemeMorphism*

Morphism of spectra of rings.

INPUT:

- `parent` – Hom-set whose domain and codomain are affine schemes
- `phi` – a ring morphism with matching domain and codomain
- `check` – boolean (default: `True`); whether to check the input for consistency

EXAMPLES:

```
sage: R.<x> = PolynomialRing(QQ)
sage: phi = R.hom([QQ(7)]); phi
Ring morphism:
  From: Univariate Polynomial Ring in x over Rational Field
  To:   Rational Field
  Defn: x |--> 7

sage: X = Spec(QQ); Y = Spec(R)
sage: f = X.hom(phi); f
Affine Scheme morphism:
  From: Spectrum of Rational Field
  To:   Spectrum of Univariate Polynomial Ring in x over Rational Field
  Defn: Ring morphism:
          From: Univariate Polynomial Ring in x over Rational Field
          To:   Rational Field
          Defn: x |--> 7

sage: f.ring_homomorphism()
Ring morphism:
  From: Univariate Polynomial Ring in x over Rational Field
  To:   Rational Field
  Defn: x |--> 7
```

```
>>> from sage.all import *
>>> R = PolynomialRing(QQ, names=('x',)); (x,) = R._first_ngens(1)
>>> phi = R.hom([QQ(Integer(7))]); phi
Ring morphism:
  From: Univariate Polynomial Ring in x over Rational Field
  To:   Rational Field
```

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```
  Defn: x |--> 7

>>> X = Spec(QQ); Y = Spec(R)
>>> f = X.hom(phi); f
Affine Scheme morphism:
  From: Spectrum of Rational Field
  To:   Spectrum of Univariate Polynomial Ring in x over Rational Field
  Defn: Ring morphism:
          From: Univariate Polynomial Ring in x over Rational Field
          To:   Rational Field
          Defn: x |--> 7

>>> f.ring_homomorphism()
Ring morphism:
  From: Univariate Polynomial Ring in x over Rational Field
  To:   Rational Field
  Defn: x |--> 7
```

ring_homomorphism()

Return the underlying ring homomorphism.

OUTPUT: a ring homomorphism

EXAMPLES:

```
sage: R.<x> = PolynomialRing(QQ)
sage: phi = R.hom([QQ(7)])
sage: X = Spec(QQ); Y = Spec(R)
sage: f = X.hom(phi)
sage: f.ring_homomorphism()
Ring morphism:
  From: Univariate Polynomial Ring in x over Rational Field
  To:   Rational Field
  Defn: x |--> 7
```

```
>>> from sage.all import *
>>> R = PolynomialRing(QQ, names=('x',)); (x,) = R._first_ngens(1)
>>> phi = R.hom([QQ(Integer(7))])
>>> X = Spec(QQ); Y = Spec(R)
>>> f = X.hom(phi)
>>> f.ring_homomorphism()
Ring morphism:
  From: Univariate Polynomial Ring in x over Rational Field
  To:   Rational Field
  Defn: x |--> 7
```

class sage.schemes.generic.morphism.**SchemeMorphism_structure_map**(*parent*, *codomain=None*)

Bases: *SchemeMorphism*

The structure morphism.

INPUT:

- `parent` – Hom-set with codomain equal to the base scheme of the domain

EXAMPLES:

```
sage: Spec(ZZ).structure_morphism()    # indirect doctest
Scheme endomorphism of Spectrum of Integer Ring
  Defn: Structure map
```

```
>>> from sage.all import *
>>> Spec(ZZ).structure_morphism()    # indirect doctest
Scheme endomorphism of Spectrum of Integer Ring
  Defn: Structure map
```

sage.schemes.generic.morphism.**is_SchemeMorphism**(*f*)

Test whether `f` is a scheme morphism.

INPUT:

- `f` – anything

OUTPUT:

boolean; return `True` if `f` is a scheme morphism or a point on an elliptic curve.

EXAMPLES:

```
sage: A.<x,y> = AffineSpace(QQ, 2); H = A.Hom(A)
sage: f = H([y, x^2 + y]); f
Scheme endomorphism of Affine Space of dimension 2 over Rational Field
  Defn: Defined on coordinates by sending (x, y) to (y, x^2 + y)
sage: from sage.schemes.generic.morphism import is_SchemeMorphism
sage: is_SchemeMorphism(f)
doctest:warning...
DeprecationWarning: The function is_SchemeMorphism is deprecated;
use 'isinstance(..., SchemeMorphism)' instead.
See https://github.com/sagemath/sage/issues/38296 for details.
True
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2); H = A.Hom(A)
>>> f = H([y, x**Integer(2) + y]); f
Scheme endomorphism of Affine Space of dimension 2 over Rational Field
  Defn: Defined on coordinates by sending (x, y) to (y, x^2 + y)
>>> from sage.schemes.generic.morphism import is_SchemeMorphism
>>> is_SchemeMorphism(f)
doctest:warning...
DeprecationWarning: The function is_SchemeMorphism is deprecated;
use 'isinstance(..., SchemeMorphism)' instead.
See https://github.com/sagemath/sage/issues/38296 for details.
True
```

CHAPTER

ELEVEN

DIVISORS ON SCHEMES

AUTHORS:

- William Stein
- David Kohel
- David Joyner
- Volker Braun (2010-07-16): Documentation, doctests, coercion fixes, bugfixes.

EXAMPLES:

```
sage: x,y,z = ProjectiveSpace(2, GF(5), names='x,y,z').gens()
sage: C = Curve(y^2*z^7 - x^9 - x*z^8)
sage: pts = C.rational_points(); pts
[(0 : 0 : 1), (0 : 1 : 0), (2 : 2 : 1), (2 : 3 : 1), (3 : 1 : 1), (3 : 4 : 1)]
sage: D1 = C.divisor(pts[0])*3
sage: D2 = C.divisor(pts[1])
sage: D3 = 10*C.divisor(pts[5])
sage: D1.parent() is D2.parent()
True
sage: D = D1 - D2 + D3; D
3*(x, y) - (x, z) + 10*(x + 2*z, y + z)
sage: D[1][0]
-1
sage: D[1][1]
Ideal (x, z) of Multivariate Polynomial Ring in x, y, z over Finite Field of size 5
sage: C.divisor([(3, pts[0]), (-1, pts[1]), (10, pts[5])])
3*(x, y) - (x, z) + 10*(x + 2*z, y + z)
```

```
>>> from sage.all import *
>>> x,y,z = ProjectiveSpace(Integer(2), GF(Integer(5)), names='x,y,z').gens()
>>> C = Curve(y**Integer(2)*z**Integer(7) - x**Integer(9) - x*z**Integer(8))
>>> pts = C.rational_points(); pts
[(0 : 0 : 1), (0 : 1 : 0), (2 : 2 : 1), (2 : 3 : 1), (3 : 1 : 1), (3 : 4 : 1)]
>>> D1 = C.divisor(pts[Integer(0)])*Integer(3)
>>> D2 = C.divisor(pts[Integer(1)])
>>> D3 = Integer(10)*C.divisor(pts[Integer(5)])
>>> D1.parent() is D2.parent()
True
>>> D = D1 - D2 + D3; D
3*(x, y) - (x, z) + 10*(x + 2*z, y + z)
>>> D[Integer(1)][Integer(0)]
```

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```
-1
>>> D[Integer(1)][Integer(1)]
Ideal (x, z) of Multivariate Polynomial Ring in x, y, z over Finite Field of size 5
>>> C.divisor([(Integer(3), pts[Integer(0)]), (-Integer(1), pts[Integer(1)]),␣
↪(Integer(10), pts[Integer(5)])])
3*(x, y) - (x, z) + 10*(x + 2*z, y + z)
```

sage.schemes.generic.divisor.**CurvePointToIdeal**(*C*, *P*)

Return the vanishing ideal of a point on a curve.

EXAMPLES:

```
sage: x,y = AffineSpace(2, QQ, names='xy').gens()
sage: C = Curve(y^2 - x^9 - x)
sage: from sage.schemes.generic.divisor import CurvePointToIdeal
sage: CurvePointToIdeal(C, (0,0))
Ideal (x, y) of Multivariate Polynomial Ring in x, y over Rational Field
```

```
>>> from sage.all import *
>>> x,y = AffineSpace(Integer(2), QQ, names='xy').gens()
>>> C = Curve(y**Integer(2) - x**Integer(9) - x)
>>> from sage.schemes.generic.divisor import CurvePointToIdeal
>>> CurvePointToIdeal(C, (Integer(0),Integer(0)))
Ideal (x, y) of Multivariate Polynomial Ring in x, y over Rational Field
```

class sage.schemes.generic.divisor.**Divisor_curve**(*v*, *parent=None*, *check=True*, *reduce=True*)

Bases: *Divisor_generic*

For any curve C, use `C.divisor(v)` to construct a divisor on C. Here v can be either

- a rational point on C
- a list of rational points
- a list of 2-tuples (c, P), where c is an integer and P is a rational point

TODO: Divisors shouldn't be restricted to rational points. The problem is that the divisor group is the formal sum of the group of points on the curve, and there's no implemented notion of point on E/K that has coordinates in L. This is what should be implemented, by adding an appropriate class to `schemes/generic/morphism.py`.

EXAMPLES:

```
sage: E = EllipticCurve([0, 0, 1, -1, 0])
sage: P = E(0,0)
sage: 10*P
(161/16 : -2065/64 : 1)
sage: D = E.divisor(P)
sage: D
(x, y)
sage: 10*D
10*(x, y)
sage: E.divisor([P, P])
2*(x, y)
sage: E.divisor([(3,P), (-4,5*P)])
3*(x, y) - 4*(x - 1/4*z, y + 5/8*z)
```

```
>>> from sage.all import *
>>> E = EllipticCurve([Integer(0), Integer(0), Integer(1), -Integer(1),␣
↪Integer(0)])
>>> P = E(Integer(0),Integer(0))
>>> Integer(10)*P
(161/16 : -2065/64 : 1)
>>> D = E.divisor(P)
>>> D
(x, y)
>>> Integer(10)*D
10*(x, y)
>>> E.divisor([P, P])
2*(x, y)
>>> E.divisor([(Integer(3),P), (-Integer(4),Integer(5)*P)])
3*(x, y) - 4*(x - 1/4*z, y + 5/8*z)
```

coefficient(*P*)

Return the coefficient of a given point P in this divisor.

EXAMPLES:

```
sage: x,y = AffineSpace(2, GF(5), names='xy').gens()
sage: C = Curve(y^2 - x^9 - x)
sage: pts = C.rational_points(); pts
[(0, 0), (2, 2), (2, 3), (3, 1), (3, 4)]
sage: D = C.divisor(pts[0])
sage: D.coefficient(pts[0])
1
sage: D = C.divisor([(3, pts[0]), (-1, pts[1])]); D
3*(x, y) - (x - 2, y - 2)
sage: D.coefficient(pts[0])
3
sage: D.coefficient(pts[1])
-1
```

```
>>> from sage.all import *
>>> x,y = AffineSpace(Integer(2), GF(Integer(5)), names='xy').gens()
>>> C = Curve(y**Integer(2) - x**Integer(9) - x)
>>> pts = C.rational_points(); pts
[(0, 0), (2, 2), (2, 3), (3, 1), (3, 4)]
>>> D = C.divisor(pts[Integer(0)])
>>> D.coefficient(pts[Integer(0)])
1
>>> D = C.divisor([(Integer(3), pts[Integer(0)]), (-Integer(1),␣
↪pts[Integer(1)])]); D
3*(x, y) - (x - 2, y - 2)
>>> D.coefficient(pts[Integer(0)])
3
>>> D.coefficient(pts[Integer(1)])
-1
```

support()

Return the support of this divisor, which is the set of points that occur in this divisor with nonzero coefficients.

EXAMPLES:

```
sage: A = AffineSpace(2, GF(5), names='xy')
sage: x, y = A.gens()
sage: C = Curve(y^2 - x^9 - x)
sage: pts = C.rational_points(); pts
[(0, 0), (2, 2), (2, 3), (3, 1), (3, 4)]
sage: D = C.divisor_group()([(3, pts[0]), (-1, pts[1])]); D
3*(x, y) - (x - 2, y - 2)
sage: D.support()
[(0, 0), (2, 2)]
```

```
>>> from sage.all import *
>>> A = AffineSpace(Integer(2), GF(Integer(5)), names='xy')
>>> x, y = A.gens()
>>> C = Curve(y**Integer(2) - x**Integer(9) - x)
>>> pts = C.rational_points(); pts
[(0, 0), (2, 2), (2, 3), (3, 1), (3, 4)]
>>> D = C.divisor_group()([(Integer(3), pts[Integer(0)]), (-Integer(1),␣
↪pts[Integer(1)])]); D
3*(x, y) - (x - 2, y - 2)
>>> D.support()
[(0, 0), (2, 2)]
```

class sage.schemes.generic.divisor.**Divisor_generic**(*v*, *parent*, *check=True*, *reduce=True*)

Bases: FormalSum

A Divisor.

scheme()

Return the scheme that this divisor is on.

EXAMPLES:

```
sage: A.<x, y> = AffineSpace(2, GF(5))
sage: C = Curve(y^2 - x^9 - x)
sage: pts = C.rational_points(); pts
[(0, 0), (2, 2), (2, 3), (3, 1), (3, 4)]
sage: D = C.divisor(pts[0])*3 - C.divisor(pts[1]); D
3*(x, y) - (x - 2, y - 2)
sage: D.scheme()
Affine Plane Curve over Finite Field of size 5 defined by -x^9 + y^2 - x
```

```
>>> from sage.all import *
>>> A = AffineSpace(Integer(2), GF(Integer(5)), names=('x', 'y',)); (x, y,) =␣
↪A._first_ngens(2)
>>> C = Curve(y**Integer(2) - x**Integer(9) - x)
>>> pts = C.rational_points(); pts
[(0, 0), (2, 2), (2, 3), (3, 1), (3, 4)]
>>> D = C.divisor(pts[Integer(0)])*Integer(3) - C.divisor(pts[Integer(1)]); D
3*(x, y) - (x - 2, y - 2)
>>> D.scheme()
Affine Plane Curve over Finite Field of size 5 defined by -x^9 + y^2 - x
```

sage.schemes.generic.divisor.**is_Divisor**(*x*)

Test whether x is an instance of *Divisor_generic*.

INPUT:

- x – anything

OUTPUT: boolean

EXAMPLES:

```
sage: from sage.schemes.generic.divisor import is_Divisor
sage: x,y = AffineSpace(2, GF(5), names='xy').gens()
sage: C = Curve(y^2 - x^9 - x)
sage: is_Divisor(C.divisor([]))
doctest:warning...
DeprecationWarning: The function is_Divisor is deprecated;
use 'isinstance(..., Divisor_generic)' instead.
See https://github.com/sagemath/sage/issues/38277 for details.
True
sage: is_Divisor("Ceci n'est pas un diviseur")
False
```

```
>>> from sage.all import *
>>> from sage.schemes.generic.divisor import is_Divisor
>>> x,y = AffineSpace(Integer(2), GF(Integer(5)), names='xy').gens()
>>> C = Curve(y**Integer(2) - x**Integer(9) - x)
>>> is_Divisor(C.divisor([]))
doctest:warning...
DeprecationWarning: The function is_Divisor is deprecated;
use 'isinstance(..., Divisor_generic)' instead.
See https://github.com/sagemath/sage/issues/38277 for details.
True
>>> is_Divisor("Ceci n'est pas un diviseur")
False
```

CHAPTER

TWELVE

DIVISOR GROUPS

AUTHORS:

- David Kohel (2006): Initial version
- Volker Braun (2010-07-16): Documentation, doctests, coercion fixes, bugfixes.

sage.schemes.generic.divisor_group.**DivisorGroup**(*scheme*, *base_ring=None*)

Return the group of divisors on the scheme.

INPUT:

- `scheme` – a scheme
- `base_ring` – usually either **Z** (default) or **Q**. The coefficient ring of the divisors. Not to be confused with the base ring of the scheme!

OUTPUT: an instance of `DivisorGroup_generic`

EXAMPLES:

```
sage: from sage.schemes.generic.divisor_group import DivisorGroup
sage: DivisorGroup(Spec(ZZ))
Group of ZZ-Divisors on Spectrum of Integer Ring
sage: DivisorGroup(Spec(ZZ), base_ring=QQ)
Group of QQ-Divisors on Spectrum of Integer Ring
```

```
>>> from sage.all import *
>>> from sage.schemes.generic.divisor_group import DivisorGroup
>>> DivisorGroup(Spec(ZZ))
Group of ZZ-Divisors on Spectrum of Integer Ring
>>> DivisorGroup(Spec(ZZ), base_ring=QQ)
Group of QQ-Divisors on Spectrum of Integer Ring
```

class sage.schemes.generic.divisor_group.**DivisorGroup_curve**(*scheme*, *base_ring*)

Bases: *DivisorGroup_generic*

Special case of the group of divisors on a curve.

class sage.schemes.generic.divisor_group.**DivisorGroup_generic**(*scheme*, *base_ring*)

Bases: `FormalSums`

The divisor group on a variety.

base_extend(*R*)

EXAMPLES:

```
sage: from sage.schemes.generic.divisor_group import DivisorGroup
sage: DivisorGroup(Spec(ZZ), ZZ).base_extend(QQ)
Group of QQ-Divisors on Spectrum of Integer Ring
sage: DivisorGroup(Spec(ZZ), ZZ).base_extend(GF(7))
Group of (Finite Field of size 7)-Divisors on Spectrum of Integer Ring
```

```
>>> from sage.all import *
>>> from sage.schemes.generic.divisor_group import DivisorGroup
>>> DivisorGroup(Spec(ZZ), ZZ).base_extend(QQ)
Group of QQ-Divisors on Spectrum of Integer Ring
>>> DivisorGroup(Spec(ZZ), ZZ).base_extend(GF(Integer(7)))
Group of (Finite Field of size 7)-Divisors on Spectrum of Integer Ring
```

Divisor groups are unique:

```
sage: A.<x, y> = AffineSpace(2, CC)                                             #␣
↪needs sage.rings.real_mpfr
sage: C = Curve(y^2 - x^9 - x)                                                  #␣
↪needs sage.rings.real_mpfr sage.schemes
sage: DivisorGroup(C, ZZ).base_extend(QQ) is DivisorGroup(C, QQ)                #␣
↪needs sage.rings.real_mpfr sage.schemes
True
```

```
>>> from sage.all import *
>>> A = AffineSpace(Integer(2), CC, names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)# needs sage.rings.real_mpfr
>>> C = Curve(y**Integer(2) - x**Integer(9) - x)                                ␣
↪               # needs sage.rings.real_mpfr sage.schemes
>>> DivisorGroup(C, ZZ).base_extend(QQ) is DivisorGroup(C, QQ)                 #␣
↪needs sage.rings.real_mpfr sage.schemes
True
```

scheme()

Return the scheme supporting the divisors.

EXAMPLES:

```
sage: from sage.schemes.generic.divisor_group import DivisorGroup
sage: Div = DivisorGroup(Spec(ZZ))    # indirect test
sage: Div.scheme()
Spectrum of Integer Ring
```

```
>>> from sage.all import *
>>> from sage.schemes.generic.divisor_group import DivisorGroup
>>> Div = DivisorGroup(Spec(ZZ))    # indirect test
>>> Div.scheme()
Spectrum of Integer Ring
```

sage.schemes.generic.divisor_group.**is_DivisorGroup**(*x*)

Return whether x is a *DivisorGroup_generic*.

INPUT:

- x – anything

OUTPUT: boolean

EXAMPLES:

```
sage: from sage.schemes.generic.divisor_group import is_DivisorGroup, DivisorGroup
sage: Div = DivisorGroup(Spec(ZZ), base_ring=QQ)
sage: is_DivisorGroup(Div)
doctest:warning...
DeprecationWarning: The function is_DivisorGroup is deprecated; use 'isinstance(..
↪., DivisorGroup_generic)' instead.
See https://github.com/sagemath/sage/issues/38022 for details.
True
sage: is_DivisorGroup('not a divisor')
False
```

```
>>> from sage.all import *
>>> from sage.schemes.generic.divisor_group import is_DivisorGroup, DivisorGroup
>>> Div = DivisorGroup(Spec(ZZ), base_ring=QQ)
>>> is_DivisorGroup(Div)
doctest:warning...
DeprecationWarning: The function is_DivisorGroup is deprecated; use 'isinstance(..
↪., DivisorGroup_generic)' instead.
See https://github.com/sagemath/sage/issues/38022 for details.
True
>>> is_DivisorGroup('not a divisor')
False
```

CHAPTER

THIRTEEN

AFFINE SCHEMES

13.1 Affine n space over a ring

sage.schemes.affine.affine_space.**AffineSpace**(*n*, *R=None*, *names=None*, *ambient_projective_space=None*, *default_embedding_index=None*)

Return affine space of dimension `n` over the ring `R`.

EXAMPLES:

The dimension and ring can be given in either order:

```
sage: AffineSpace(3, QQ, 'x')
Affine Space of dimension 3 over Rational Field
sage: AffineSpace(5, QQ, 'x')
Affine Space of dimension 5 over Rational Field
sage: A = AffineSpace(2, QQ, names='XY'); A
Affine Space of dimension 2 over Rational Field
sage: A.coordinate_ring()
Multivariate Polynomial Ring in X, Y over Rational Field
```

```
>>> from sage.all import *
>>> AffineSpace(Integer(3), QQ, 'x')
Affine Space of dimension 3 over Rational Field
>>> AffineSpace(Integer(5), QQ, 'x')
Affine Space of dimension 5 over Rational Field
>>> A = AffineSpace(Integer(2), QQ, names='XY'); A
Affine Space of dimension 2 over Rational Field
>>> A.coordinate_ring()
Multivariate Polynomial Ring in X, Y over Rational Field
```

Use the divide operator for base extension:

```
sage: AffineSpace(5, names='x')/GF(17)
Affine Space of dimension 5 over Finite Field of size 17
```

```
>>> from sage.all import *
>>> AffineSpace(Integer(5), names='x')/GF(Integer(17))
Affine Space of dimension 5 over Finite Field of size 17
```

The default base ring is **Z**:

```
sage: AffineSpace(5, names='x')
Affine Space of dimension 5 over Integer Ring
```

```
>>> from sage.all import *
>>> AffineSpace(Integer(5), names='x')
Affine Space of dimension 5 over Integer Ring
```

There is also an affine space associated to each polynomial ring:

```
sage: R = GF(7)['x, y, z']
sage: A = AffineSpace(R); A
Affine Space of dimension 3 over Finite Field of size 7
sage: A.coordinate_ring() is R
True
```

```
>>> from sage.all import *
>>> R = GF(Integer(7))['x, y, z']
>>> A = AffineSpace(R); A
Affine Space of dimension 3 over Finite Field of size 7
>>> A.coordinate_ring() is R
True
```

class sage.schemes.affine.affine_space.**AffineSpace_field**(*n*, *R*, *names*, *ambient_projective_space*, *default_embedding_index*)

Bases: *AffineSpace_generic*

curve(*F*)

Return a curve defined by `F` in this affine space.

INPUT:

- `F` – a polynomial, or a list or tuple of polynomials in the coordinate ring of this affine space

EXAMPLES:

```
sage: A.<x,y,z> = AffineSpace(QQ, 3)
sage: A.curve([y - x^4, z - y^5])                                           #␣
↪needs sage.schemes
Affine Curve over Rational Field defined by -x^4 + y, -y^5 + z
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(3), names=('x', 'y', 'z',)); (x, y, z,) = A._
↪first_ngens(3)
>>> A.curve([y - x**Integer(4), z - y**Integer(5)])                          ␣
↪                # needs sage.schemes
Affine Curve over Rational Field defined by -x^4 + y, -y^5 + z
```

line_through(*p*, *q*)

Return the line through `p` and `q`.

INPUT:

- `p`, `q` – distinct rational points of the affine space

EXAMPLES:

```
sage: # needs sage.libs.singular sage.schemes
sage: A3.<x,y,z> = AffineSpace(3, QQ)
sage: p1 = A3(1, 2, 3)
sage: p2 = A3(4, 5, 6)
sage: L = A3.line_through(p1, p2); L
Affine Curve over Rational Field defined by -1/6*x + 1/6*y - 1/6,
  -1/6*x + 1/6*z - 1/3, -1/6*y + 1/6*z - 1/6, -1/6*x + 1/3*y - 1/6*z
sage: L(p1)
(1, 2, 3)
sage: L(p2)
(4, 5, 6)
sage: A3.line_through(p1, p1)
Traceback (most recent call last):
...
ValueError: not distinct points
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular sage.schemes
>>> A3 = AffineSpace(Integer(3), QQ, names=('x', 'y', 'z',)); (x, y, z,) = A3.
↪_first_ngens(3)
>>> p1 = A3(Integer(1), Integer(2), Integer(3))
>>> p2 = A3(Integer(4), Integer(5), Integer(6))
>>> L = A3.line_through(p1, p2); L
Affine Curve over Rational Field defined by -1/6*x + 1/6*y - 1/6,
  -1/6*x + 1/6*z - 1/3, -1/6*y + 1/6*z - 1/6, -1/6*x + 1/3*y - 1/6*z
>>> L(p1)
(1, 2, 3)
>>> L(p2)
(4, 5, 6)
>>> A3.line_through(p1, p1)
Traceback (most recent call last):
...
ValueError: not distinct points
```

points_of_bounded_height(***kwds*)

Return an iterator of the points in this affine space of absolute height of at most the given bound.

Bound check is strict for the rational field. Requires this space to be affine space over a number field. Uses the Doyle-Krumm algorithm 4 (algorithm 5 for imaginary quadratic) for computing algebraic numbers up to a given height [DK2013].

The algorithm requires floating point arithmetic, so the user is allowed to specify the precision for such calculations. Additionally, due to floating point issues, points slightly larger than the bound may be returned. This can be controlled by lowering the tolerance.

INPUT: keyword arguments:

- `bound` – a real number
- `tolerance` – a rational number in (0,1] used in Doyle-Krumm algorithm-4
- `precision` – the precision to use for computing the elements of bounded height of number fields

OUTPUT: an iterator of points in self

EXAMPLES:

```
sage: A.<x,y> = AffineSpace(QQ, 2)
sage: list(A.points_of_bounded_height(bound=3))
[(0, 0), (1, 0), (-1, 0), (1/2, 0), (-1/2, 0), (2, 0), (-2, 0), (0, 1),
 (1, 1), (-1, 1), (1/2, 1), (-1/2, 1), (2, 1), (-2, 1), (0, -1), (1, -1),
 (-1, -1), (1/2, -1), (-1/2, -1), (2, -1), (-2, -1), (0, 1/2), (1, 1/2),
 (-1, 1/2), (1/2, 1/2), (-1/2, 1/2), (2, 1/2), (-2, 1/2), (0, -1/2), (1, -1/
↪2),
 (-1, -1/2), (1/2, -1/2), (-1/2, -1/2), (2, -1/2), (-2, -1/2), (0, 2), (1, 2),
 (-1, 2), (1/2, 2), (-1/2, 2), (2, 2), (-2, 2), (0, -2), (1, -2), (-1, -2),
 (1/2, -2), (-1/2, -2), (2, -2), (-2, -2)]
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> list(A.points_of_bounded_height(bound=Integer(3)))
[(0, 0), (1, 0), (-1, 0), (1/2, 0), (-1/2, 0), (2, 0), (-2, 0), (0, 1),
 (1, 1), (-1, 1), (1/2, 1), (-1/2, 1), (2, 1), (-2, 1), (0, -1), (1, -1),
 (-1, -1), (1/2, -1), (-1/2, -1), (2, -1), (-2, -1), (0, 1/2), (1, 1/2),
 (-1, 1/2), (1/2, 1/2), (-1/2, 1/2), (2, 1/2), (-2, 1/2), (0, -1/2), (1, -1/
↪2),
 (-1, -1/2), (1/2, -1/2), (-1/2, -1/2), (2, -1/2), (-2, -1/2), (0, 2), (1, 2),
 (-1, 2), (1/2, 2), (-1/2, 2), (2, 2), (-2, 2), (0, -2), (1, -2), (-1, -2),
 (1/2, -2), (-1/2, -2), (2, -2), (-2, -2)]
```

```
sage: u = QQ['u'].0
sage: A.<x,y> = AffineSpace(NumberField(u^2 - 2, 'v'), 2)                    #␣
↪needs sage.rings.number_field
sage: len(list(A.points_of_bounded_height(bound=2, tolerance=0.1)))          #␣
↪needs sage.rings.number_field
529
```

```
>>> from sage.all import *
>>> u = QQ['u'].gen(0)
>>> A = AffineSpace(NumberField(u**Integer(2) - Integer(2), 'v'), Integer(2),␣
↪names=('x', 'y',)); (x, y,) = A._first_ngens(2)# needs sage.rings.number_
↪field
>>> len(list(A.points_of_bounded_height(bound=Integer(2),␣
↪tolerance=RealNumber('0.1'))))          # needs sage.rings.number_field
529
```

translation(*p*, *q=None*)

Return the automorphism of the affine space translating `p` to the origin.

If `q` is given, the automorphism translates `p` to `q`.

INPUT:

- `p` – a rational point
- `q` – (default: `None`) a rational point

EXAMPLES:

```
sage: A.<x,y,z> = AffineSpace(QQ, 3)
sage: p = A(1,2,3)
sage: q = A(4,5,6)
sage: A.translation(p, q)
Scheme endomorphism of Affine Space of dimension 3 over Rational Field
  Defn: Defined on coordinates by sending (x, y, z) to
        (x + 3, y + 3, z + 3)
sage: phi = A.translation(p)
sage: psi = A.translation(A.origin(), q)
sage: psi * phi
Scheme endomorphism of Affine Space of dimension 3 over Rational Field
  Defn: Defined on coordinates by sending (x, y, z) to
        (x + 3, y + 3, z + 3)
sage: psi * phi == A.translation(p, q)
True
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(3), names=('x', 'y', 'z',)); (x, y, z,) = A._
↪first_ngens(3)
>>> p = A(Integer(1),Integer(2),Integer(3))
>>> q = A(Integer(4),Integer(5),Integer(6))
>>> A.translation(p, q)
Scheme endomorphism of Affine Space of dimension 3 over Rational Field
  Defn: Defined on coordinates by sending (x, y, z) to
        (x + 3, y + 3, z + 3)
>>> phi = A.translation(p)
>>> psi = A.translation(A.origin(), q)
>>> psi * phi
Scheme endomorphism of Affine Space of dimension 3 over Rational Field
  Defn: Defined on coordinates by sending (x, y, z) to
        (x + 3, y + 3, z + 3)
>>> psi * phi == A.translation(p, q)
True
```

weil_restriction()

Compute the Weil restriction of this affine space over some extension field.

If the field is a finite field, then this computes the Weil restriction to the prime subfield.

OUTPUT: affine space of dimension `d * self.dimension_relative()` over the base field of `self.base_ring()`.

EXAMPLES:

```
sage: # needs sage.rings.number_field
sage: R.<x> = QQ[]
sage: K.<w> = NumberField(x^5 - 2)
sage: AK.<x,y> = AffineSpace(K, 2)
sage: AK.weil_restriction()
Affine Space of dimension 10 over Rational Field
sage: R.<x> = K[]
sage: L.<v> = K.extension(x^2 + 1)
sage: AL.<x,y> = AffineSpace(L, 2)
sage: AL.weil_restriction()
```

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```
Affine Space of dimension 4 over Number Field in w
 with defining polynomial x^5 - 2
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> K = NumberField(x**Integer(5) - Integer(2), names=('w',)); (w,) = K._
↪first_ngens(1)
>>> AK = AffineSpace(K, Integer(2), names=('x', 'y',)); (x, y,) = AK._first_
↪ngens(2)
>>> AK.weil_restriction()
Affine Space of dimension 10 over Rational Field
>>> R = K['x']; (x,) = R._first_ngens(1)
>>> L = K.extension(x**Integer(2) + Integer(1), names=('v',)); (v,) = L._
↪first_ngens(1)
>>> AL = AffineSpace(L, Integer(2), names=('x', 'y',)); (x, y,) = AL._first_
↪ngens(2)
>>> AL.weil_restriction()
Affine Space of dimension 4 over Number Field in w
 with defining polynomial x^5 - 2
```

class sage.schemes.affine.affine_space.**AffineSpace_finite_field**(*n*, *R*, *names*, *ambient_projective_space*, *default_embedding_index*)

Bases: *AffineSpace_field*

class sage.schemes.affine.affine_space.**AffineSpace_generic**(*n*, *R*, *names*, *ambient_projective_space*, *default_embedding_index*)

Bases: *AmbientSpace*, *AffineScheme*

Affine space of dimension n over the ring R.

EXAMPLES:

```
sage: X.<x,y,z> = AffineSpace(3, QQ)
sage: X.base_scheme()
Spectrum of Rational Field
sage: X.base_ring()
Rational Field
sage: X.category()
Category of schemes over Rational Field
sage: X.structure_morphism()
Scheme morphism:
  From: Affine Space of dimension 3 over Rational Field
  To:   Spectrum of Rational Field
  Defn: Structure map
```

```
>>> from sage.all import *
>>> X = AffineSpace(Integer(3), QQ, names=('x', 'y', 'z',)); (x, y, z,) = X._
↪first_ngens(3)
>>> X.base_scheme()
Spectrum of Rational Field
```

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```
>>> X.base_ring()
Rational Field
>>> X.category()
Category of schemes over Rational Field
>>> X.structure_morphism()
Scheme morphism:
  From: Affine Space of dimension 3 over Rational Field
  To:   Spectrum of Rational Field
  Defn: Structure map
```

Loading and saving:

```
sage: loads(X.dumps()) == X
True
```

```
>>> from sage.all import *
>>> loads(X.dumps()) == X
True
```

We create several other examples of affine spaces:

```
sage: AffineSpace(5, PolynomialRing(QQ, 'z'), 'Z')
Affine Space of dimension 5 over Univariate Polynomial Ring in z over Rational␣
↪Field

sage: AffineSpace(RealField(), 3, 'Z')                                          #␣
↪needs sage.rings.real_mpfr
Affine Space of dimension 3 over Real Field with 53 bits of precision

sage: AffineSpace(Qp(7), 2, 'x')                                                #␣
↪needs sage.rings.padics
Affine Space of dimension 2 over 7-adic Field with capped relative precision 20
```

```
>>> from sage.all import *
>>> AffineSpace(Integer(5), PolynomialRing(QQ, 'z'), 'Z')
Affine Space of dimension 5 over Univariate Polynomial Ring in z over Rational␣
↪Field

>>> AffineSpace(RealField(), Integer(3), 'Z')                                   ␣
↪     # needs sage.rings.real_mpfr
Affine Space of dimension 3 over Real Field with 53 bits of precision

>>> AffineSpace(Qp(Integer(7)), Integer(2), 'x')                                ␣
↪              # needs sage.rings.padics
Affine Space of dimension 2 over 7-adic Field with capped relative precision 20
```

Even 0-dimensional affine spaces are supported:

```
sage: AffineSpace(0)
Affine Space of dimension 0 over Integer Ring
```

```
>>> from sage.all import *
>>> AffineSpace(Integer(0))
Affine Space of dimension 0 over Integer Ring
```

change_ring(*R*)

Return an affine space over ring `R` and otherwise the same as this space.

INPUT:

- `R` – commutative ring or morphism

OUTPUT: an affine space over `R`

Note

There is no need to have any relation between `R` and the base ring of this space, if you want to have such a relation, use `self.base_extend(R)` instead.

EXAMPLES:

```
sage: A.<x,y,z> = AffineSpace(3, ZZ)
sage: AQ = A.change_ring(QQ); AQ
Affine Space of dimension 3 over Rational Field
sage: AQ.change_ring(GF(5))
Affine Space of dimension 3 over Finite Field of size 5
```

```
>>> from sage.all import *
>>> A = AffineSpace(Integer(3), ZZ, names=('x', 'y', 'z',)); (x, y, z,) = A._
↪first_ngens(3)
>>> AQ = A.change_ring(QQ); AQ
Affine Space of dimension 3 over Rational Field
>>> AQ.change_ring(GF(Integer(5)))
Affine Space of dimension 3 over Finite Field of size 5
```

```
sage: K.<w> = QuadraticField(5)                                                 #␣
↪needs sage.rings.number_field
sage: A = AffineSpace(K, 2, 't')                                                #␣
↪needs sage.rings.number_field
sage: A.change_ring(K.embeddings(CC)[1])                                        #␣
↪needs sage.rings.number_field
Affine Space of dimension 2 over Complex Field with 53 bits of precision
```

```
>>> from sage.all import *
>>> K = QuadraticField(Integer(5), names=('w',)); (w,) = K._first_ngens(1)#␣
↪needs sage.rings.number_field
>>> A = AffineSpace(K, Integer(2), 't')                                          ␣
↪     # needs sage.rings.number_field
>>> A.change_ring(K.embeddings(CC)[Integer(1)])                                  ␣
↪     # needs sage.rings.number_field
Affine Space of dimension 2 over Complex Field with 53 bits of precision
```

chebyshev_polynomial(*n*, *kind='first'*, *monic=False*)

Generate an endomorphism of this affine line by a Chebyshev polynomial.

Chebyshev polynomials are a sequence of recursively defined orthogonal polynomials. Chebyshev of the first kind are defined as $T_0(x) = 1$, $T_1(x) = x$, and $T_{n+1}(x) = 2xT_n(x) - T_{n-1}(x)$. Chebyshev of the second kind are defined as $U_0(x) = 1$, $U_1(x) = 2x$, and $U_{n+1}(x) = 2xU_n(x) - U_{n-1}(x)$.

INPUT:

- `n` – nonnegative integer
- `kind` – `'first'` (default) or `'second'` specifying which kind of Chebyshev the user would like to generate
- `monic` – boolean (default: `False`) specifying if the polynomial defining the system should be monic or not

OUTPUT: `DynamicalSystem_affine`

EXAMPLES:

```
sage: A.<x> = AffineSpace(QQ, 1)
sage: A.chebyshev_polynomial(5, 'first')                                    #␣
↪needs sage.schemes
Dynamical System of Affine Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x) to (16*x^5 - 20*x^3 + 5*x)
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(1), names=('x',)); (x,) = A._first_ngens(1)
>>> A.chebyshev_polynomial(Integer(5), 'first')                             ␣
↪     # needs sage.schemes
Dynamical System of Affine Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x) to (16*x^5 - 20*x^3 + 5*x)
```

```
sage: A.<x> = AffineSpace(QQ, 1)
sage: A.chebyshev_polynomial(3, 'second')                                   #␣
↪needs sage.schemes
Dynamical System of Affine Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x) to (8*x^3 - 4*x)
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(1), names=('x',)); (x,) = A._first_ngens(1)
>>> A.chebyshev_polynomial(Integer(3), 'second')                            ␣
↪     # needs sage.schemes
Dynamical System of Affine Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x) to (8*x^3 - 4*x)
```

```
sage: A.<x> = AffineSpace(QQ, 1)
sage: A.chebyshev_polynomial(3, 2)                                          #␣
↪needs sage.schemes
Traceback (most recent call last):
...
ValueError: keyword 'kind' must have a value of either 'first' or 'second'
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(1), names=('x',)); (x,) = A._first_ngens(1)
>>> A.chebyshev_polynomial(Integer(3), Integer(2))                          ␣
↪             # needs sage.schemes
```

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```
Traceback (most recent call last):
...
ValueError: keyword 'kind' must have a value of either 'first' or 'second'
```

```
sage: A.<x> = AffineSpace(QQ, 1)
sage: A.chebyshev_polynomial(-4, 'second')
Traceback (most recent call last):
...
ValueError: first parameter 'n' must be a nonnegative integer
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(1), names=('x',)); (x,) = A._first_ngens(1)
>>> A.chebyshev_polynomial(-Integer(4), 'second')
Traceback (most recent call last):
...
ValueError: first parameter 'n' must be a nonnegative integer
```

```
sage: A = AffineSpace(QQ, 2, 'x')
sage: A.chebyshev_polynomial(2)
Traceback (most recent call last):
...
TypeError: affine space must be of dimension 1
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(2), 'x')
>>> A.chebyshev_polynomial(Integer(2))
Traceback (most recent call last):
...
TypeError: affine space must be of dimension 1
```

```
sage: A.<x> = AffineSpace(QQ, 1)
sage: A.chebyshev_polynomial(7, monic=True)                                 #␣
↪needs sage.schemes
Dynamical System of Affine Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x) to (x^7 - 7*x^5 + 14*x^3 - 7*x)
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(1), names=('x',)); (x,) = A._first_ngens(1)
>>> A.chebyshev_polynomial(Integer(7), monic=True)                          ␣
↪     # needs sage.schemes
Dynamical System of Affine Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x) to (x^7 - 7*x^5 + 14*x^3 - 7*x)
```

```
sage: F.<t> = FunctionField(QQ)
sage: A.<x> = AffineSpace(F, 1)
sage: A.chebyshev_polynomial(4, monic=True)                                 #␣
↪needs sage.schemes
Dynamical System of Affine Space of dimension 1
over Rational function field in t over Rational Field
  Defn: Defined on coordinates by sending (x) to (x^4 + (-4)*x^2 + 2)
```

```
>>> from sage.all import *
>>> F = FunctionField(QQ, names=('t',)); (t,) = F._first_ngens(1)
>>> A = AffineSpace(F, Integer(1), names=('x',)); (x,) = A._first_ngens(1)
>>> A.chebyshev_polynomial(Integer(4), monic=True)
↪      # needs sage.schemes
Dynamical System of Affine Space of dimension 1
over Rational function field in t over Rational Field
  Defn: Defined on coordinates by sending (x) to (x^4 + (-4)*x^2 + 2)
```

coordinate_ring()

Return the coordinate ring of this scheme, if defined.

EXAMPLES:

```
sage: R = AffineSpace(2, GF(9,'alpha'), 'z').coordinate_ring(); R
↪needs sage.rings.finite_rings
Multivariate Polynomial Ring in z0, z1 over Finite Field in alpha of size 3^2
sage: AffineSpace(3, R, 'x').coordinate_ring()
↪needs sage.rings.finite_rings
Multivariate Polynomial Ring in x0, x1, x2 over Multivariate Polynomial Ring
in z0, z1 over Finite Field in alpha of size 3^2
```

```
>>> from sage.all import *
>>> R = AffineSpace(Integer(2), GF(Integer(9),'alpha'), 'z').coordinate_
↪ring(); R           # needs sage.rings.finite_rings
Multivariate Polynomial Ring in z0, z1 over Finite Field in alpha of size 3^2
>>> AffineSpace(Integer(3), R, 'x').coordinate_ring()
↪      # needs sage.rings.finite_rings
Multivariate Polynomial Ring in x0, x1, x2 over Multivariate Polynomial Ring
in z0, z1 over Finite Field in alpha of size 3^2
```

ngens()

Return the number of generators of `self`, i.e. the number of variables in the coordinate ring of `self`.

EXAMPLES:

```
sage: AffineSpace(3, QQ).ngens()
3
sage: AffineSpace(7, ZZ).ngens()
7
```

```
>>> from sage.all import *
>>> AffineSpace(Integer(3), QQ).ngens()
3
>>> AffineSpace(Integer(7), ZZ).ngens()
7
```

origin()

Return the rational point at the origin of this affine space.

EXAMPLES:

```
sage: A.<x,y,z> = AffineSpace(QQ, 3)
sage: A.origin()
```

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```
(0, 0, 0)
sage: _ == A(0,0,0)
True
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(3), names=('x', 'y', 'z',)); (x, y, z,) = A._
↪first_ngens(3)
>>> A.origin()
(0, 0, 0)
>>> _ == A(Integer(0),Integer(0),Integer(0))
True
```

projective_embedding(*i=None*, *PP=None*)

Return a morphism from this space into an ambient projective space of the same dimension.

INPUT:

- `i` – integer (default: dimension of self = last coordinate) determines which projective embedding to compute. The embedding is that which has a 1 in the i-th coordinate, numbered from 0.
- `PP` – (default: `None`) ambient projective space, i.e., codomain of morphism; this is constructed if it is not given.

EXAMPLES:

```
sage: AA = AffineSpace(2, QQ, 'x')
sage: pi = AA.projective_embedding(0); pi
Scheme morphism:
  From: Affine Space of dimension 2 over Rational Field
  To:   Projective Space of dimension 2 over Rational Field
  Defn: Defined on coordinates by sending (x0, x1) to (1 : x0 : x1)
sage: z = AA(3, 4)
sage: pi(z)
(1/4 : 3/4 : 1)
sage: pi(AA(0,2))
(1/2 : 0 : 1)
sage: pi = AA.projective_embedding(1); pi
Scheme morphism:
  From: Affine Space of dimension 2 over Rational Field
  To:   Projective Space of dimension 2 over Rational Field
  Defn: Defined on coordinates by sending (x0, x1) to (x0 : 1 : x1)
sage: pi(z)
(3/4 : 1/4 : 1)
sage: pi = AA.projective_embedding(2)
sage: pi(z)
(3 : 4 : 1)
```

```
>>> from sage.all import *
>>> AA = AffineSpace(Integer(2), QQ, 'x')
>>> pi = AA.projective_embedding(Integer(0)); pi
Scheme morphism:
  From: Affine Space of dimension 2 over Rational Field
  To:   Projective Space of dimension 2 over Rational Field
```

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```
  Defn: Defined on coordinates by sending (x0, x1) to (1 : x0 : x1)
>>> z = AA(Integer(3), Integer(4))
>>> pi(z)
(1/4 : 3/4 : 1)
>>> pi(AA(Integer(0),Integer(2)))
(1/2 : 0 : 1)
>>> pi = AA.projective_embedding(Integer(1)); pi
Scheme morphism:
  From: Affine Space of dimension 2 over Rational Field
  To:   Projective Space of dimension 2 over Rational Field
  Defn: Defined on coordinates by sending (x0, x1) to (x0 : 1 : x1)
>>> pi(z)
(3/4 : 1/4 : 1)
>>> pi = AA.projective_embedding(Integer(2))
>>> pi(z)
(3 : 4 : 1)
```

```
sage: A.<x,y> = AffineSpace(ZZ, 2)
sage: A.projective_embedding(2).codomain().affine_patch(2) == A
True
```

```
>>> from sage.all import *
>>> A = AffineSpace(ZZ, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> A.projective_embedding(Integer(2)).codomain().affine_patch(Integer(2)) ==␣
↪A
True
```

rational_points(*F=None*)

Return the list of `F`-rational points on the affine space `self`, where `F` is a given finite field, or the base ring of `self`.

EXAMPLES:

```
sage: A = AffineSpace(1, GF(3))
sage: A.rational_points()
[(0), (1), (2)]
sage: A.rational_points(GF(3^2, 'b'))                                    #␣
↪needs sage.rings.finite_rings
[(0), (b), (b + 1), (2*b + 1), (2), (2*b), (2*b + 2), (b + 2), (1)]

sage: AffineSpace(2, ZZ).rational_points(GF(2))
[(0, 0), (0, 1), (1, 0), (1, 1)]
```

```
>>> from sage.all import *
>>> A = AffineSpace(Integer(1), GF(Integer(3)))
>>> A.rational_points()
[(0), (1), (2)]
>>> A.rational_points(GF(Integer(3)**Integer(2), 'b'))                    ␣
↪              # needs sage.rings.finite_rings
[(0), (b), (b + 1), (2*b + 1), (2), (2*b), (2*b + 2), (b + 2), (1)]
```

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```
>>> AffineSpace(Integer(2), ZZ).rational_points(GF(Integer(2)))
[(0, 0), (0, 1), (1, 0), (1, 1)]
```

subscheme(*X*, ***kwds*)

Return the closed subscheme defined by X.

INPUT:

- X – list or tuple of equations

EXAMPLES:

```
sage: A.<x,y> = AffineSpace(QQ, 2)
sage: X = A.subscheme([x, y^2, x*y^2]); X
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  x,
  y^2,
  x*y^2
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> X = A.subscheme([x, y**Integer(2), x*y**Integer(2)]); X
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  x,
  y^2,
  x*y^2
```

```
sage: # needs sage.libs.singular
sage: X.defining_polynomials ()
(x, y^2, x*y^2)
sage: I = X.defining_ideal(); I
Ideal (x, y^2, x*y^2) of Multivariate Polynomial Ring in x, y over Rational␣
↪Field
sage: I.groebner_basis()
[y^2, x]
sage: X.dimension()
0
sage: X.base_ring()
Rational Field
sage: X.base_scheme()
Spectrum of Rational Field
sage: X.structure_morphism()
Scheme morphism:
  From: Closed subscheme of Affine Space of dimension 2 over Rational Field
        defined by: x, y^2, x*y^2
  To:   Spectrum of Rational Field
  Defn: Structure map
sage: X.dimension()
0
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> X.defining_polynomials ()
(x, y^2, x*y^2)
>>> I = X.defining_ideal(); I
Ideal (x, y^2, x*y^2) of Multivariate Polynomial Ring in x, y over Rational␣
↪Field
>>> I.groebner_basis()
[y^2, x]
>>> X.dimension()
0
>>> X.base_ring()
Rational Field
>>> X.base_scheme()
Spectrum of Rational Field
>>> X.structure_morphism()
Scheme morphism:
  From: Closed subscheme of Affine Space of dimension 2 over Rational Field
        defined by: x, y^2, x*y^2
  To:   Spectrum of Rational Field
  Defn: Structure map
>>> X.dimension()
0
```

sage.schemes.affine.affine_space.**is_AffineSpace**(*x*)

Return `True` if `x` is an affine space.

EXAMPLES:

```
sage: from sage.schemes.affine.affine_space import is_AffineSpace
sage: is_AffineSpace(AffineSpace(5, names='x'))
doctest:warning...
DeprecationWarning: The function is_AffineSpace is deprecated; use 'isinstance(...
↪, AffineSpace_generic)' instead.
See https://github.com/sagemath/sage/issues/38022 for details.
True
sage: is_AffineSpace(AffineSpace(5, GF(9, 'alpha'), names='x'))                #␣
↪needs sage.rings.finite_rings
True
sage: is_AffineSpace(Spec(ZZ))
False
```

```
>>> from sage.all import *
>>> from sage.schemes.affine.affine_space import is_AffineSpace
>>> is_AffineSpace(AffineSpace(Integer(5), names='x'))
doctest:warning...
DeprecationWarning: The function is_AffineSpace is deprecated; use 'isinstance(...
↪, AffineSpace_generic)' instead.
See https://github.com/sagemath/sage/issues/38022 for details.
True
>>> is_AffineSpace(AffineSpace(Integer(5), GF(Integer(9), 'alpha'), names='x'))  ␣
↪              # needs sage.rings.finite_rings
True
```

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```
>>> is_AffineSpace(Spec(ZZ))
False
```

13.2 Morphisms on affine schemes

This module implements morphisms from affine schemes. A morphism from an affine scheme to an affine scheme is determined by rational functions that define what the morphism does on points in the ambient affine space. A morphism from an affine scheme to a projective scheme is determined by homogeneous polynomials.

EXAMPLES:

```
sage: A2.<x,y> = AffineSpace(QQ, 2)
sage: P2.<x0,x1,x2> = ProjectiveSpace(QQ, 2)
sage: A2.hom([x, x + y], A2)
Scheme endomorphism of Affine Space of dimension 2 over Rational Field
  Defn: Defined on coordinates by sending (x, y) to (x, x + y)
sage: A2.hom([1, x, x + y], P2)
Scheme morphism:
  From: Affine Space of dimension 2 over Rational Field
  To:   Projective Space of dimension 2 over Rational Field
  Defn: Defined on coordinates by sending (x, y) to (1 : x : x + y)
```

```
>>> from sage.all import *
>>> A2 = AffineSpace(QQ, Integer(2), names=('x', 'y',)); (x, y,) = A2._first_ngens(2)
>>> P2 = ProjectiveSpace(QQ, Integer(2), names=('x0', 'x1', 'x2',)); (x0, x1, x2,) =␣
↪P2._first_ngens(3)
>>> A2.hom([x, x + y], A2)
Scheme endomorphism of Affine Space of dimension 2 over Rational Field
  Defn: Defined on coordinates by sending (x, y) to (x, x + y)
>>> A2.hom([Integer(1), x, x + y], P2)
Scheme morphism:
  From: Affine Space of dimension 2 over Rational Field
  To:   Projective Space of dimension 2 over Rational Field
  Defn: Defined on coordinates by sending (x, y) to (1 : x : x + y)
```

AUTHORS:

- David Kohel, William Stein: initial version
- Volker Braun (2011-08-08): renamed classes, more documentation, misc cleanups
- Ben Hutz (2013-03): iteration functionality and new directory structure for affine/projective
- Kwankyu Lee (2020-02): added indeterminacy_locus() and image()

class sage.schemes.affine.affine_morphism.**SchemeMorphism_polynomial_affine_space**(*parent*, *polys*, *check=True*)

Bases: *SchemeMorphism_polynomial*

A morphism of schemes determined by rational functions.

EXAMPLES:

```
sage: RA.<x,y> = QQ[]
sage: A2 = AffineSpace(RA)
sage: RP.<u,v,w> = QQ[]
sage: P2 = ProjectiveSpace(RP)
sage: H = A2.Hom(P2)
sage: f = H([x, y, 1])
sage: f
Scheme morphism:
  From: Affine Space of dimension 2 over Rational Field
  To:   Projective Space of dimension 2 over Rational Field
  Defn: Defined on coordinates by sending (x, y) to (x : y : 1)
```

```
>>> from sage.all import *
>>> RA = QQ['x, y']; (x, y,) = RA._first_ngens(2)
>>> A2 = AffineSpace(RA)
>>> RP = QQ['u, v, w']; (u, v, w,) = RP._first_ngens(3)
>>> P2 = ProjectiveSpace(RP)
>>> H = A2.Hom(P2)
>>> f = H([x, y, Integer(1)])
>>> f
Scheme morphism:
  From: Affine Space of dimension 2 over Rational Field
  To:   Projective Space of dimension 2 over Rational Field
  Defn: Defined on coordinates by sending (x, y) to (x : y : 1)
```

as_dynamical_system()

Return this endomorphism as a DynamicalSystem_affine.

OUTPUT: DynamicalSystem_affine

EXAMPLES:

```
sage: A.<x,y,z> = AffineSpace(ZZ, 3)
sage: H = End(A)
sage: f = H([x^2, y^2, z^2])
sage: type(f.as_dynamical_system())                                             #␣
↪needs sage.schemes
<class 'sage.dynamics.arithmetic_dynamics.affine_ds.DynamicalSystem_affine'>
```

```
>>> from sage.all import *
>>> A = AffineSpace(ZZ, Integer(3), names=('x', 'y', 'z',)); (x, y, z,) = A._
↪first_ngens(3)
>>> H = End(A)
>>> f = H([x**Integer(2), y**Integer(2), z**Integer(2)])
>>> type(f.as_dynamical_system())                                               #␣
↪needs sage.schemes
<class 'sage.dynamics.arithmetic_dynamics.affine_ds.DynamicalSystem_affine'>
```

```
sage: A.<x,y> = AffineSpace(ZZ, 2)
sage: H = End(A)
sage: f = H([x^2 - y^2, y^2])
sage: type(f.as_dynamical_system())                                             #␣
```

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```
↪needs sage.schemes
<class 'sage.dynamics.arithmetic_dynamics.affine_ds.DynamicalSystem_affine'>
```

```
>>> from sage.all import *
>>> A = AffineSpace(ZZ, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> H = End(A)
>>> f = H([x**Integer(2) - y**Integer(2), y**Integer(2)])
>>> type(f.as_dynamical_system())                                    #␣
↪needs sage.schemes
<class 'sage.dynamics.arithmetic_dynamics.affine_ds.DynamicalSystem_affine'>
```

```
sage: A.<x> = AffineSpace(GF(5), 1)
sage: H = End(A)
sage: f = H([x^2])
sage: type(f.as_dynamical_system())                                  #␣
↪needs sage.schemes
<class 'sage.dynamics.arithmetic_dynamics.affine_ds.DynamicalSystem_affine_
↪finite_field'>
```

```
>>> from sage.all import *
>>> A = AffineSpace(GF(Integer(5)), Integer(1), names=('x',)); (x,) = A._
↪first_ngens(1)
>>> H = End(A)
>>> f = H([x**Integer(2)])
>>> type(f.as_dynamical_system())                                    #␣
↪needs sage.schemes
<class 'sage.dynamics.arithmetic_dynamics.affine_ds.DynamicalSystem_affine_
↪finite_field'>
```

```
sage: P.<x,y> = AffineSpace(RR, 2)
sage: f = DynamicalSystem([x^2 + y^2, y^2], P)                       #␣
↪needs sage.schemes
sage: g = f.as_dynamical_system()                                    #␣
↪needs sage.schemes
sage: g is f                                                         #␣
↪needs sage.schemes
True
```

```
>>> from sage.all import *
>>> P = AffineSpace(RR, Integer(2), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> f = DynamicalSystem([x**Integer(2) + y**Integer(2), y**Integer(2)], P)  ␣
↪                            # needs sage.schemes
>>> g = f.as_dynamical_system()                                      #␣
↪needs sage.schemes
>>> g is f                                                           #␣
↪needs sage.schemes
True
```

degree()

Return the degree of the affine morphism.

EXAMPLES:

```
sage: R.<x> = AffineSpace(QQ, 1)
sage: H = Hom(R, R)
sage: f = H([x^7])
sage: f.degree()
7
```

```
>>> from sage.all import *
>>> R = AffineSpace(QQ, Integer(1), names=('x',)); (x,) = R._first_ngens(1)
>>> H = Hom(R, R)
>>> f = H([x**Integer(7)])
>>> f.degree()
7
```

```
sage: R.<x,y,z> = AffineSpace(QQ, 3)
sage: H = Hom(R, R)
sage: f = H([x^3, y^2 + 5, z^4 + y])
sage: f.degree()
4
```

```
>>> from sage.all import *
>>> R = AffineSpace(QQ, Integer(3), names=('x', 'y', 'z',)); (x, y, z,) = R._
↪first_ngens(3)
>>> H = Hom(R, R)
>>> f = H([x**Integer(3), y**Integer(2) + Integer(5), z**Integer(4) + y])
>>> f.degree()
4
```

global_height(*prec=None*)

Take the height of the homogenization, and return the global height of the coefficients as a projective point.

INPUT:

- `prec` – desired floating point precision (default: default RealField precision)

OUTPUT: a real number

EXAMPLES:

```
sage: A.<x> = AffineSpace(QQ, 1)
sage: H = Hom(A, A)
sage: f = H([1/1331*x^2 + 4000])
sage: f.global_height()                                                    #␣
↪needs sage.symbolic
15.4877354584971
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(1), names=('x',)); (x,) = A._first_ngens(1)
>>> H = Hom(A, A)
>>> f = H([Integer(1)/Integer(1331)*x**Integer(2) + Integer(4000)])
>>> f.global_height()                                                      #␣
```

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```
↪needs sage.symbolic
15.4877354584971
```

```
sage: # needs sage.rings.number_field
sage: R.<x> = PolynomialRing(QQ)
sage: k.<w> = NumberField(x^2 + 5)
sage: A.<x,y> = AffineSpace(k, 2)
sage: H = Hom(A, A)
sage: f = H([13*w*x^2 + 4*y, 1/w*y^2])
sage: f.global_height(prec=2)
4.0
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = PolynomialRing(QQ, names=('x',)); (x,) = R._first_ngens(1)
>>> k = NumberField(x**Integer(2) + Integer(5), names=('w',)); (w,) = k._
↪first_ngens(1)
>>> A = AffineSpace(k, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> H = Hom(A, A)
>>> f = H([Integer(13)*w*x**Integer(2) + Integer(4)*y, Integer(1)/
↪w*y**Integer(2)])
>>> f.global_height(prec=Integer(2))
4.0
```

```
sage: A.<x> = AffineSpace(ZZ, 1)
sage: H = Hom(A, A)
sage: f = H([7*x^2 + 1513])
sage: f.global_height()                                                    #␣
↪needs sage.symbolic
7.32184971378836
```

```
>>> from sage.all import *
>>> A = AffineSpace(ZZ, Integer(1), names=('x',)); (x,) = A._first_ngens(1)
>>> H = Hom(A, A)
>>> f = H([Integer(7)*x**Integer(2) + Integer(1513)])
>>> f.global_height()                                                      #␣
↪needs sage.symbolic
7.32184971378836
```

```
sage: A.<x> = AffineSpace(QQ, 1)
sage: B.<y,z> = AffineSpace(QQ, 2)
sage: H = Hom(A, B)
sage: f = H([1/3*x^2 + 10, 7*x^3])
sage: f.global_height()                                                    #␣
↪needs sage.symbolic
3.40119738166216
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(1), names=('x',)); (x,) = A._first_ngens(1)
```

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```
>>> B = AffineSpace(QQ, Integer(2), names=('y', 'z',)); (y, z,) = B._first_
↪ngens(2)
>>> H = Hom(A, B)
>>> f = H([Integer(1)/Integer(3)*x**Integer(2) + Integer(10),␣
↪Integer(7)*x**Integer(3)])
>>> f.global_height()                                                    #␣
↪needs sage.symbolic
3.40119738166216
```

```
sage: P.<x,y> = AffineSpace(QQ, 2)
sage: A.<z> = AffineSpace(QQ, 1)
sage: H = Hom(P, A)
sage: f = H([1/1331*x^2 + 4000*y])
sage: f.global_height()                                                 #␣
↪needs sage.symbolic
15.4877354584971
```

```
>>> from sage.all import *
>>> P = AffineSpace(QQ, Integer(2), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> A = AffineSpace(QQ, Integer(1), names=('z',)); (z,) = A._first_ngens(1)
>>> H = Hom(P, A)
>>> f = H([Integer(1)/Integer(1331)*x**Integer(2) + Integer(4000)*y])
>>> f.global_height()                                                    #␣
↪needs sage.symbolic
15.4877354584971
```

homogenize(*n*)

Return the homogenization of this map.

If it's domain is a subscheme, the domain of the homogenized map is the projective embedding of the domain. The domain and codomain can be homogenized at different coordinates: `n[0]` for the domain and `n[1]` for the codomain.

INPUT:

- `n` – tuple of nonnegative integers; if `n` is an integer, then the two values of the tuple are assumed to be the same

OUTPUT: a morphism from the projective embedding of the domain of this map

EXAMPLES:

```
sage: A.<x,y> = AffineSpace(ZZ, 2)
sage: H = Hom(A, A)
sage: f = H([(x^2-2)/x^5, y^2])
sage: f.homogenize(2)
Scheme endomorphism of Projective Space of dimension 2 over Integer Ring
  Defn: Defined on coordinates by sending (x0 : x1 : x2) to
        (x0^2*x2^5 - 2*x2^7 : x0^5*x1^2 : x0^5*x2^2)
```

```
>>> from sage.all import *
>>> A = AffineSpace(ZZ, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
```

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```
>>> H = Hom(A, A)
>>> f = H([(x**Integer(2)-Integer(2))/x**Integer(5), y**Integer(2)])
>>> f.homogenize(Integer(2))
Scheme endomorphism of Projective Space of dimension 2 over Integer Ring
  Defn: Defined on coordinates by sending (x0 : x1 : x2) to
        (x0^2*x2^5 - 2*x2^7 : x0^5*x1^2 : x0^5*x2^2)
```

```
sage: # needs sage.rings.real_mpfr
sage: A.<x,y> = AffineSpace(CC, 2)
sage: H = Hom(A, A)
sage: f = H([(x^2-2)/(x*y), y^2 - x])
sage: f.homogenize((2, 0))
Scheme endomorphism of Projective Space of dimension 2
 over Complex Field with 53 bits of precision
  Defn: Defined on coordinates by sending (x0 : x1 : x2) to
        (x0*x1*x2^2 : x0^2*x2^2 + (-2.00000000000000)*x2^4 : x0*x1^3 - x0^
↪2*x1*x2)
```

```
>>> from sage.all import *
>>> # needs sage.rings.real_mpfr
>>> A = AffineSpace(CC, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> H = Hom(A, A)
>>> f = H([(x**Integer(2)-Integer(2))/(x*y), y**Integer(2) - x])
>>> f.homogenize((Integer(2), Integer(0)))
Scheme endomorphism of Projective Space of dimension 2
 over Complex Field with 53 bits of precision
  Defn: Defined on coordinates by sending (x0 : x1 : x2) to
        (x0*x1*x2^2 : x0^2*x2^2 + (-2.00000000000000)*x2^4 : x0*x1^3 - x0^
↪2*x1*x2)
```

```
sage: A.<x,y> = AffineSpace(ZZ, 2)
sage: X = A.subscheme([x - y^2])
sage: H = Hom(X, X)
sage: f = H([9*y^2, 3*y])
sage: f.homogenize(2)                                                    #␣
↪needs sage.libs.singular
Scheme endomorphism of Closed subscheme of Projective Space
 of dimension 2 over Integer Ring defined by: x1^2 - x0*x2
  Defn: Defined on coordinates by sending (x0 : x1 : x2) to
        (9*x1^2 : 3*x1*x2 : x2^2)
```

```
>>> from sage.all import *
>>> A = AffineSpace(ZZ, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> X = A.subscheme([x - y**Integer(2)])
>>> H = Hom(X, X)
>>> f = H([Integer(9)*y**Integer(2), Integer(3)*y])
>>> f.homogenize(Integer(2))                                             ␣
↪     # needs sage.libs.singular
Scheme endomorphism of Closed subscheme of Projective Space
```

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```
 of dimension 2 over Integer Ring defined by: x1^2 - x0*x2
  Defn: Defined on coordinates by sending (x0 : x1 : x2) to
        (9*x1^2 : 3*x1*x2 : x2^2)
```

```
sage: R.<t> = PolynomialRing(ZZ)
sage: A.<x,y> = AffineSpace(R, 2)
sage: H = Hom(A, A)
sage: f = H([(x^2-2)/y, y^2 - x])
sage: f.homogenize((2, 0))
Scheme endomorphism of Projective Space of dimension 2
 over Univariate Polynomial Ring in t over Integer Ring
  Defn: Defined on coordinates by sending (x0 : x1 : x2) to
        (x1*x2^2 : x0^2*x2 + (-2)*x2^3 : x1^3 - x0*x1*x2)
```

```
>>> from sage.all import *
>>> R = PolynomialRing(ZZ, names=('t',)); (t,) = R._first_ngens(1)
>>> A = AffineSpace(R, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> H = Hom(A, A)
>>> f = H([(x**Integer(2)-Integer(2))/y, y**Integer(2) - x])
>>> f.homogenize((Integer(2), Integer(0)))
Scheme endomorphism of Projective Space of dimension 2
 over Univariate Polynomial Ring in t over Integer Ring
  Defn: Defined on coordinates by sending (x0 : x1 : x2) to
        (x1*x2^2 : x0^2*x2 + (-2)*x2^3 : x1^3 - x0*x1*x2)
```

```
sage: A.<x> = AffineSpace(QQ, 1)
sage: H = End(A)
sage: f = H([x^2 - 1])
sage: f.homogenize((1, 0))
Scheme endomorphism of Projective Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x0 : x1) to
        (x1^2 : x0^2 - x1^2)
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(1), names=('x',)); (x,) = A._first_ngens(1)
>>> H = End(A)
>>> f = H([x**Integer(2) - Integer(1)])
>>> f.homogenize((Integer(1), Integer(0)))
Scheme endomorphism of Projective Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x0 : x1) to
        (x1^2 : x0^2 - x1^2)
```

```
sage: # needs sage.rings.number_field
sage: R.<a> = PolynomialRing(QQbar)
sage: A.<x,y> = AffineSpace(R, 2)
sage: H = End(A)
sage: f = H([QQbar(sqrt(2))*x*y, a*x^2])                                    #␣
↪needs sage.symbolic
sage: f.homogenize(2)                                                       #␣
↪needs sage.libs.singular sage.symbolic
```

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```
Scheme endomorphism of Projective Space of dimension 2
 over Univariate Polynomial Ring in a over Algebraic Field
  Defn: Defined on coordinates by sending (x0 : x1 : x2) to
        (1.414213562373095?*x0*x1 : a*x0^2 : x2^2)
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = PolynomialRing(QQbar, names=('a',)); (a,) = R._first_ngens(1)
>>> A = AffineSpace(R, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> H = End(A)
>>> f = H([QQbar(sqrt(Integer(2)))*x*y, a*x**Integer(2)])                ␣
↪               # needs sage.symbolic
>>> f.homogenize(Integer(2))                                             ␣
↪     # needs sage.libs.singular sage.symbolic
Scheme endomorphism of Projective Space of dimension 2
 over Univariate Polynomial Ring in a over Algebraic Field
  Defn: Defined on coordinates by sending (x0 : x1 : x2) to
        (1.414213562373095?*x0*x1 : a*x0^2 : x2^2)
```

```
sage: P.<x,y,z> = AffineSpace(QQ, 3)
sage: H = End(P)
sage: f = H([x^2 - 2*x*y + z*x, z^2 -y^2 , 5*z*y])
sage: f.homogenize(2).dehomogenize(2) == f
True
```

```
>>> from sage.all import *
>>> P = AffineSpace(QQ, Integer(3), names=('x', 'y', 'z',)); (x, y, z,) = P._
↪first_ngens(3)
>>> H = End(P)
>>> f = H([x**Integer(2) - Integer(2)*x*y + z*x, z**Integer(2) -y**Integer(2)␣
↪, Integer(5)*z*y])
>>> f.homogenize(Integer(2)).dehomogenize(Integer(2)) == f
True
```

```
sage: K.<c> = FunctionField(QQ)
sage: A.<x> = AffineSpace(K, 1)
sage: f = Hom(A, A)([x^2 + c])
sage: f.homogenize(1)
Scheme endomorphism of Projective Space of dimension 1
 over Rational function field in c over Rational Field
  Defn: Defined on coordinates by sending (x0 : x1) to
        (x0^2 + c*x1^2 : x1^2)
```

```
>>> from sage.all import *
>>> K = FunctionField(QQ, names=('c',)); (c,) = K._first_ngens(1)
>>> A = AffineSpace(K, Integer(1), names=('x',)); (x,) = A._first_ngens(1)
>>> f = Hom(A, A)([x**Integer(2) + c])
>>> f.homogenize(Integer(1))
Scheme endomorphism of Projective Space of dimension 1
 over Rational function field in c over Rational Field
```

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```
  Defn: Defined on coordinates by sending (x0 : x1) to
        (x0^2 + c*x1^2 : x1^2)
```

```
sage: # needs sage.rings.number_field
sage: A.<z> = AffineSpace(QQbar, 1)
sage: H = End(A)
sage: f = H([2*z / (z^2 + 2*z + 3)])
sage: f.homogenize(1)
Scheme endomorphism of Projective Space of dimension 1
 over Algebraic Field
  Defn: Defined on coordinates by sending (x0 : x1) to
        (2*x0*x1 : x0^2 + 2*x0*x1 + 3*x1^2)
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> A = AffineSpace(QQbar, Integer(1), names=('z',)); (z,) = A._first_ngens(1)
>>> H = End(A)
>>> f = H([Integer(2)*z / (z**Integer(2) + Integer(2)*z + Integer(3))])
>>> f.homogenize(Integer(1))
Scheme endomorphism of Projective Space of dimension 1
 over Algebraic Field
  Defn: Defined on coordinates by sending (x0 : x1) to
        (2*x0*x1 : x0^2 + 2*x0*x1 + 3*x1^2)
```

```
sage: # needs sage.rings.number_field
sage: R.<c,d> = QQbar[]
sage: A.<x> = AffineSpace(R, 1)
sage: H = Hom(A, A)
sage: F = H([d*x^2 + c])
sage: F.homogenize(1)
Scheme endomorphism of Projective Space of dimension 1
 over Multivariate Polynomial Ring in c, d over Algebraic Field
  Defn: Defined on coordinates by sending (x0 : x1) to
        (d*x0^2 + c*x1^2 : x1^2)
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = QQbar['c, d']; (c, d,) = R._first_ngens(2)
>>> A = AffineSpace(R, Integer(1), names=('x',)); (x,) = A._first_ngens(1)
>>> H = Hom(A, A)
>>> F = H([d*x**Integer(2) + c])
>>> F.homogenize(Integer(1))
Scheme endomorphism of Projective Space of dimension 1
 over Multivariate Polynomial Ring in c, d over Algebraic Field
  Defn: Defined on coordinates by sending (x0 : x1) to
        (d*x0^2 + c*x1^2 : x1^2)
```

jacobian()

Return the Jacobian matrix of partial derivative of this map.

The (i, j) entry of the Jacobian matrix is the partial derivative `diff(functions[i], variables[j])`.

OUTPUT: matrix with coordinates in the coordinate ring of the map

EXAMPLES:

```
sage: A.<z> = AffineSpace(QQ, 1)
sage: H = End(A)
sage: f = H([z^2 - 3/4])
sage: f.jacobian()                                                          #␣
↪needs sage.modules
[2*z]
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(1), names=('z',)); (z,) = A._first_ngens(1)
>>> H = End(A)
>>> f = H([z**Integer(2) - Integer(3)/Integer(4)])
>>> f.jacobian()                                                            #␣
↪needs sage.modules
[2*z]
```

```
sage: A.<x,y> = AffineSpace(QQ, 2)
sage: H = End(A)
sage: f = H([x^3 - 25*x + 12*y, 5*y^2*x - 53*y + 24])
sage: f.jacobian()                                                          #␣
↪needs sage.modules
[ 3*x^2 - 25          12]
[      5*y^2 10*x*y - 53]
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> H = End(A)
>>> f = H([x**Integer(3) - Integer(25)*x + Integer(12)*y,␣
↪Integer(5)*y**Integer(2)*x - Integer(53)*y + Integer(24)])
>>> f.jacobian()                                                            #␣
↪needs sage.modules
[ 3*x^2 - 25          12]
[      5*y^2 10*x*y - 53]
```

```
sage: A.<x,y> = AffineSpace(ZZ, 2)
sage: H = End(A)
sage: f = H([(x^2 - x*y)/(1+y), (5+y)/(2+x)])
sage: f.jacobian()                                                          #␣
↪needs sage.modules
[          (2*x - y)/(y + 1) (-x^2 - x)/(y^2 + 2*y + 1)]
[  (-y - 5)/(x^2 + 4*x + 4)                   1/(x + 2)]
```

```
>>> from sage.all import *
>>> A = AffineSpace(ZZ, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> H = End(A)
>>> f = H([(x**Integer(2) - x*y)/(Integer(1)+y), (Integer(5)+y)/
↪(Integer(2)+x)])
>>> f.jacobian()                                                            #␣
↪needs sage.modules
```

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```
[          (2*x - y)/(y + 1)  (-x^2 - x)/(y^2 + 2*y + 1)]
[   (-y - 5)/(x^2 + 4*x + 4)                    1/(x + 2)]
```

local_height(*v*, *prec=None*)

Return the maximum of the local heights of the coefficients in any of the coordinate functions of this map.

INPUT:

- `v` – a prime or prime ideal of the base ring
- `prec` – desired floating point precision (default: default RealField precision)

OUTPUT: a real number

EXAMPLES:

```
sage: P.<x,y> = AffineSpace(QQ, 2)
sage: H = Hom(P, P)
sage: f = H([1/1331*x^2 + 1/4000*y^2, 210*x*y])
sage: f.local_height(1331)                                                  #␣
↪needs sage.rings.real_mpfr
7.19368581839511
```

```
>>> from sage.all import *
>>> P = AffineSpace(QQ, Integer(2), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> H = Hom(P, P)
>>> f = H([Integer(1)/Integer(1331)*x**Integer(2) + Integer(1)/
↪Integer(4000)*y**Integer(2), Integer(210)*x*y])
>>> f.local_height(Integer(1331))                                           ␣
↪     # needs sage.rings.real_mpfr
7.19368581839511
```

```
sage: P.<x,y,z> = AffineSpace(QQ, 3)
sage: H = Hom(P, P)
sage: f = H([4*x^2 + 3/100*y^2, 8/210*x*y, 1/10000*z^2])
sage: f.local_height(2)                                                     #␣
↪needs sage.rings.real_mpfr
2.77258872223978
```

```
>>> from sage.all import *
>>> P = AffineSpace(QQ, Integer(3), names=('x', 'y', 'z',)); (x, y, z,) = P._
↪first_ngens(3)
>>> H = Hom(P, P)
>>> f = H([Integer(4)*x**Integer(2) + Integer(3)/Integer(100)*y**Integer(2),␣
↪Integer(8)/Integer(210)*x*y, Integer(1)/Integer(10000)*z**Integer(2)])
>>> f.local_height(Integer(2))                                              ␣
↪     # needs sage.rings.real_mpfr
2.77258872223978
```

```
sage: P.<x,y,z> = AffineSpace(QQ, 3)
sage: H = Hom(P, P)
sage: f = H([4*x^2 + 3/100*y^2, 8/210*x*y, 1/10000*z^2])
```

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```
sage: f.local_height(2, prec=2)                                                 #␣
↪needs sage.rings.real_mpfr
3.0
```

```
>>> from sage.all import *
>>> P = AffineSpace(QQ, Integer(3), names=('x', 'y', 'z',)); (x, y, z,) = P._
↪first_ngens(3)
>>> H = Hom(P, P)
>>> f = H([Integer(4)*x**Integer(2) + Integer(3)/Integer(100)*y**Integer(2),␣
↪Integer(8)/Integer(210)*x*y, Integer(1)/Integer(10000)*z**Integer(2)])
>>> f.local_height(Integer(2), prec=Integer(2))                                 ␣
↪              # needs sage.rings.real_mpfr
3.0
```

```
sage: # needs sage.rings.number_field
sage: R.<z> = PolynomialRing(QQ)
sage: K.<w> = NumberField(z^2 - 2)
sage: P.<x,y> = AffineSpace(K, 2)
sage: H = Hom(P, P)
sage: f = H([2*x^2 + w/3*y^2, 1/w*y^2])
sage: f.local_height(K.ideal(3))
1.09861228866811
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = PolynomialRing(QQ, names=('z',)); (z,) = R._first_ngens(1)
>>> K = NumberField(z**Integer(2) - Integer(2), names=('w',)); (w,) = K._
↪first_ngens(1)
>>> P = AffineSpace(K, Integer(2), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> H = Hom(P, P)
>>> f = H([Integer(2)*x**Integer(2) + w/Integer(3)*y**Integer(2), Integer(1)/
↪w*y**Integer(2)])
>>> f.local_height(K.ideal(Integer(3)))
1.09861228866811
```

local_height_arch(*i*, *prec=None*)

Return the maximum of the local height at the `i`-th infinite place of the coefficients in any of the coordinate functions of this map.

INPUT:

- `i` – integer
- `prec` – desired floating point precision (default: default RealField precision)

OUTPUT: a real number

EXAMPLES:

```
sage: P.<x,y> = AffineSpace(QQ, 2)
sage: H = Hom(P, P)
sage: f = H([1/1331*x^2 + 1/4000*y^2, 210*x*y]);
sage: f.local_height_arch(0)                                                    #␣
```

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```
↪needs sage.rings.real_mpfr
5.34710753071747
```

```
>>> from sage.all import *
>>> P = AffineSpace(QQ, Integer(2), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> H = Hom(P, P)
>>> f = H([Integer(1)/Integer(1331)*x**Integer(2) + Integer(1)/
↪Integer(4000)*y**Integer(2), Integer(210)*x*y]);
>>> f.local_height_arch(Integer(0))                                    ␣
↪     # needs sage.rings.real_mpfr
5.34710753071747
```

```
sage: P.<x,y> = AffineSpace(QQ, 2)
sage: H = Hom(P, P)
sage: f = H([1/1331*x^2 + 1/4000*y^2, 210*x*y]);
sage: f.local_height_arch(0, prec=5)                                   #␣
↪needs sage.rings.real_mpfr
5.2
```

```
>>> from sage.all import *
>>> P = AffineSpace(QQ, Integer(2), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> H = Hom(P, P)
>>> f = H([Integer(1)/Integer(1331)*x**Integer(2) + Integer(1)/
↪Integer(4000)*y**Integer(2), Integer(210)*x*y]);
>>> f.local_height_arch(Integer(0), prec=Integer(5))                   ␣
↪              # needs sage.rings.real_mpfr
5.2
```

```
sage: # needs sage.rings.number_field
sage: R.<z> = PolynomialRing(QQ)
sage: K.<w> = NumberField(z^2 - 2)
sage: P.<x,y> = AffineSpace(K, 2)
sage: H = Hom(P, P)
sage: f = H([2*x^2 + w/3*y^2, 1/w*y^2])
sage: f.local_height_arch(1)
0.69314718055994530941723212145820
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = PolynomialRing(QQ, names=('z',)); (z,) = R._first_ngens(1)
>>> K = NumberField(z**Integer(2) - Integer(2), names=('w',)); (w,) = K._
↪first_ngens(1)
>>> P = AffineSpace(K, Integer(2), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> H = Hom(P, P)
>>> f = H([Integer(2)*x**Integer(2) + w/Integer(3)*y**Integer(2), Integer(1)/
↪w*y**Integer(2)])
>>> f.local_height_arch(Integer(1))
0.69314718055994530941723212145820
```

class sage.schemes.affine.affine_morphism.**SchemeMorphism_polynomial_affine_space_field**(*parent*, *polys*, *check=True*)

Bases: *SchemeMorphism_polynomial_affine_space*

image()

Return the scheme-theoretic image of the morphism.

OUTPUT: a subscheme of the ambient space of the codomain

EXAMPLES:

```
sage: # needs sage.libs.singular
sage: A1.<w> = AffineSpace(QQ, 1)
sage: A2.<x,y> = AffineSpace(QQ, 2)
sage: f = A2.hom([x + y], A1)
sage: f.image()
Closed subscheme of Affine Space of dimension 1 over Rational Field defined␣
↪by:
  (no polynomials)
sage: f = A2.hom([x, x], A2)
sage: f.image()
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  x - y
sage: f = A2.hom([x^2, x^3], A2)
sage: f.image()
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  x^3 - y^2
sage: P2.<x0,x1,x2> = ProjectiveSpace(QQ, 2)
sage: f = A2.hom([x, x^2, x^3], P2)
sage: f.image()
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  x1^2 - x0*x2
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> A1 = AffineSpace(QQ, Integer(1), names=('w',)); (w,) = A1._first_ngens(1)
>>> A2 = AffineSpace(QQ, Integer(2), names=('x', 'y',)); (x, y,) = A2._first_
↪ngens(2)
>>> f = A2.hom([x + y], A1)
>>> f.image()
Closed subscheme of Affine Space of dimension 1 over Rational Field defined␣
↪by:
  (no polynomials)
>>> f = A2.hom([x, x], A2)
>>> f.image()
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  x - y
>>> f = A2.hom([x**Integer(2), x**Integer(3)], A2)
```

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```
>>> f.image()
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  x^3 - y^2
>>> P2 = ProjectiveSpace(QQ, Integer(2), names=('x0', 'x1', 'x2',)); (x0, x1,␣
↪x2,) = P2._first_ngens(3)
>>> f = A2.hom([x, x**Integer(2), x**Integer(3)], P2)
>>> f.image()
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  x1^2 - x0*x2
```

indeterminacy_locus()

Return the indeterminacy locus of this map as a rational map on the domain.

The indeterminacy locus is the intersection of all the base indeterminacy locuses of maps that define the same rational map as by this map.

OUTPUT: a subscheme of the domain of the map

EXAMPLES:

```
sage: A.<x,y> = AffineSpace(QQ, 2)
sage: H = End(A)
sage: f = H([x - y, x^2 - y^2])
sage: f.indeterminacy_locus()                                                #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  1
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> H = End(A)
>>> f = H([x - y, x**Integer(2) - y**Integer(2)])
>>> f.indeterminacy_locus()                                                  #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  1
```

```
sage: A.<x,y> = AffineSpace(QQ, 2)
sage: f = A.hom([x, x/y], A)
sage: f.indeterminacy_locus()                                                #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  y
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
```

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```
>>> f = A.hom([x, x/y], A)
>>> f.indeterminacy_locus()                                                    #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  y
```

indeterminacy_points(*F=None*)

Return the points in the indeterminacy locus of this map.

If the dimension of the indeterminacy locus is not zero, an error is raised.

INPUT:

- `F` – a field; if not given, the base ring of the domain is assumed

OUTPUT: indeterminacy points of the map defined over `F`

EXAMPLES:

```
sage: A.<x,y> = AffineSpace(QQ, 2)
sage: H = End(A)
sage: f = H([x - y, x^2 - y^2])
sage: f.indeterminacy_points()                                              #␣
↪needs sage.libs.singular
[]
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> H = End(A)
>>> f = H([x - y, x**Integer(2) - y**Integer(2)])
>>> f.indeterminacy_points()                                                  #␣
↪needs sage.libs.singular
[]
```

```
sage: A2.<x,y> = AffineSpace(QQ, 2)
sage: P2.<x0,x1,x2> = ProjectiveSpace(QQ, 2)
sage: f = A2.hom([x*y, y, x], P2)
sage: f.indeterminacy_points()                                              #␣
↪needs sage.libs.singular
[(0, 0)]
```

```
>>> from sage.all import *
>>> A2 = AffineSpace(QQ, Integer(2), names=('x', 'y',)); (x, y,) = A2._first_
↪ngens(2)
>>> P2 = ProjectiveSpace(QQ, Integer(2), names=('x0', 'x1', 'x2',)); (x0, x1,␣
↪x2,) = P2._first_ngens(3)
>>> f = A2.hom([x*y, y, x], P2)
>>> f.indeterminacy_points()                                                  #␣
↪needs sage.libs.singular
[(0, 0)]
```

reduce_base_field()

Return this map defined over the field of definition of the coefficients.

The base field of the map could be strictly larger than the field where all of the coefficients are defined. This function reduces the base field to the minimal possible. This can be done when the base ring is a number field, QQbar, a finite field, or algebraic closure of a finite field.

OUTPUT: a scheme morphism

EXAMPLES:

```
sage: # needs sage.rings.finite_rings
sage: K.<t> = GF(5^4)
sage: A.<x> = AffineSpace(K, 1)
sage: A2.<a,b> = AffineSpace(K, 2)
sage: H = End(A)
sage: H2 = Hom(A, A2)
sage: H3 = Hom(A2, A)
sage: f = H([x^2 + 2*(t^3 + t^2 + t + 3)])
sage: f.reduce_base_field()
Scheme endomorphism of Affine Space of dimension 1
 over Finite Field in t2 of size 5^2
  Defn: Defined on coordinates by sending (x) to (x^2 + (2*t2))
sage: f2 = H2([x^2 + 4, 2*x])
sage: f2.reduce_base_field()
Scheme morphism:
  From: Affine Space of dimension 1 over Finite Field of size 5
  To:   Affine Space of dimension 2 over Finite Field of size 5
  Defn: Defined on coordinates by sending (x) to (x^2 - 1, 2*x)
sage: f3 = H3([a^2 + t*b])
sage: f3.reduce_base_field()
Scheme morphism:
  From: Affine Space of dimension 2 over Finite Field in t of size 5^4
  To:   Affine Space of dimension 1 over Finite Field in t of size 5^4
  Defn: Defined on coordinates by sending (a, b) to (a^2 + t*b)
```

```
>>> from sage.all import *
>>> # needs sage.rings.finite_rings
>>> K = GF(Integer(5)**Integer(4), names=('t',)); (t,) = K._first_ngens(1)
>>> A = AffineSpace(K, Integer(1), names=('x',)); (x,) = A._first_ngens(1)
>>> A2 = AffineSpace(K, Integer(2), names=('a', 'b',)); (a, b,) = A2._first_
↪ngens(2)
>>> H = End(A)
>>> H2 = Hom(A, A2)
>>> H3 = Hom(A2, A)
>>> f = H([x**Integer(2) + Integer(2)*(t**Integer(3) + t**Integer(2) + t +␣
↪Integer(3))])
>>> f.reduce_base_field()
Scheme endomorphism of Affine Space of dimension 1
 over Finite Field in t2 of size 5^2
  Defn: Defined on coordinates by sending (x) to (x^2 + (2*t2))
>>> f2 = H2([x**Integer(2) + Integer(4), Integer(2)*x])
>>> f2.reduce_base_field()
Scheme morphism:
  From: Affine Space of dimension 1 over Finite Field of size 5
```

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```
  To:   Affine Space of dimension 2 over Finite Field of size 5
  Defn: Defined on coordinates by sending (x) to (x^2 - 1, 2*x)
>>> f3 = H3([a**Integer(2) + t*b])
>>> f3.reduce_base_field()
Scheme morphism:
  From: Affine Space of dimension 2 over Finite Field in t of size 5^4
  To:   Affine Space of dimension 1 over Finite Field in t of size 5^4
  Defn: Defined on coordinates by sending (a, b) to (a^2 + t*b)
```

```
sage: # needs sage.rings.number_field
sage: K.<v> = CyclotomicField(4)
sage: A.<x> = AffineSpace(K, 1)
sage: H = End(A)
sage: f = H([x^2 + v])
sage: g = f.reduce_base_field(); g
Scheme endomorphism of Affine Space of dimension 1
 over Cyclotomic Field of order 4 and degree 2
  Defn: Defined on coordinates by sending (x) to (x^2 + v)
sage: g.base_ring() is K
True
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> K = CyclotomicField(Integer(4), names=('v',)); (v,) = K._first_ngens(1)
>>> A = AffineSpace(K, Integer(1), names=('x',)); (x,) = A._first_ngens(1)
>>> H = End(A)
>>> f = H([x**Integer(2) + v])
>>> g = f.reduce_base_field(); g
Scheme endomorphism of Affine Space of dimension 1
 over Cyclotomic Field of order 4 and degree 2
  Defn: Defined on coordinates by sending (x) to (x^2 + v)
>>> g.base_ring() is K
True
```

```
sage: # needs sage.rings.number_field
sage: A.<x> = AffineSpace(QQbar, 1)
sage: H = End(A)
sage: f = H([(QQbar(sqrt(2))*x^2 + 1/QQbar(sqrt(3))) / (5*x)])              #␣
↪needs sage.symbolic
sage: f.reduce_base_field()                                                 #␣
↪needs sage.symbolic
Scheme endomorphism of Affine Space of dimension 1 over Number Field in a
 with defining polynomial y^4 - 4*y^2 + 1 with a = ...?
  Defn: Defined on coordinates by sending (x) to
        (((a^3 - 3*a)*x^2 + (-1/3*a^2 + 2/3))/(5*x))
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> A = AffineSpace(QQbar, Integer(1), names=('x',)); (x,) = A._first_ngens(1)
>>> H = End(A)
>>> f = H([(QQbar(sqrt(Integer(2)))*x**Integer(2) + Integer(1)/
```

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```
↪QQbar(sqrt(Integer(3)))) / (Integer(5)*x)])              # needs sage.
↪symbolic
>>> f.reduce_base_field()                                                #␣
↪needs sage.symbolic
Scheme endomorphism of Affine Space of dimension 1 over Number Field in a
 with defining polynomial y^4 - 4*y^2 + 1 with a = ...?
  Defn: Defined on coordinates by sending (x) to
        (((a^3 - 3*a)*x^2 + (-1/3*a^2 + 2/3))/(5*x))
```

```
sage: # needs sage.rings.number_field
sage: R.<x> = PolynomialRing(QQ)
sage: A.<x> = AffineSpace(QQbar, 1)
sage: H = End(A)
sage: f = H([QQbar(3^(1/3))*x^2 + QQbar(sqrt(-2))])                    #␣
↪needs sage.symbolic
sage: f.reduce_base_field()                                            #␣
↪needs sage.symbolic
Scheme endomorphism of Affine Space of dimension 1 over Number Field in a␣
↪with defining polynomial y^6 + 6*y^4 - 6*y^3 + 12*y^2 + 36*y + 17 with a =␣
↪1.442249570307409? - 1.414213562373095?*I
  Defn: Defined on coordinates by sending (x) to
        ((-48/269*a^5 + 27/269*a^4 - 320/269*a^3 + 468/269*a^2 - 772/269*a
        - 1092/269)*x^2 + (-48/269*a^5 + 27/269*a^4 - 320/269*a^3 + 468/269*a^
↪2
        - 1041/269*a - 1092/269))
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = PolynomialRing(QQ, names=('x',)); (x,) = R._first_ngens(1)
>>> A = AffineSpace(QQbar, Integer(1), names=('x',)); (x,) = A._first_ngens(1)
>>> H = End(A)
>>> f = H([QQbar(Integer(3)**(Integer(1)/Integer(3)))*x**Integer(2) +␣
↪QQbar(sqrt(-Integer(2)))])                          # needs sage.symbolic
>>> f.reduce_base_field()                                                #␣
↪needs sage.symbolic
Scheme endomorphism of Affine Space of dimension 1 over Number Field in a␣
↪with defining polynomial y^6 + 6*y^4 - 6*y^3 + 12*y^2 + 36*y + 17 with a =␣
↪1.442249570307409? - 1.414213562373095?*I
  Defn: Defined on coordinates by sending (x) to
        ((-48/269*a^5 + 27/269*a^4 - 320/269*a^3 + 468/269*a^2 - 772/269*a
        - 1092/269)*x^2 + (-48/269*a^5 + 27/269*a^4 - 320/269*a^3 + 468/269*a^
↪2
        - 1041/269*a - 1092/269))
```

```
sage: # needs sage.rings.number_field
sage: R.<x> = PolynomialRing(QQ)
sage: K.<a> = NumberField(x^3 - x + 1,
....:                     embedding=(x^3 + x + 1).roots(ring=CC)[0][0])
sage: A.<x> = AffineSpace(K, 1)
sage: A2.<u,v> = AffineSpace(K, 2)
sage: H = Hom(A, A2)
```

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```
sage: f = H([x^2 + a*x + 3, 5*x])
sage: f.reduce_base_field()
Scheme morphism:
  From: Affine Space of dimension 1 over Number Field in a with
        defining polynomial x^3 - x + 1 with a = -1.324717957244746?
  To:   Affine Space of dimension 2 over Number Field in a with
        defining polynomial x^3 - x + 1 with a = -1.324717957244746?
  Defn: Defined on coordinates by sending (x) to (x^2 + a*x + 3, 5*x)
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = PolynomialRing(QQ, names=('x',)); (x,) = R._first_ngens(1)
>>> K = NumberField(x**Integer(3) - x + Integer(1),
...                 embedding=(x**Integer(3) + x + Integer(1)).
↪roots(ring=CC)[Integer(0)][Integer(0)], names=('a',)); (a,) = K._first_
↪ngens(1)
>>> A = AffineSpace(K, Integer(1), names=('x',)); (x,) = A._first_ngens(1)
>>> A2 = AffineSpace(K, Integer(2), names=('u', 'v',)); (u, v,) = A2._first_
↪ngens(2)
>>> H = Hom(A, A2)
>>> f = H([x**Integer(2) + a*x + Integer(3), Integer(5)*x])
>>> f.reduce_base_field()
Scheme morphism:
  From: Affine Space of dimension 1 over Number Field in a with
        defining polynomial x^3 - x + 1 with a = -1.324717957244746?
  To:   Affine Space of dimension 2 over Number Field in a with
        defining polynomial x^3 - x + 1 with a = -1.324717957244746?
  Defn: Defined on coordinates by sending (x) to (x^2 + a*x + 3, 5*x)
```

```
sage: # needs sage.rings.number_field
sage: K.<v> = QuadraticField(2)
sage: A.<x> = AffineSpace(K, 1)
sage: H = End(A)
sage: f = H([3*x^2 + x + 1])
sage: f.reduce_base_field()
Scheme endomorphism of Affine Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x) to (3*x^2 + x + 1)
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> K = QuadraticField(Integer(2), names=('v',)); (v,) = K._first_ngens(1)
>>> A = AffineSpace(K, Integer(1), names=('x',)); (x,) = A._first_ngens(1)
>>> H = End(A)
>>> f = H([Integer(3)*x**Integer(2) + x + Integer(1)])
>>> f.reduce_base_field()
Scheme endomorphism of Affine Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x) to (3*x^2 + x + 1)
```

```
sage: # needs sage.rings.finite_rings
sage: K.<t> = GF(5^6)
sage: A.<x> = AffineSpace(K, 1)
```

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```
sage: H = End(A)
sage: f = H([x^2 + x*(t^3 + 2*t^2 + 4*t) + (t^5 + 3*t^4 + t^2 + 4*t)])
sage: f.reduce_base_field()
Scheme endomorphism of Affine Space of dimension 1
 over Finite Field in t of size 5^6
  Defn: Defined on coordinates by sending (x) to
        (x^2 + (t^3 + 2*t^2 - t)*x + (t^5 - 2*t^4 + t^2 - t))
```

```
>>> from sage.all import *
>>> # needs sage.rings.finite_rings
>>> K = GF(Integer(5)**Integer(6), names=('t',)); (t,) = K._first_ngens(1)
>>> A = AffineSpace(K, Integer(1), names=('x',)); (x,) = A._first_ngens(1)
>>> H = End(A)
>>> f = H([x**Integer(2) + x*(t**Integer(3) + Integer(2)*t**Integer(2) +␣
↪Integer(4)*t) + (t**Integer(5) + Integer(3)*t**Integer(4) + t**Integer(2) +␣
↪Integer(4)*t)])
>>> f.reduce_base_field()
Scheme endomorphism of Affine Space of dimension 1
 over Finite Field in t of size 5^6
  Defn: Defined on coordinates by sending (x) to
        (x^2 + (t^3 + 2*t^2 - t)*x + (t^5 - 2*t^4 + t^2 - t))
```

weil_restriction()

Compute the Weil restriction of this morphism over some extension field.

If the field is a finite field, then this computes the Weil restriction to the prime subfield.

A Weil restriction of scalars - denoted $Res_{L/k}$ - is a functor which, for any finite extension of fields L/k and any algebraic variety X over L, produces another corresponding variety $Res_{L/k}(X)$, defined over k. It is useful for reducing questions about varieties over large fields to questions about more complicated varieties over smaller fields. Since it is a functor it also applied to morphisms. In particular, the functor applied to a morphism gives the equivalent morphism from the Weil restriction of the domain to the Weil restriction of the codomain.

OUTPUT: scheme morphism on the Weil restrictions of the domain
and codomain of the map.

EXAMPLES:

```
sage: # needs sage.rings.number_field
sage: K.<v> = QuadraticField(5)
sage: A.<x,y> = AffineSpace(K, 2)
sage: H = End(A)
sage: f = H([x^2 - y^2, y^2])
sage: f.weil_restriction()                                                  #␣
↪needs sage.libs.singular
Scheme endomorphism of Affine Space of dimension 4 over Rational Field
  Defn: Defined on coordinates by sending (z0, z1, z2, z3) to
        (z0^2 + 5*z1^2 - z2^2 - 5*z3^2, 2*z0*z1 - 2*z2*z3, z2^2 + 5*z3^2,␣
↪2*z2*z3)
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
```

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```
>>> K = QuadraticField(Integer(5), names=('v',)); (v,) = K._first_ngens(1)
>>> A = AffineSpace(K, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> H = End(A)
>>> f = H([x**Integer(2) - y**Integer(2), y**Integer(2)])
>>> f.weil_restriction()                                                    #␣
↪needs sage.libs.singular
Scheme endomorphism of Affine Space of dimension 4 over Rational Field
  Defn: Defined on coordinates by sending (z0, z1, z2, z3) to
        (z0^2 + 5*z1^2 - z2^2 - 5*z3^2, 2*z0*z1 - 2*z2*z3, z2^2 + 5*z3^2,␣
↪2*z2*z3)
```

```
sage: # needs sage.rings.number_field
sage: K.<v> = QuadraticField(5)
sage: PS.<x,y> = AffineSpace(K, 2)
sage: H = Hom(PS, PS)
sage: f = H([x, y])
sage: F = f.weil_restriction()
sage: P = PS(2, 1)
sage: Q = P.weil_restriction()
sage: f(P).weil_restriction() == F(Q)                                       #␣
↪needs sage.libs.singular
True
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> K = QuadraticField(Integer(5), names=('v',)); (v,) = K._first_ngens(1)
>>> PS = AffineSpace(K, Integer(2), names=('x', 'y',)); (x, y,) = PS._first_
↪ngens(2)
>>> H = Hom(PS, PS)
>>> f = H([x, y])
>>> F = f.weil_restriction()
>>> P = PS(Integer(2), Integer(1))
>>> Q = P.weil_restriction()
>>> f(P).weil_restriction() == F(Q)                                         #␣
↪needs sage.libs.singular
True
```

class sage.schemes.affine.affine_morphism.**SchemeMorphism_polynomial_affine_space_finite_field**(*parent*, *polys*, *check=Ti*

Bases: *SchemeMorphism_polynomial_affine_space_field*

class sage.schemes.affine.affine_morphism.**SchemeMorphism_polynomial_affine_subscheme_field**(*parent*, *polys*, *check=True*)

Bases: *SchemeMorphism_polynomial_affine_space_field*

Morphisms from subschemes of affine spaces defined over fields.

image()

Return the scheme-theoretic image of the morphism.

OUTPUT: a subscheme of the ambient space of the codomain

EXAMPLES:

```
sage: A1.<w> = AffineSpace(QQ, 1)
sage: A2.<x,y> = AffineSpace(QQ, 2)
sage: X = A2.subscheme(0)
sage: f = X.hom([x + y], A1)
sage: f.image()                                                             #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 1 over Rational Field defined␣
↪by:
  (no polynomials)
```

```
>>> from sage.all import *
>>> A1 = AffineSpace(QQ, Integer(1), names=('w',)); (w,) = A1._first_ngens(1)
>>> A2 = AffineSpace(QQ, Integer(2), names=('x', 'y',)); (x, y,) = A2._first_
↪ngens(2)
>>> X = A2.subscheme(Integer(0))
>>> f = X.hom([x + y], A1)
>>> f.image()                                                               #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 1 over Rational Field defined␣
↪by:
  (no polynomials)
```

```
sage: A2.<x,y> = AffineSpace(QQ, 2)
sage: X = A2.subscheme([x*y^2 - y^3 - 1])
sage: f = X.hom([y, y/x], A2)
sage: f.image()                                                             #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  -x^3*y + x^3 - y
```

```
>>> from sage.all import *
>>> A2 = AffineSpace(QQ, Integer(2), names=('x', 'y',)); (x, y,) = A2._first_
↪ngens(2)
>>> X = A2.subscheme([x*y**Integer(2) - y**Integer(3) - Integer(1)])
>>> f = X.hom([y, y/x], A2)
>>> f.image()                                                               #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  -x^3*y + x^3 - y
```

indeterminacy_locus()

Return the indeterminacy locus of this map.

The map defines a rational map on the domain. The output is the subscheme of the domain on which the rational map is not defined by any representative of the rational map. See *representatives()*.

EXAMPLES:

```
sage: A2.<x1,x2> = AffineSpace(QQ, 2)
sage: X = A2.subscheme(0)
sage: A1.<x> = AffineSpace(QQ, 1)
sage: f = X.hom([x1/x2], A1)
sage: f.indeterminacy_locus()                                                 #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  x2
```

```
>>> from sage.all import *
>>> A2 = AffineSpace(QQ, Integer(2), names=('x1', 'x2',)); (x1, x2,) = A2._
↪first_ngens(2)
>>> X = A2.subscheme(Integer(0))
>>> A1 = AffineSpace(QQ, Integer(1), names=('x',)); (x,) = A1._first_ngens(1)
>>> f = X.hom([x1/x2], A1)
>>> f.indeterminacy_locus()                                                   #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  x2
```

```
sage: A2.<x1,x2> = AffineSpace(QQ, 2)
sage: X = A2.subscheme(0)
sage: P1.<a,b> = ProjectiveSpace(QQ, 1)
sage: f = X.hom([x1,x2], P1)
sage: L = f.indeterminacy_locus()                                             #␣
↪needs sage.libs.singular
sage: L.rational_points()                                                     #␣
↪needs sage.libs.singular
[(0, 0)]
```

```
>>> from sage.all import *
>>> A2 = AffineSpace(QQ, Integer(2), names=('x1', 'x2',)); (x1, x2,) = A2._
↪first_ngens(2)
>>> X = A2.subscheme(Integer(0))
>>> P1 = ProjectiveSpace(QQ, Integer(1), names=('a', 'b',)); (a, b,) = P1._
↪first_ngens(2)
>>> f = X.hom([x1,x2], P1)
>>> L = f.indeterminacy_locus()                                               #␣
↪needs sage.libs.singular
>>> L.rational_points()                                                       #␣
↪needs sage.libs.singular
[(0, 0)]
```

```
sage: A2.<x,y> = AffineSpace(QQ, 2)
sage: X = A2.subscheme([x^2 - y^2 - y])
sage: A1.<a> = AffineSpace(QQ, 1)
sage: f = X.hom([x/y], A1)
sage: f.indeterminacy_locus()                                                 #␣
```

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```
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  y,
  x
```

```
>>> from sage.all import *
>>> A2 = AffineSpace(QQ, Integer(2), names=('x', 'y',)); (x, y,) = A2._first_
↪ngens(2)
>>> X = A2.subscheme([x**Integer(2) - y**Integer(2) - y])
>>> A1 = AffineSpace(QQ, Integer(1), names=('a',)); (a,) = A1._first_ngens(1)
>>> f = X.hom([x/y], A1)
>>> f.indeterminacy_locus()                                                #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  y,
  x
```

```
sage: A3.<x,y,z> = AffineSpace(QQ, 3)
sage: X = A3.subscheme(x^2 - y*z - x)
sage: A2.<a,b> = AffineSpace(QQ, 2)
sage: f = X.hom([y, y/x], A2)
sage: L = f.indeterminacy_locus(); L                                        #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 3 over Rational Field defined␣
↪by:
  x,
  y*z
sage: L.dimension()                                                         #␣
↪needs sage.libs.singular
1
```

```
>>> from sage.all import *
>>> A3 = AffineSpace(QQ, Integer(3), names=('x', 'y', 'z',)); (x, y, z,) = A3.
↪_first_ngens(3)
>>> X = A3.subscheme(x**Integer(2) - y*z - x)
>>> A2 = AffineSpace(QQ, Integer(2), names=('a', 'b',)); (a, b,) = A2._first_
↪ngens(2)
>>> f = X.hom([y, y/x], A2)
>>> L = f.indeterminacy_locus(); L                                          #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 3 over Rational Field defined␣
↪by:
  x,
  y*z
>>> L.dimension()                                                           #␣
↪needs sage.libs.singular
1
```

is_morphism()

Return `True` if the map is defined everywhere on the domain.

EXAMPLES:

```
sage: P2.<x,y,z> = ProjectiveSpace(QQ,2)
sage: P1.<a,b> = ProjectiveSpace(QQ,1)
sage: X = P2.subscheme([x^2 - y^2 - y*z])
sage: f = X.hom([x,y], P1)
sage: f.is_morphism()                                                       #␣
↪needs sage.libs.singular
True
```

```
>>> from sage.all import *
>>> P2 = ProjectiveSpace(QQ,Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P2._first_ngens(3)
>>> P1 = ProjectiveSpace(QQ,Integer(1), names=('a', 'b',)); (a, b,) = P1._
↪first_ngens(2)
>>> X = P2.subscheme([x**Integer(2) - y**Integer(2) - y*z])
>>> f = X.hom([x,y], P1)
>>> f.is_morphism()                                                         #␣
↪needs sage.libs.singular
True
```

representatives()

Return all maps representing the same rational map as by this map.

EXAMPLES:

```
sage: A2.<x,y> = AffineSpace(QQ, 2)
sage: X = A2.subscheme(0)
sage: f = X.hom([x, x/y], A2)
sage: f.representatives()                                                   #␣
↪needs sage.libs.singular
[Scheme morphism:
   From: Closed subscheme of Affine Space of dimension 2 over Rational Field
         defined by: 0
   To:   Affine Space of dimension 2 over Rational Field
   Defn: Defined on coordinates by sending (x, y) to (x, x/y)]
```

```
>>> from sage.all import *
>>> A2 = AffineSpace(QQ, Integer(2), names=('x', 'y',)); (x, y,) = A2._first_
↪ngens(2)
>>> X = A2.subscheme(Integer(0))
>>> f = X.hom([x, x/y], A2)
>>> f.representatives()                                                     #␣
↪needs sage.libs.singular
[Scheme morphism:
   From: Closed subscheme of Affine Space of dimension 2 over Rational Field
         defined by: 0
   To:   Affine Space of dimension 2 over Rational Field
   Defn: Defined on coordinates by sending (x, y) to (x, x/y)]
```

```
sage: # needs sage.libs.singular
sage: A2.<x,y> = AffineSpace(QQ, 2)
sage: A1.<a> = AffineSpace(QQ, 1)
```

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```
sage: X = A2.subscheme([x^2 - y^2 - y])
sage: f = X.hom([x/y], A1)
sage: f.representatives()
[Scheme morphism:
   From: Closed subscheme of Affine Space of dimension 2 over Rational Field
         defined by: x^2 - y^2 - y
   To:   Affine Space of dimension 1 over Rational Field
   Defn: Defined on coordinates by sending (x, y) to (x/y),
 Scheme morphism:
   From: Closed subscheme of Affine Space of dimension 2 over Rational Field
         defined by: x^2 - y^2 - y
   To:   Affine Space of dimension 1 over Rational Field
   Defn: Defined on coordinates by sending (x, y) to ((y + 1)/x)]
sage: g = _[1]
sage: g.representatives()
[Scheme morphism:
   From: Closed subscheme of Affine Space of dimension 2 over Rational Field
         defined by: x^2 - y^2 - y
   To:   Affine Space of dimension 1 over Rational Field
   Defn: Defined on coordinates by sending (x, y) to (x/y),
 Scheme morphism:
   From: Closed subscheme of Affine Space of dimension 2 over Rational Field
         defined by: x^2 - y^2 - y
   To:   Affine Space of dimension 1 over Rational Field
   Defn: Defined on coordinates by sending (x, y) to ((y + 1)/x)]
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> A2 = AffineSpace(QQ, Integer(2), names=('x', 'y',)); (x, y,) = A2._first_
↪ngens(2)
>>> A1 = AffineSpace(QQ, Integer(1), names=('a',)); (a,) = A1._first_ngens(1)
>>> X = A2.subscheme([x**Integer(2) - y**Integer(2) - y])
>>> f = X.hom([x/y], A1)
>>> f.representatives()
[Scheme morphism:
   From: Closed subscheme of Affine Space of dimension 2 over Rational Field
         defined by: x^2 - y^2 - y
   To:   Affine Space of dimension 1 over Rational Field
   Defn: Defined on coordinates by sending (x, y) to (x/y),
 Scheme morphism:
   From: Closed subscheme of Affine Space of dimension 2 over Rational Field
         defined by: x^2 - y^2 - y
   To:   Affine Space of dimension 1 over Rational Field
   Defn: Defined on coordinates by sending (x, y) to ((y + 1)/x)]
>>> g = _[Integer(1)]
>>> g.representatives()
[Scheme morphism:
   From: Closed subscheme of Affine Space of dimension 2 over Rational Field
         defined by: x^2 - y^2 - y
   To:   Affine Space of dimension 1 over Rational Field
   Defn: Defined on coordinates by sending (x, y) to (x/y),
 Scheme morphism:
```

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```
   From: Closed subscheme of Affine Space of dimension 2 over Rational Field
         defined by: x^2 - y^2 - y
   To:   Affine Space of dimension 1 over Rational Field
   Defn: Defined on coordinates by sending (x, y) to ((y + 1)/x)]
```

```
sage: A2.<x,y> = AffineSpace(QQ, 2)
sage: P1.<a,b> = ProjectiveSpace(QQ, 1)
sage: X = A2.subscheme([x^2 - y^2 - y])
sage: f = X.hom([x, y], P1)
sage: f.representatives()                                                    #␣
↪needs sage.libs.singular
[Scheme morphism:
   From: Closed subscheme of Affine Space of dimension 2 over Rational Field
         defined by: x^2 - y^2 - y
   To:   Projective Space of dimension 1 over Rational Field
   Defn: Defined on coordinates by sending (x, y) to
         (x : y),
 Scheme morphism:
   From: Closed subscheme of Affine Space of dimension 2 over Rational Field
         defined by: x^2 - y^2 - y
   To:   Projective Space of dimension 1 over Rational Field
   Defn: Defined on coordinates by sending (x, y) to (y + 1 : x)]
```

```
>>> from sage.all import *
>>> A2 = AffineSpace(QQ, Integer(2), names=('x', 'y',)); (x, y,) = A2._first_
↪ngens(2)
>>> P1 = ProjectiveSpace(QQ, Integer(1), names=('a', 'b',)); (a, b,) = P1._
↪first_ngens(2)
>>> X = A2.subscheme([x**Integer(2) - y**Integer(2) - y])
>>> f = X.hom([x, y], P1)
>>> f.representatives()                                                      #␣
↪needs sage.libs.singular
[Scheme morphism:
   From: Closed subscheme of Affine Space of dimension 2 over Rational Field
         defined by: x^2 - y^2 - y
   To:   Projective Space of dimension 1 over Rational Field
   Defn: Defined on coordinates by sending (x, y) to
         (x : y),
 Scheme morphism:
   From: Closed subscheme of Affine Space of dimension 2 over Rational Field
         defined by: x^2 - y^2 - y
   To:   Projective Space of dimension 1 over Rational Field
   Defn: Defined on coordinates by sending (x, y) to (y + 1 : x)]
```

13.3 Points on affine varieties

This module implements scheme morphism for points on affine varieties.

AUTHORS:

- David Kohel, William Stein (2006): initial version

- Volker Braun (2011-08-08): renamed classes, more documentation, misc cleanups
- Ben Hutz (2013): many improvements

class sage.schemes.affine.affine_point.**SchemeMorphism_point_affine**(*X*, *v*, *check=True*)

Bases: *SchemeMorphism_point*

A rational point on an affine scheme.

INPUT:

- `X` – a subscheme of an ambient affine space over a ring R
- `v` – list/tuple/iterable of coordinates in R
- `check` – boolean (default: `True`); whether to check the input for consistency

EXAMPLES:

```
sage: A = AffineSpace(2, QQ)
sage: A(1, 2)
(1, 2)
```

```
>>> from sage.all import *
>>> A = AffineSpace(Integer(2), QQ)
>>> A(Integer(1), Integer(2))
(1, 2)
```

global_height(*prec=None*)

Return the logarithmic height of the point.

INPUT:

- `prec` – desired floating point precision (default: default RealField precision)

OUTPUT: a real number

EXAMPLES:

```
sage: P.<x,y> = AffineSpace(QQ, 2)
sage: Q = P(41, 1/12)
sage: Q.global_height()                                                    #␣
↪needs sage.rings.real_mpfr
3.71357206670431
```

```
>>> from sage.all import *
>>> P = AffineSpace(QQ, Integer(2), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> Q = P(Integer(41), Integer(1)/Integer(12))
>>> Q.global_height()                                                      #␣
↪needs sage.rings.real_mpfr
3.71357206670431
```

```
sage: P = AffineSpace(ZZ, 4, 'x')
sage: Q = P(3, 17, -51, 5)
sage: Q.global_height()                                                    #␣
↪needs sage.rings.real_mpfr
3.93182563272433
```

```
>>> from sage.all import *
>>> P = AffineSpace(ZZ, Integer(4), 'x')
>>> Q = P(Integer(3), Integer(17), -Integer(51), Integer(5))
>>> Q.global_height()                                                    #␣
↪needs sage.rings.real_mpfr
3.93182563272433
```

```
sage: R.<x> = PolynomialRing(QQ)
sage: k.<w> = NumberField(x^2 + 5)                                       #␣
↪needs sage.rings.number_field
sage: A = AffineSpace(k, 2, 'z')                                         #␣
↪needs sage.rings.number_field
sage: A([3, 5*w + 1]).global_height(prec=100)                            #␣
↪needs sage.rings.number_field sage.rings.real_mpfr
2.4181409534757389986565376694
```

```
>>> from sage.all import *
>>> R = PolynomialRing(QQ, names=('x',)); (x,) = R._first_ngens(1)
>>> k = NumberField(x**Integer(2) + Integer(5), names=('w',)); (w,) = k._
↪first_ngens(1)# needs sage.rings.number_field
>>> A = AffineSpace(k, Integer(2), 'z')                                  ␣
↪     # needs sage.rings.number_field
>>> A([Integer(3), Integer(5)*w + Integer(1)]).global_
↪height(prec=Integer(100))                                 # needs sage.rings.
↪number_field sage.rings.real_mpfr
2.4181409534757389986565376694
```

Todo

P-adic heights.

homogenize(*n*)

Return the homogenization of the point at the `nth` coordinate.

INPUT:

- `n` – integer between 0 and dimension of the map, inclusive

OUTPUT: a point in the projectivization of the codomain of the map

EXAMPLES:

```
sage: A.<x,y> = AffineSpace(ZZ, 2)
sage: Q = A(2, 3)
sage: Q.homogenize(2).dehomogenize(2) == Q
True

::

sage: A.<x,y> = AffineSpace(QQ, 2)
sage: Q = A(2, 3)
sage: P = A(0, 1)
```

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```
sage: Q.homogenize(2).codomain() == P.homogenize(2).codomain()
True
```

```
>>> from sage.all import *
>>> A = AffineSpace(ZZ, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> Q = A(Integer(2), Integer(3))
>>> Q.homogenize(Integer(2)).dehomogenize(Integer(2)) == Q
True

::

>>> A = AffineSpace(QQ, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> Q = A(Integer(2), Integer(3))
>>> P = A(Integer(0), Integer(1))
>>> Q.homogenize(Integer(2)).codomain() == P.homogenize(Integer(2)).codomain()
True
```

class sage.schemes.affine.affine_point.**SchemeMorphism_point_affine_field**(*X*, *v*, *check=True*)

Bases: *SchemeMorphism_point_affine*

as_subscheme()

Return the subscheme associated with this rational point.

EXAMPLES:

```
sage: A2.<x,y> = AffineSpace(QQ, 2)
sage: p1 = A2.point([0,0]).as_subscheme(); p1
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  x, y
sage: p2 = A2.point([1,1]).as_subscheme(); p2
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  x - 1, y - 1
sage: p1 + p2
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  x - y, y^2 - y
```

```
>>> from sage.all import *
>>> A2 = AffineSpace(QQ, Integer(2), names=('x', 'y',)); (x, y,) = A2._first_
↪ngens(2)
>>> p1 = A2.point([Integer(0),Integer(0)]).as_subscheme(); p1
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  x, y
>>> p2 = A2.point([Integer(1),Integer(1)]).as_subscheme(); p2
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  x - 1, y - 1
```

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```
>>> p1 + p2
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  x - y, y^2 - y
```

intersection_multiplicity(*X*)

Return the intersection multiplicity of the codomain of this point and `X` at this point.

This uses the intersection_multiplicity implementations for projective/affine subschemes. This point must be a point on an affine subscheme.

INPUT:

- `X` – a subscheme in the same ambient space as that of the codomain of this point

OUTPUT: integer

EXAMPLES:

```
sage: # needs sage.libs.singular
sage: A.<x,y> = AffineSpace(GF(17), 2)
sage: X = A.subscheme([y^2 - x^3 + 2*x^2 - x])
sage: Y = A.subscheme([y - 2*x + 2])
sage: Q1 = Y([1,0])
sage: Q1.intersection_multiplicity(X)
2
sage: Q2 = X([4,6])
sage: Q2.intersection_multiplicity(Y)
1
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> A = AffineSpace(GF(Integer(17)), Integer(2), names=('x', 'y',)); (x, y,)␣
↪= A._first_ngens(2)
>>> X = A.subscheme([y**Integer(2) - x**Integer(3) + Integer(2)*x**Integer(2)␣
↪- x])
>>> Y = A.subscheme([y - Integer(2)*x + Integer(2)])
>>> Q1 = Y([Integer(1),Integer(0)])
>>> Q1.intersection_multiplicity(X)
2
>>> Q2 = X([Integer(4),Integer(6)])
>>> Q2.intersection_multiplicity(Y)
1
```

```
sage: A.<x,y,z,w> = AffineSpace(QQ, 4)
sage: X = A.subscheme([x^2 - y*z^2, z - 2*w^2])
sage: Q = A([2,1,2,-1])
sage: Q.intersection_multiplicity(X)
Traceback (most recent call last):
...
TypeError: this point must be a point on an affine subscheme
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(4), names=('x', 'y', 'z', 'w',)); (x, y, z, w,
```

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```
↪) = A._first_ngens(4)
>>> X = A.subscheme([x**Integer(2) - y*z**Integer(2), z -␣
↪Integer(2)*w**Integer(2)])
>>> Q = A([Integer(2),Integer(1),Integer(2),-Integer(1)])
>>> Q.intersection_multiplicity(X)
Traceback (most recent call last):
...
TypeError: this point must be a point on an affine subscheme
```

multiplicity()

Return the multiplicity of this point on its codomain.

Uses the subscheme multiplicity implementation. This point must be a point on an affine subscheme.

OUTPUT: integer

EXAMPLES:

```
sage: A.<x,y,z> = AffineSpace(QQ, 3)
sage: X = A.subscheme([y^2 - x^7*z])
sage: Q1 = X([1,1,1])
sage: Q1.multiplicity()                                                    #␣
↪needs sage.libs.singular
1
sage: Q2 = X([0,0,2])
sage: Q2.multiplicity()                                                    #␣
↪needs sage.libs.singular
2
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(3), names=('x', 'y', 'z',)); (x, y, z,) = A._
↪first_ngens(3)
>>> X = A.subscheme([y**Integer(2) - x**Integer(7)*z])
>>> Q1 = X([Integer(1),Integer(1),Integer(1)])
>>> Q1.multiplicity()                                                      #␣
↪needs sage.libs.singular
1
>>> Q2 = X([Integer(0),Integer(0),Integer(2)])
>>> Q2.multiplicity()                                                      #␣
↪needs sage.libs.singular
2
```

weil_restriction()

Compute the Weil restriction of this point over some extension field.

If the field is a finite field, then this computes the Weil restriction to the prime subfield.

A Weil restriction of scalars - denoted $Res_{L/k}$ - is a functor which, for any finite extension of fields L/k and any algebraic variety X over L, produces another corresponding variety $Res_{L/k}(X)$, defined over k. It is useful for reducing questions about varieties over large fields to questions about more complicated varieties over smaller fields. This functor applied to a point gives the equivalent point on the Weil restriction of its codomain.

OUTPUT: scheme point on the Weil restriction of the codomain of this point

EXAMPLES:

```
sage: # needs sage.libs.singular sage.rings.finite_rings
sage: A.<x,y,z> = AffineSpace(GF(5^3, 't'), 3)
sage: X = A.subscheme([y^2 - x*z, z^2 + y])
sage: Y = X.weil_restriction()
sage: P = X([1, -1, 1])
sage: Q = P.weil_restriction();Q
(1, 0, 0, 4, 0, 0, 1, 0, 0)
sage: Q.codomain() == Y
True
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular sage.rings.finite_rings
>>> A = AffineSpace(GF(Integer(5)**Integer(3), 't'), Integer(3), names=('x',
↪'y', 'z',)); (x, y, z,) = A._first_ngens(3)
>>> X = A.subscheme([y**Integer(2) - x*z, z**Integer(2) + y])
>>> Y = X.weil_restriction()
>>> P = X([Integer(1), -Integer(1), Integer(1)])
>>> Q = P.weil_restriction();Q
(1, 0, 0, 4, 0, 0, 1, 0, 0)
>>> Q.codomain() == Y
True
```

```
sage: # needs sage.libs.singular sage.rings.number_field
sage: R.<x> = QQ[]
sage: K.<w> = NumberField(x^5 - 2)
sage: R.<x> = K[]
sage: L.<v> = K.extension(x^2 + w)
sage: A.<x,y> = AffineSpace(L, 2)
sage: P = A([w^3 - v, 1 + w + w*v])
sage: P.weil_restriction()
(w^3, -1, w + 1, w)
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular sage.rings.number_field
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> K = NumberField(x**Integer(5) - Integer(2), names=('w',)); (w,) = K._
↪first_ngens(1)
>>> R = K['x']; (x,) = R._first_ngens(1)
>>> L = K.extension(x**Integer(2) + w, names=('v',)); (v,) = L._first_ngens(1)
>>> A = AffineSpace(L, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> P = A([w**Integer(3) - v, Integer(1) + w + w*v])
>>> P.weil_restriction()
(w^3, -1, w + 1, w)
```

class sage.schemes.affine.affine_point.**SchemeMorphism_point_affine_finite_field**(*X*, *v*, *check=True*)

Bases: *SchemeMorphism_point_affine_field*

13.4 Subschemes of affine space

AUTHORS:

- David Kohel, William Stein (2005): initial version
- Ben Hutz (2013): affine subschemes

class sage.schemes.affine.affine_subscheme.**AlgebraicScheme_subscheme_affine**(*A*, *polynomials*, *embedding_center=None*, *embedding_codomain=None*, *embedding_images=None*)

Bases: *AlgebraicScheme_subscheme*

An algebraic subscheme of affine space.

INPUT:

- `A` – ambient affine space
- `polynomials` – single polynomial, ideal or iterable of defining polynomials

EXAMPLES:

```
sage: A3.<x, y, z> = AffineSpace(QQ, 3)
sage: A3.subscheme([x^2 - y*z])
Closed subscheme of Affine Space of dimension 3 over Rational Field defined by:
  x^2 - y*z
```

```
>>> from sage.all import *
>>> A3 = AffineSpace(QQ, Integer(3), names=('x', 'y', 'z',)); (x, y, z,) = A3._
↪first_ngens(3)
>>> A3.subscheme([x**Integer(2) - y*z])
Closed subscheme of Affine Space of dimension 3 over Rational Field defined by:
  x^2 - y*z
```

dimension()

Return the dimension of the affine algebraic subscheme.

EXAMPLES:

```
sage: # needs sage.libs.singular
sage: A.<x,y> = AffineSpace(2, QQ)
sage: A.subscheme([]).dimension()
2
sage: A.subscheme([x]).dimension()
1
sage: A.subscheme([x^5]).dimension()
1
sage: A.subscheme([x^2 + y^2 - 1]).dimension()
1
```

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```
sage: A.subscheme([x*(x-1), y*(y-1)]).dimension()
0
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> A = AffineSpace(Integer(2), QQ, names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> A.subscheme([]).dimension()
2
>>> A.subscheme([x]).dimension()
1
>>> A.subscheme([x**Integer(5)]).dimension()
1
>>> A.subscheme([x**Integer(2) + y**Integer(2) - Integer(1)]).dimension()
1
>>> A.subscheme([x*(x-Integer(1)), y*(y-Integer(1))]).dimension()
0
```

Something less obvious:

```
sage: A.<x,y,z,w> = AffineSpace(4, QQ)
sage: X = A.subscheme([x^2, x^2*y^2 + z^2, z^2 - w^2, 10*x^2 + w^2 - z^2])
sage: X
Closed subscheme of Affine Space of dimension 4 over Rational Field defined␣
↪by:
  x^2,
  x^2*y^2 + z^2,
  z^2 - w^2,
  10*x^2 - z^2 + w^2
sage: X.dimension()                                                          #␣
↪needs sage.libs.singular
1
```

```
>>> from sage.all import *
>>> A = AffineSpace(Integer(4), QQ, names=('x', 'y', 'z', 'w',)); (x, y, z, w,
↪) = A._first_ngens(4)
>>> X = A.subscheme([x**Integer(2), x**Integer(2)*y**Integer(2) +␣
↪z**Integer(2), z**Integer(2) - w**Integer(2), Integer(10)*x**Integer(2) +␣
↪w**Integer(2) - z**Integer(2)])
>>> X
Closed subscheme of Affine Space of dimension 4 over Rational Field defined␣
↪by:
  x^2,
  x^2*y^2 + z^2,
  z^2 - w^2,
  10*x^2 - z^2 + w^2
>>> X.dimension()                                                            #␣
↪needs sage.libs.singular
1
```

intersection_multiplicity(X, P)

Return the intersection multiplicity of this subscheme and the subscheme `X` at the point `P`.

The intersection of this subscheme with `X` must be proper, that is $\text{codim}(self \cap X) = \text{codim}(self) + \text{codim}(X)$, and must also be finite. We use Serre's Tor formula to compute the intersection multiplicity. If I, J are the defining ideals of `self`, `X`, respectively, then this is $\sum_{i=0}^{\infty}(-1)^i \text{length}(\text{Tor}^i_{\mathcal{O}_{A,p}}(\mathcal{O}_{A,p}/I, \mathcal{O}_{A,p}/J))$ where A is the affine ambient space of these subschemes.

INPUT:

- `X` – subscheme in the same ambient space as this subscheme
- `P` – a point in the intersection of this subscheme with `X`

OUTPUT: integer

EXAMPLES:

```
sage: A.<x,y> = AffineSpace(QQ, 2)
sage: C = Curve([y^2 - x^3 - x^2], A)                                          #␣
↪needs sage.libs.singular
sage: D = Curve([y^2 + x^3], A)                                                #␣
↪needs sage.libs.singular
sage: Q = A([0,0])
sage: C.intersection_multiplicity(D, Q)                                        #␣
↪needs sage.libs.singular
4
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> C = Curve([y**Integer(2) - x**Integer(3) - x**Integer(2)], A)              ␣
↪                          # needs sage.libs.singular
>>> D = Curve([y**Integer(2) + x**Integer(3)], A)                              ␣
↪                 # needs sage.libs.singular
>>> Q = A([Integer(0),Integer(0)])
>>> C.intersection_multiplicity(D, Q)                                          #␣
↪needs sage.libs.singular
4
```

```
sage: # needs sage.rings.number_field
sage: R.<a> = QQ[]
sage: K.<b> = NumberField(a^6 - 3*a^5 + 5*a^4 - 5*a^3 + 5*a^2 - 3*a + 1)
sage: A.<x,y,z,w> = AffineSpace(K, 4)
sage: X = A.subscheme([x*y, y*z + 7, w^3 - x^3])
sage: Y = A.subscheme([x - z^3 + z + 1])
sage: Q = A([0,
....:        -7*b^5 + 21*b^4 - 28*b^3 + 21*b^2 - 21*b + 14,
....:        -b^5 + 2*b^4 - 3*b^3 + 2*b^2 - 2*b,
....:        0])
sage: X.intersection_multiplicity(Y, Q)                                        #␣
↪needs sage.libs.singular
3
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = QQ['a']; (a,) = R._first_ngens(1)
>>> K = NumberField(a**Integer(6) - Integer(3)*a**Integer(5) +␣
```

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```
↪Integer(5)*a**Integer(4) - Integer(5)*a**Integer(3) +␣
↪Integer(5)*a**Integer(2) - Integer(3)*a + Integer(1), names=('b',)); (b,) =␣
↪K._first_ngens(1)
>>> A = AffineSpace(K, Integer(4), names=('x', 'y', 'z', 'w',)); (x, y, z, w,
↪) = A._first_ngens(4)
>>> X = A.subscheme([x*y, y*z + Integer(7), w**Integer(3) - x**Integer(3)])
>>> Y = A.subscheme([x - z**Integer(3) + z + Integer(1)])
>>> Q = A([Integer(0),
...        -Integer(7)*b**Integer(5) + Integer(21)*b**Integer(4) -␣
↪Integer(28)*b**Integer(3) + Integer(21)*b**Integer(2) - Integer(21)*b +␣
↪Integer(14),
...        -b**Integer(5) + Integer(2)*b**Integer(4) -␣
↪Integer(3)*b**Integer(3) + Integer(2)*b**Integer(2) - Integer(2)*b,
...        Integer(0)])
>>> X.intersection_multiplicity(Y, Q)                                    #␣
↪needs sage.libs.singular
3
```

```
sage: A.<x,y,z> = AffineSpace(QQ, 3)
sage: X = A.subscheme([z^2 - 1])
sage: Y = A.subscheme([z - 1, y - x^2])
sage: Q = A([1,1,1])
sage: X.intersection_multiplicity(Y, Q)                                   #␣
↪needs sage.libs.singular
Traceback (most recent call last):
...
TypeError: the intersection of this subscheme and (=Closed subscheme of␣
↪Affine Space of dimension 3
over Rational Field defined by: z - 1, -x^2 + y) must be proper and finite
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(3), names=('x', 'y', 'z',)); (x, y, z,) = A._
↪first_ngens(3)
>>> X = A.subscheme([z**Integer(2) - Integer(1)])
>>> Y = A.subscheme([z - Integer(1), y - x**Integer(2)])
>>> Q = A([Integer(1),Integer(1),Integer(1)])
>>> X.intersection_multiplicity(Y, Q)                                     #␣
↪needs sage.libs.singular
Traceback (most recent call last):
...
TypeError: the intersection of this subscheme and (=Closed subscheme of␣
↪Affine Space of dimension 3
over Rational Field defined by: z - 1, -x^2 + y) must be proper and finite
```

```
sage: A.<x,y,z,w,t> = AffineSpace(QQ, 5)
sage: X = A.subscheme([x*y, t^2*w, w^3*z])
sage: Y = A.subscheme([y*w + z])
sage: Q = A([0,0,0,0,0])
sage: X.intersection_multiplicity(Y, Q)                                   #␣
↪needs sage.libs.singular
Traceback (most recent call last):
```

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```
...
TypeError: the intersection of this subscheme and (=Closed subscheme of␣
↪Affine Space of dimension 5
over Rational Field defined by: y*w + z) must be proper and finite
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(5), names=('x', 'y', 'z', 'w', 't',)); (x, y,␣
↪z, w, t,) = A._first_ngens(5)
>>> X = A.subscheme([x*y, t**Integer(2)*w, w**Integer(3)*z])
>>> Y = A.subscheme([y*w + z])
>>> Q = A([Integer(0),Integer(0),Integer(0),Integer(0),Integer(0)])
>>> X.intersection_multiplicity(Y, Q)                                    #␣
↪needs sage.libs.singular
Traceback (most recent call last):
...
TypeError: the intersection of this subscheme and (=Closed subscheme of␣
↪Affine Space of dimension 5
over Rational Field defined by: y*w + z) must be proper and finite
```

is_smooth(*point=None*)

Test whether the algebraic subscheme is smooth.

INPUT:

- `point` – a point or `None` (default). The point to test smoothness at

OUTPUT:

boolean; if no point was specified, returns whether the algebraic subscheme is smooth everywhere. Otherwise, smoothness at the specified point is tested.

EXAMPLES:

```
sage: A2.<x,y> = AffineSpace(2, QQ)
sage: cuspidal_curve = A2.subscheme([y^2 - x^3])
sage: cuspidal_curve
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  -x^3 + y^2
sage: smooth_point = cuspidal_curve.point([1,1])
sage: smooth_point in cuspidal_curve
True
sage: singular_point = cuspidal_curve.point([0,0])
sage: singular_point in cuspidal_curve
True
sage: cuspidal_curve.is_smooth(smooth_point)                              #␣
↪needs sage.libs.singular
True
sage: cuspidal_curve.is_smooth(singular_point)                            #␣
↪needs sage.libs.singular
False
sage: cuspidal_curve.is_smooth()                                          #␣
↪needs sage.libs.singular
False
```

```
>>> from sage.all import *
>>> A2 = AffineSpace(Integer(2), QQ, names=('x', 'y',)); (x, y,) = A2._first_
↪ngens(2)
>>> cuspidal_curve = A2.subscheme([y**Integer(2) - x**Integer(3)])
>>> cuspidal_curve
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  -x^3 + y^2
>>> smooth_point = cuspidal_curve.point([Integer(1),Integer(1)])
>>> smooth_point in cuspidal_curve
True
>>> singular_point = cuspidal_curve.point([Integer(0),Integer(0)])
>>> singular_point in cuspidal_curve
True
>>> cuspidal_curve.is_smooth(smooth_point)                                    #␣
↪needs sage.libs.singular
True
>>> cuspidal_curve.is_smooth(singular_point)                                  #␣
↪needs sage.libs.singular
False
>>> cuspidal_curve.is_smooth()                                                #␣
↪needs sage.libs.singular
False
```

multiplicity(*P*)

Return the multiplicity of `P` on this subscheme.

This is computed as the multiplicity of the local ring of this subscheme corresponding to `P`. This subscheme must be defined over a field. An error is raised if `P` is not a point on this subscheme.

INPUT:

- `P` – a point on this subscheme

OUTPUT: integer

EXAMPLES:

```
sage: A.<x,y,z,w> = AffineSpace(QQ, 4)
sage: X = A.subscheme([z*y - x^7, w - 2*z])
sage: Q1 = A([1,1/3,3,6])
sage: X.multiplicity(Q1)                                                    #␣
↪needs sage.libs.singular
1
sage: Q2 = A([0,0,0,0])
sage: X.multiplicity(Q2)                                                    #␣
↪needs sage.libs.singular
2
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(4), names=('x', 'y', 'z', 'w',)); (x, y, z, w,
↪) = A._first_ngens(4)
>>> X = A.subscheme([z*y - x**Integer(7), w - Integer(2)*z])
>>> Q1 = A([Integer(1),Integer(1)/Integer(3),Integer(3),Integer(6)])
>>> X.multiplicity(Q1)                                                        #␣
```

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```
↪needs sage.libs.singular
1
>>> Q2 = A([Integer(0),Integer(0),Integer(0),Integer(0)])
>>> X.multiplicity(Q2)                                                    #␣
↪needs sage.libs.singular
2
```

```
sage: A.<x,y,z,w,v> = AffineSpace(GF(23), 5)
sage: C = A.curve([x^8 - y, y^7 - z, z^3 - 1, w^5 - v^3])                  #␣
↪needs sage.libs.singular sage.schemes
sage: Q = A([22,1,1,0,0])
sage: C.multiplicity(Q)                                                    #␣
↪needs sage.libs.singular sage.schemes
3
```

```
>>> from sage.all import *
>>> A = AffineSpace(GF(Integer(23)), Integer(5), names=('x', 'y', 'z', 'w', 'v
↪',)); (x, y, z, w, v,) = A._first_ngens(5)
>>> C = A.curve([x**Integer(8) - y, y**Integer(7) - z, z**Integer(3) -␣
↪Integer(1), w**Integer(5) - v**Integer(3)])                    # needs sage.
↪libs.singular sage.schemes
>>> Q = A([Integer(22),Integer(1),Integer(1),Integer(0),Integer(0)])
>>> C.multiplicity(Q)                                                    #␣
↪needs sage.libs.singular sage.schemes
3
```

```
sage: # needs sage.rings.number_field
sage: K.<a> = QuadraticField(-1)
sage: A.<x,y,z,w,t> = AffineSpace(K, 5)
sage: X = A.subscheme([y^7 - x^2*z^5 + z^3*t^8 - x^2*y^4*z - t^8])
sage: Q1 = A([1,1,0,1,-1])
sage: X.multiplicity(Q1)                                                   #␣
↪needs sage.libs.singular
1
sage: Q2 = A([0,0,0,-a,0])
sage: X.multiplicity(Q2)                                                   #␣
↪needs sage.libs.singular
7
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> K = QuadraticField(-Integer(1), names=('a',)); (a,) = K._first_ngens(1)
>>> A = AffineSpace(K, Integer(5), names=('x', 'y', 'z', 'w', 't',)); (x, y,␣
↪z, w, t,) = A._first_ngens(5)
>>> X = A.subscheme([y**Integer(7) - x**Integer(2)*z**Integer(5) +␣
↪z**Integer(3)*t**Integer(8) - x**Integer(2)*y**Integer(4)*z -␣
↪t**Integer(8)])
>>> Q1 = A([Integer(1),Integer(1),Integer(0),Integer(1),-Integer(1)])
>>> X.multiplicity(Q1)                                                    #␣
↪needs sage.libs.singular
1
```

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```
>>> Q2 = A([Integer(0),Integer(0),Integer(0),-a,Integer(0)])
>>> X.multiplicity(Q2)                                                    #␣
↪needs sage.libs.singular
7
```

Check that Issue #27479 is fixed:

```
sage: A1.<x> = AffineSpace(QQ, 1)
sage: X = A1.subscheme([x^1789 + x])
sage: Q = X([0])
sage: X.multiplicity(Q)                                                  #␣
↪needs sage.libs.singular
1
```

```
>>> from sage.all import *
>>> A1 = AffineSpace(QQ, Integer(1), names=('x',)); (x,) = A1._first_ngens(1)
>>> X = A1.subscheme([x**Integer(1789) + x])
>>> Q = X([Integer(0)])
>>> X.multiplicity(Q)                                                    #␣
↪needs sage.libs.singular
1
```

projective_closure(*i=None*, *PP=None*)

Return the projective closure of this affine subscheme.

INPUT:

- `i` – (default: `None`) determines the embedding to use to compute the projective closure of this affine subscheme. The embedding used is the one which has a 1 in the i-th coordinate, numbered from 0.
- `PP` – (default: `None`) ambient projective space, i.e., ambient space of codomain of morphism; this is constructed if it is not given

OUTPUT: a projective subscheme

EXAMPLES:

```
sage: A.<x,y,z,w> = AffineSpace(QQ, 4)
sage: X = A.subscheme([x^2 - y, x*y - z, y^2 - w,
....:                  x*z - w, y*z - x*w, z^2 - y*w])
sage: X.projective_closure()                                             #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 4 over Rational Field
 defined by:
  x0^2 - x1*x4,
  x0*x1 - x2*x4,
  x1^2 - x3*x4,
  x0*x2 - x3*x4,
  x1*x2 - x0*x3,
  x2^2 - x1*x3
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(4), names=('x', 'y', 'z', 'w',)); (x, y, z, w,
↪) = A._first_ngens(4)
```

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```
>>> X = A.subscheme([x**Integer(2) - y, x*y - z, y**Integer(2) - w,
...                  x*z - w, y*z - x*w, z**Integer(2) - y*w])
>>> X.projective_closure()                                                    #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 4 over Rational Field
 defined by:
  x0^2 - x1*x4,
  x0*x1 - x2*x4,
  x1^2 - x3*x4,
  x0*x2 - x3*x4,
  x1*x2 - x0*x3,
  x2^2 - x1*x3
```

```
sage: A.<x,y,z> = AffineSpace(QQ, 3)
sage: P.<a,b,c,d> = ProjectiveSpace(QQ, 3)
sage: X = A.subscheme([z - x^2 - y^2])
sage: X.projective_closure(1, P).ambient_space() == P                         #␣
↪needs sage.libs.singular
True
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(3), names=('x', 'y', 'z',)); (x, y, z,) = A._
↪first_ngens(3)
>>> P = ProjectiveSpace(QQ, Integer(3), names=('a', 'b', 'c', 'd',)); (a, b,␣
↪c, d,) = P._first_ngens(4)
>>> X = A.subscheme([z - x**Integer(2) - y**Integer(2)])
>>> X.projective_closure(Integer(1), P).ambient_space() == P                  ␣
↪     # needs sage.libs.singular
True
```

projective_embedding(*i=None*, *PP=None*)

Return a morphism from this affine scheme into an ambient projective space of the same dimension.

The codomain of this morphism is the projective closure of this affine scheme in `PP`, if given, or otherwise in a new projective space that is constructed.

INPUT:

- `i` – integer (default: dimension of self = last coordinate); determines which projective embedding to compute. The embedding is that which has a 1 in the i-th coordinate, numbered from 0.
- `PP` – (default: `None`) ambient projective space, i.e., ambient space of codomain of morphism; this is constructed if it is not given

EXAMPLES:

```
sage: A.<x, y, z> = AffineSpace(3, ZZ)
sage: S = A.subscheme([x*y - z])
sage: S.projective_embedding()                                                #␣
↪needs sage.libs.singular
Scheme morphism:
  From: Closed subscheme of Affine Space of dimension 3 over Integer Ring
        defined by: x*y - z
  To:   Closed subscheme of Projective Space of dimension 3 over Integer Ring
```

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```
       defined by: x0*x1 - x2*x3
  Defn: Defined on coordinates by sending (x, y, z) to (x : y : z : 1)
```

```
>>> from sage.all import *
>>> A = AffineSpace(Integer(3), ZZ, names=('x', 'y', 'z',)); (x, y, z,) = A._
↪first_ngens(3)
>>> S = A.subscheme([x*y - z])
>>> S.projective_embedding()                                                #␣
↪needs sage.libs.singular
Scheme morphism:
  From: Closed subscheme of Affine Space of dimension 3 over Integer Ring
        defined by: x*y - z
  To:   Closed subscheme of Projective Space of dimension 3 over Integer Ring
        defined by: x0*x1 - x2*x3
  Defn: Defined on coordinates by sending (x, y, z) to (x : y : z : 1)
```

```
sage: A.<x, y, z> = AffineSpace(3, ZZ)
sage: P = ProjectiveSpace(3, ZZ, 'u')
sage: S = A.subscheme([x^2 - y*z])
sage: S.projective_embedding(1, P)                                       #␣
↪needs sage.libs.singular
Scheme morphism:
  From: Closed subscheme of Affine Space of dimension 3 over Integer Ring
        defined by: x^2 - y*z
  To:   Closed subscheme of Projective Space of dimension 3 over Integer Ring
        defined by: u0^2 - u2*u3
  Defn: Defined on coordinates by sending (x, y, z) to (x : 1 : y : z)
```

```
>>> from sage.all import *
>>> A = AffineSpace(Integer(3), ZZ, names=('x', 'y', 'z',)); (x, y, z,) = A._
↪first_ngens(3)
>>> P = ProjectiveSpace(Integer(3), ZZ, 'u')
>>> S = A.subscheme([x**Integer(2) - y*z])
>>> S.projective_embedding(Integer(1), P)                                   ␣
↪     # needs sage.libs.singular
Scheme morphism:
  From: Closed subscheme of Affine Space of dimension 3 over Integer Ring
        defined by: x^2 - y*z
  To:   Closed subscheme of Projective Space of dimension 3 over Integer Ring
        defined by: u0^2 - u2*u3
  Defn: Defined on coordinates by sending (x, y, z) to (x : 1 : y : z)
```

```
sage: A.<x,y,z> = AffineSpace(QQ, 3)
sage: X = A.subscheme([y - x^2, z - x^3])
sage: X.projective_embedding()                                           #␣
↪needs sage.libs.singular
Scheme morphism:
  From: Closed subscheme of Affine Space of dimension 3 over Rational Field
        defined by: -x^2 + y, -x^3 + z
  To:   Closed subscheme of Projective Space of dimension 3 over Rational␣
↪Field
```

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```
        defined by: x0^2 - x1*x3, x0*x1 - x2*x3, x1^2 - x0*x2
  Defn: Defined on coordinates by sending (x, y, z) to (x : y : z : 1)
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(3), names=('x', 'y', 'z',)); (x, y, z,) = A._
↪first_ngens(3)
>>> X = A.subscheme([y - x**Integer(2), z - x**Integer(3)])
>>> X.projective_embedding()                                                #␣
↪needs sage.libs.singular
Scheme morphism:
  From: Closed subscheme of Affine Space of dimension 3 over Rational Field
        defined by: -x^2 + y, -x^3 + z
  To:   Closed subscheme of Projective Space of dimension 3 over Rational␣
↪Field
        defined by: x0^2 - x1*x3, x0*x1 - x2*x3, x1^2 - x0*x2
  Defn: Defined on coordinates by sending (x, y, z) to (x : y : z : 1)
```

When taking a closed subscheme of an affine space with a projective embedding, the subscheme inherits the embedding:

```
sage: A.<u,v> = AffineSpace(2, QQ, default_embedding_index=1)
sage: X = A.subscheme(u - v)                                               #␣
↪needs sage.libs.singular
sage: X.projective_embedding()                                             #␣
↪needs sage.libs.singular
Scheme morphism:
  From: Closed subscheme of Affine Space of dimension 2 over Rational Field
        defined by: u - v
  To:   Closed subscheme of Projective Space of dimension 2 over Rational␣
↪Field
        defined by: x0 - x2
  Defn: Defined on coordinates by sending (u, v) to (u : 1 : v)
sage: phi = X.projective_embedding()                                       #␣
↪needs sage.libs.singular
sage: psi = A.projective_embedding()
sage: phi(X(2, 2)) == psi(A(X(2, 2)))                                     #␣
↪needs sage.libs.singular
True
```

```
>>> from sage.all import *
>>> A = AffineSpace(Integer(2), QQ, default_embedding_index=Integer(1),␣
↪names=('u', 'v',)); (u, v,) = A._first_ngens(2)
>>> X = A.subscheme(u - v)                                                 #␣
↪needs sage.libs.singular
>>> X.projective_embedding()                                               #␣
↪needs sage.libs.singular
Scheme morphism:
  From: Closed subscheme of Affine Space of dimension 2 over Rational Field
        defined by: u - v
  To:   Closed subscheme of Projective Space of dimension 2 over Rational␣
↪Field
        defined by: x0 - x2
```

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```
  Defn: Defined on coordinates by sending (u, v) to (u : 1 : v)
>>> phi = X.projective_embedding()                                    #␣
↪needs sage.libs.singular
>>> psi = A.projective_embedding()
>>> phi(X(Integer(2), Integer(2))) == psi(A(X(Integer(2), Integer(2))))      ␣
↪                                  # needs sage.libs.singular
True
```

class sage.schemes.affine.affine_subscheme.**AlgebraicScheme_subscheme_affine_field**(*A*, *polynomials*, *embedding_center=None*, *embedding_codomain=None*, *embedding_images=None*)

Bases: *AlgebraicScheme_subscheme_affine*

Algebraic subschemes of projective spaces defined over fields.

tangent_space(*p*)

Return the tangent space at the point `p`.

The points of the tangent space are the tangent vectors at `p`.

INPUT:

- `p` – a rational point

EXAMPLES:

```
sage: A3.<x,y,z> = AffineSpace(3, QQ)
sage: X = A3.subscheme(z - x*y)
sage: X.tangent_space(A3.origin())                                     #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 3 over Rational Field
 defined by:
  z
sage: X.tangent_space(X(1,1,1))                                        #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 3 over Rational Field
 defined by:
  -x - y + z
```

```
>>> from sage.all import *
>>> A3 = AffineSpace(Integer(3), QQ, names=('x', 'y', 'z',)); (x, y, z,) = A3.
↪_first_ngens(3)
```

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```
>>> X = A3.subscheme(z - x*y)
>>> X.tangent_space(A3.origin())                                              #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 3 over Rational Field
 defined by:
  z
>>> X.tangent_space(X(Integer(1),Integer(1),Integer(1)))                       ␣
↪                        # needs sage.libs.singular
Closed subscheme of Affine Space of dimension 3 over Rational Field
 defined by:
  -x - y + z
```

Tangent space at a point may have higher dimension than the dimension of the point.

```
sage: # needs sage.libs.singular
sage: C = Curve([x + y + z, x^2 - y^2*z^2 + z^3])
sage: C.singular_points()
[(0, 0, 0)]
sage: p = C(0,0,0)
sage: C.tangent_space(p)
Closed subscheme of Affine Space of dimension 3 over Rational Field
 defined by:
  x + y + z
sage: _.dimension()
2
sage: q = C(1,0,-1)
sage: C.tangent_space(q)
Closed subscheme of Affine Space of dimension 3 over Rational Field
 defined by:
  x + y + z,
  2*x + 3*z
sage: _.dimension()
1
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> C = Curve([x + y + z, x**Integer(2) - y**Integer(2)*z**Integer(2) +␣
↪z**Integer(3)])
>>> C.singular_points()
[(0, 0, 0)]
>>> p = C(Integer(0),Integer(0),Integer(0))
>>> C.tangent_space(p)
Closed subscheme of Affine Space of dimension 3 over Rational Field
 defined by:
  x + y + z
>>> _.dimension()
2
>>> q = C(Integer(1),Integer(0),-Integer(1))
>>> C.tangent_space(q)
Closed subscheme of Affine Space of dimension 3 over Rational Field
 defined by:
  x + y + z,
```

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```
  2*x + 3*z
>>> _.dimension()
1
```

13.5 Enumeration of rational points on affine schemes

Naive algorithms for enumerating rational points over **Q** or finite fields over for general schemes.

Warning

Incorrect results and infinite loops may occur if using a wrong function.

(For instance using an affine function for a projective scheme or a finite field function for a scheme defined over an infinite field.)

EXAMPLES:

Affine, over **Q**:

```
sage: from sage.schemes.affine.affine_rational_point import enum_affine_rational_field
sage: A.<x,y,z> = AffineSpace(3, QQ)
sage: S = A.subscheme([2*x - 3*y])
sage: enum_affine_rational_field(S, 2)
[(0, 0, -2), (0, 0, -1), (0, 0, -1/2), (0, 0, 0),
 (0, 0, 1/2), (0, 0, 1), (0, 0, 2)]
```

```
>>> from sage.all import *
>>> from sage.schemes.affine.affine_rational_point import enum_affine_rational_field
>>> A = AffineSpace(Integer(3), QQ, names=('x', 'y', 'z',)); (x, y, z,) = A._first_
↪ngens(3)
>>> S = A.subscheme([Integer(2)*x - Integer(3)*y])
>>> enum_affine_rational_field(S, Integer(2))
[(0, 0, -2), (0, 0, -1), (0, 0, -1/2), (0, 0, 0),
 (0, 0, 1/2), (0, 0, 1), (0, 0, 2)]
```

Affine over a finite field:

```
sage: from sage.schemes.affine.affine_rational_point import enum_affine_finite_field
sage: A.<w,x,y,z> = AffineSpace(4, GF(2))
sage: enum_affine_finite_field(A(GF(2)))
[(0, 0, 0, 0), (0, 0, 0, 1), (0, 0, 1, 0), (0, 0, 1, 1), (0, 1, 0, 0),
 (0, 1, 0, 1), (0, 1, 1, 0), (0, 1, 1, 1), (1, 0, 0, 0), (1, 0, 0, 1),
 (1, 0, 1, 0), (1, 0, 1, 1), (1, 1, 0, 0), (1, 1, 0, 1), (1, 1, 1, 0),
 (1, 1, 1, 1)]
```

```
>>> from sage.all import *
>>> from sage.schemes.affine.affine_rational_point import enum_affine_finite_field
>>> A = AffineSpace(Integer(4), GF(Integer(2)), names=('w', 'x', 'y', 'z',)); (w, x,␣
↪y, z,) = A._first_ngens(4)
>>> enum_affine_finite_field(A(GF(Integer(2))))
```

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```
[(0, 0, 0, 0), (0, 0, 0, 1), (0, 0, 1, 0), (0, 0, 1, 1), (0, 1, 0, 0),
 (0, 1, 0, 1), (0, 1, 1, 0), (0, 1, 1, 1), (1, 0, 0, 0), (1, 0, 0, 1),
 (1, 0, 1, 0), (1, 0, 1, 1), (1, 1, 0, 0), (1, 1, 0, 1), (1, 1, 1, 0),
 (1, 1, 1, 1)]
```

AUTHORS:

- David R. Kohel <kohel@maths.usyd.edu.au>: original version.
- John Cremona and Charlie Turner <charlotteturner@gmail.com> (06-2010): improvements to clarity and documentation.

sage.schemes.affine.affine_rational_point.**enum_affine_finite_field**(*X*)

Enumerates affine points on scheme X defined over a finite field.

INPUT:

- X – a scheme defined over a finite field or a set of abstract rational points of such a scheme

OUTPUT:

- a list containing the affine points of X over the finite field, sorted.

EXAMPLES:

```
sage: from sage.schemes.affine.affine_rational_point import enum_affine_finite_
↪field
sage: F = GF(7)
sage: A.<w,x,y,z> = AffineSpace(4, F)
sage: C = A.subscheme([w^2 + x + 4, y*z*x - 6, z*y + w*x])
sage: enum_affine_finite_field(C(F))
[]
sage: C = A.subscheme([w^2 + x + 4, y*z*x - 6])
sage: enum_affine_finite_field(C(F))
[(0, 3, 1, 2), (0, 3, 2, 1), (0, 3, 3, 3), (0, 3, 4, 4), (0, 3, 5, 6),
 (0, 3, 6, 5), (1, 2, 1, 3), (1, 2, 2, 5), (1, 2, 3, 1), (1, 2, 4, 6),
 (1, 2, 5, 2), (1, 2, 6, 4), (2, 6, 1, 1), (2, 6, 2, 4), (2, 6, 3, 5),
 (2, 6, 4, 2), (2, 6, 5, 3), (2, 6, 6, 6), (3, 1, 1, 6), (3, 1, 2, 3),
 (3, 1, 3, 2), (3, 1, 4, 5), (3, 1, 5, 4), (3, 1, 6, 1), (4, 1, 1, 6),
 (4, 1, 2, 3), (4, 1, 3, 2), (4, 1, 4, 5), (4, 1, 5, 4), (4, 1, 6, 1),
 (5, 6, 1, 1), (5, 6, 2, 4), (5, 6, 3, 5), (5, 6, 4, 2), (5, 6, 5, 3),
 (5, 6, 6, 6), (6, 2, 1, 3), (6, 2, 2, 5), (6, 2, 3, 1), (6, 2, 4, 6),
 (6, 2, 5, 2), (6, 2, 6, 4)]
```

```
>>> from sage.all import *
>>> from sage.schemes.affine.affine_rational_point import enum_affine_finite_field
>>> F = GF(Integer(7))
>>> A = AffineSpace(Integer(4), F, names=('w', 'x', 'y', 'z',)); (w, x, y, z,) =␣
↪A._first_ngens(4)
>>> C = A.subscheme([w**Integer(2) + x + Integer(4), y*z*x - Integer(6), z*y +␣
↪w*x])
>>> enum_affine_finite_field(C(F))
[]
>>> C = A.subscheme([w**Integer(2) + x + Integer(4), y*z*x - Integer(6)])
>>> enum_affine_finite_field(C(F))
[(0, 3, 1, 2), (0, 3, 2, 1), (0, 3, 3, 3), (0, 3, 4, 4), (0, 3, 5, 6),
```

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```
 (0, 3, 6, 5), (1, 2, 1, 3), (1, 2, 2, 5), (1, 2, 3, 1), (1, 2, 4, 6),
 (1, 2, 5, 2), (1, 2, 6, 4), (2, 6, 1, 1), (2, 6, 2, 4), (2, 6, 3, 5),
 (2, 6, 4, 2), (2, 6, 5, 3), (2, 6, 6, 6), (3, 1, 1, 6), (3, 1, 2, 3),
 (3, 1, 3, 2), (3, 1, 4, 5), (3, 1, 5, 4), (3, 1, 6, 1), (4, 1, 1, 6),
 (4, 1, 2, 3), (4, 1, 3, 2), (4, 1, 4, 5), (4, 1, 5, 4), (4, 1, 6, 1),
 (5, 6, 1, 1), (5, 6, 2, 4), (5, 6, 3, 5), (5, 6, 4, 2), (5, 6, 5, 3),
 (5, 6, 6, 6), (6, 2, 1, 3), (6, 2, 2, 5), (6, 2, 3, 1), (6, 2, 4, 6),
 (6, 2, 5, 2), (6, 2, 6, 4)]
```

```
sage: A.<x,y,z> = AffineSpace(3, GF(3))
sage: S = A.subscheme(x + y)
sage: enum_affine_finite_field(S)
[(0, 0, 0), (0, 0, 1), (0, 0, 2), (1, 2, 0), (1, 2, 1), (1, 2, 2),
 (2, 1, 0), (2, 1, 1), (2, 1, 2)]
```

```
>>> from sage.all import *
>>> A = AffineSpace(Integer(3), GF(Integer(3)), names=('x', 'y', 'z',)); (x, y, z,
↪) = A._first_ngens(3)
>>> S = A.subscheme(x + y)
>>> enum_affine_finite_field(S)
[(0, 0, 0), (0, 0, 1), (0, 0, 2), (1, 2, 0), (1, 2, 1), (1, 2, 2),
 (2, 1, 0), (2, 1, 1), (2, 1, 2)]
```

ALGORITHM:

Checks all points in affine space to see if they lie on X.

Warning

If `X` is defined over an infinite field, this code will not finish!

AUTHORS:

- John Cremona and Charlie Turner (06-2010)

`sage.schemes.affine.affine_rational_point.`**`enum_affine_number_field`**(*X*, ***kwds*)

Enumerates affine points on scheme `X` defined over a number field. Simply checks all of the points of absolute height up to `B` and adds those that are on the scheme to the list.

This algorithm computes 2 lists: L containing elements x in K such that H_k(x) <= B, and a list L' containing elements x in K that, due to floating point issues, may be slightly larger then the bound. This can be controlled by lowering the tolerance.

ALGORITHM:

This is an implementation of the revised algorithm (Algorithm 4) in [DK2013]. Algorithm 5 is used for imaginary quadratic fields.

INPUT: keyword arguments:

- `bound` – a real number
- `tolerance` – a rational number in (0,1] used in Doyle-Krumm algorithm-4
- `precision` – the precision to use for computing the elements of bounded height of number fields

OUTPUT:

- a list containing the affine points of X of absolute height up to B, sorted.

EXAMPLES:

```
sage: # needs sage.rings.number_field
sage: from sage.schemes.affine.affine_rational_point import enum_affine_number_
↪field
sage: u = QQ['u'].0
sage: K = NumberField(u^2 + 2, 'v')
sage: A.<x,y,z> = AffineSpace(K, 3)
sage: X = A.subscheme([y^2 - x])
sage: enum_affine_number_field(X(K), bound=2**0.5)
[(0, 0, -1), (0, 0, -v), (0, 0, -1/2*v), (0, 0, 0), (0, 0, 1/2*v),
 (0, 0, v), (0, 0, 1), (1, -1, -1), (1, -1, -v), (1, -1, -1/2*v),
 (1, -1, 0), (1, -1, 1/2*v), (1, -1, v), (1, -1, 1), (1, 1, -1),
 (1, 1, -v), (1, 1, -1/2*v), (1, 1, 0), (1, 1, 1/2*v), (1, 1, v), (1, 1, 1)]
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> from sage.schemes.affine.affine_rational_point import enum_affine_number_field
>>> u = QQ['u'].gen(0)
>>> K = NumberField(u**Integer(2) + Integer(2), 'v')
>>> A = AffineSpace(K, Integer(3), names=('x', 'y', 'z',)); (x, y, z,) = A._first_
↪ngens(3)
>>> X = A.subscheme([y**Integer(2) - x])
>>> enum_affine_number_field(X(K), bound=Integer(2)**RealNumber('0.5'))
[(0, 0, -1), (0, 0, -v), (0, 0, -1/2*v), (0, 0, 0), (0, 0, 1/2*v),
 (0, 0, v), (0, 0, 1), (1, -1, -1), (1, -1, -v), (1, -1, -1/2*v),
 (1, -1, 0), (1, -1, 1/2*v), (1, -1, v), (1, -1, 1), (1, 1, -1),
 (1, 1, -v), (1, 1, -1/2*v), (1, 1, 0), (1, 1, 1/2*v), (1, 1, v), (1, 1, 1)]
```

```
sage: # needs sage.rings.number_field
sage: from sage.schemes.affine.affine_rational_point import enum_affine_number_
↪field
sage: u = QQ['u'].0
sage: K = NumberField(u^2 + 3, 'v')
sage: A.<x,y> = AffineSpace(K, 2)
sage: X = A.subscheme(x - y)
sage: enum_affine_number_field(X, bound=3**0.25)
[(-1, -1), (-1/2*v - 1/2, -1/2*v - 1/2), (1/2*v - 1/2, 1/2*v - 1/2),
 (0, 0), (-1/2*v + 1/2, -1/2*v + 1/2), (1/2*v + 1/2, 1/2*v + 1/2), (1, 1)]
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> from sage.schemes.affine.affine_rational_point import enum_affine_number_field
>>> u = QQ['u'].gen(0)
>>> K = NumberField(u**Integer(2) + Integer(3), 'v')
>>> A = AffineSpace(K, Integer(2), names=('x', 'y',)); (x, y,) = A._first_ngens(2)
>>> X = A.subscheme(x - y)
>>> enum_affine_number_field(X, bound=Integer(3)**RealNumber('0.25'))
[(-1, -1), (-1/2*v - 1/2, -1/2*v - 1/2), (1/2*v - 1/2, 1/2*v - 1/2),
 (0, 0), (-1/2*v + 1/2, -1/2*v + 1/2), (1/2*v + 1/2, 1/2*v + 1/2), (1, 1)]
```

sage.schemes.affine.affine_rational_point.**enum_affine_rational_field**(X, B)

Enumerates affine rational points on scheme X up to bound B.

INPUT:

- X – a scheme or set of abstract rational points of a scheme
- B – a positive integer bound

OUTPUT:

- a list containing the affine points of X of height up to B, sorted.

EXAMPLES:

```
sage: A.<x,y,z> = AffineSpace(3, QQ)
sage: from sage.schemes.affine.affine_rational_point import enum_affine_rational_
↪field
sage: enum_affine_rational_field(A(QQ), 1)
[(-1, -1, -1), (-1, -1, 0), (-1, -1, 1), (-1, 0, -1), (-1, 0, 0), (-1, 0, 1),
 (-1, 1, -1), (-1, 1, 0), (-1, 1, 1), (0, -1, -1), (0, -1, 0), (0, -1, 1),
 (0, 0, -1), (0, 0, 0), (0, 0, 1), (0, 1, -1), (0, 1, 0), (0, 1, 1), (1, -1, -1),
 (1, -1, 0), (1, -1, 1), (1, 0, -1), (1, 0, 0), (1, 0, 1), (1, 1, -1), (1, 1, 0),
 (1, 1, 1)]
```

```
>>> from sage.all import *
>>> A = AffineSpace(Integer(3), QQ, names=('x', 'y', 'z',)); (x, y, z,) = A._
↪first_ngens(3)
>>> from sage.schemes.affine.affine_rational_point import enum_affine_rational_
↪field
>>> enum_affine_rational_field(A(QQ), Integer(1))
[(-1, -1, -1), (-1, -1, 0), (-1, -1, 1), (-1, 0, -1), (-1, 0, 0), (-1, 0, 1),
 (-1, 1, -1), (-1, 1, 0), (-1, 1, 1), (0, -1, -1), (0, -1, 0), (0, -1, 1),
 (0, 0, -1), (0, 0, 0), (0, 0, 1), (0, 1, -1), (0, 1, 0), (0, 1, 1), (1, -1, -1),
 (1, -1, 0), (1, -1, 1), (1, 0, -1), (1, 0, 0), (1, 0, 1), (1, 1, -1), (1, 1, 0),
 (1, 1, 1)]
```

```
sage: A.<w,x,y,z> = AffineSpace(4, QQ)
sage: S = A.subscheme([x^2 - y*z + 1, w^3 + z + y^2])
sage: enum_affine_rational_field(S(QQ), 1)
[(0, 0, -1, -1)]
sage: enum_affine_rational_field(S(QQ), 2)
[(0, 0, -1, -1), (1, -1, -1, -2), (1, 1, -1, -2)]
```

```
>>> from sage.all import *
>>> A = AffineSpace(Integer(4), QQ, names=('w', 'x', 'y', 'z',)); (w, x, y, z,) =␣
↪A._first_ngens(4)
>>> S = A.subscheme([x**Integer(2) - y*z + Integer(1), w**Integer(3) + z +␣
↪y**Integer(2)])
>>> enum_affine_rational_field(S(QQ), Integer(1))
[(0, 0, -1, -1)]
>>> enum_affine_rational_field(S(QQ), Integer(2))
[(0, 0, -1, -1), (1, -1, -1, -2), (1, 1, -1, -2)]
```

```
sage: A.<x,y> = AffineSpace(2, QQ)
sage: C = Curve(x^2 + y - x)                                                #␣
↪needs sage.libs.singular
sage: enum_affine_rational_field(C, 10)          # long time (3 s)          #␣
↪needs sage.libs.singular
[(-2, -6), (-1, -2), (-2/3, -10/9), (-1/2, -3/4), (-1/3, -4/9),
 (0, 0), (1/3, 2/9), (1/2, 1/4), (2/3, 2/9), (1, 0),
 (4/3, -4/9), (3/2, -3/4), (5/3, -10/9), (2, -2), (3, -6)]
```

```
>>> from sage.all import *
>>> A = AffineSpace(Integer(2), QQ, names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> C = Curve(x**Integer(2) + y - x)                                        ␣
↪      # needs sage.libs.singular
>>> enum_affine_rational_field(C, Integer(10))          # long time (3 s)   ␣
↪     # needs sage.libs.singular
[(-2, -6), (-1, -2), (-2/3, -10/9), (-1/2, -3/4), (-1/3, -4/9),
 (0, 0), (1/3, 2/9), (1/2, 1/4), (2/3, 2/9), (1, 0),
 (4/3, -4/9), (3/2, -3/4), (5/3, -10/9), (2, -2), (3, -6)]
```

AUTHORS:

- David R. Kohel <kohel@maths.usyd.edu.au>: original version.
- Charlie Turner (06-2010): small adjustments.
- Raman Raghukul 2018: updated.

13.6 Set of homomorphisms between two affine schemes

For schemes X and Y, this module implements the set of morphisms $Hom(X, Y)$. This is done by *SchemeHomset_generic*.

As a special case, the Hom-sets can also represent the points of a scheme. Recall that the K-rational points of a scheme X over k can be identified with the set of morphisms $Spec(K) \to X$. In Sage the rational points are implemented by such scheme morphisms. This is done by *SchemeHomset_points* and its subclasses.

Note

You should not create the Hom-sets manually. Instead, use the `Hom()` method that is inherited by all schemes.

AUTHORS:

- William Stein (2006): initial version.
- Ben Hutz (2018): add numerical point support

class sage.schemes.affine.affine_homset.**SchemeHomset_points_affine**(*X*, *Y*, *category=None*, *check=True*, *base=Integer Ring*)

Bases: *SchemeHomset_points*

Set of rational points of an affine variety.

INPUT:

See *SchemeHomset_generic*.

EXAMPLES:

```
sage: from sage.schemes.affine.affine_homset import SchemeHomset_points_affine
sage: SchemeHomset_points_affine(Spec(QQ), AffineSpace(ZZ,2))
Set of rational points of Affine Space of dimension 2 over Rational Field
```

```
>>> from sage.all import *
>>> from sage.schemes.affine.affine_homset import SchemeHomset_points_affine
>>> SchemeHomset_points_affine(Spec(QQ), AffineSpace(ZZ,Integer(2)))
Set of rational points of Affine Space of dimension 2 over Rational Field
```

numerical_points(*F=None*, ***kwds*)

Return some or all numerical approximations of rational points of an affine scheme.

This is for dimension 0 subschemes only and the points are determined through a groebner calculation over the base ring and then numerically approximating the roots of the resulting polynomials. If the base ring is a number field, the embedding into `F` must be known.

INPUT:

- `F` – numerical ring

kwds:

- `zero_tolerance` – positive real number (default: 10^(-10)). For numerically inexact fields, points are on the subscheme if they satisfy the equations to within tolerance.

OUTPUT: list of points in the ambient space

Warning

For numerically inexact fields the list of points returned may contain repeated or be missing points due to tolerance.

EXAMPLES:

```
sage: # needs sage.libs.singular sage.rings.number_field
sage: K.<v> = QuadraticField(3)
sage: A.<x,y> = AffineSpace(K, 2)
sage: X = A.subscheme([x^3 - v^2*y, y - v*x^2 + 3])
sage: L = X(K).numerical_points(F=RR); L  # abs tol 1e-14
[(-1.18738247880014, -0.558021142104134),
 (1.57693558184861, 1.30713548084184),
 (4.80659931965815, 37.0162574656220)]
sage: L[0].codomain()
Affine Space of dimension 2 over Real Field with 53 bits of precision
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular sage.rings.number_field
>>> K = QuadraticField(Integer(3), names=('v',)); (v,) = K._first_ngens(1)
>>> A = AffineSpace(K, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> X = A.subscheme([x**Integer(3) - v**Integer(2)*y, y - v*x**Integer(2) +␣
```

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```
↪Integer(3)])
>>> L = X(K).numerical_points(F=RR); L  # abs tol 1e-14
[(-1.18738247880014, -0.558021142104134),
 (1.57693558184861, 1.30713548084184),
 (4.80659931965815, 37.0162574656220)]
>>> L[Integer(0)].codomain()
Affine Space of dimension 2 over Real Field with 53 bits of precision
```

```
sage: A.<x,y> = AffineSpace(QQ, 2)
sage: X = A.subscheme([y^2 - x^2 - 3*x, x^2 - 10*y])
sage: len(X(QQ).numerical_points(F=ComplexField(100)))                    #␣
↪needs sage.libs.singular
4
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> X = A.subscheme([y**Integer(2) - x**Integer(2) - Integer(3)*x,␣
↪x**Integer(2) - Integer(10)*y])
>>> len(X(QQ).numerical_points(F=ComplexField(Integer(100))))                ␣
↪     # needs sage.libs.singular
4
```

```
sage: A.<x1, x2> = AffineSpace(QQ, 2)
sage: E = A.subscheme([30*x1^100 + 1000*x2^2 + 2000*x1*x2 + 1, x1 + x2])
sage: len(E(A.base_ring()).numerical_points(F=CDF, zero_tolerance=1e-9))    #␣
↪needs sage.libs.singular
100
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(2), names=('x1', 'x2',)); (x1, x2,) = A._
↪first_ngens(2)
>>> E = A.subscheme([Integer(30)*x1**Integer(100) +␣
↪Integer(1000)*x2**Integer(2) + Integer(2000)*x1*x2 + Integer(1), x1 + x2])
>>> len(E(A.base_ring()).numerical_points(F=CDF, zero_tolerance=RealNumber(
↪'1e-9')))     # needs sage.libs.singular
100
```

points(***kwds*)

Return some or all rational points of an affine scheme.

For dimension 0 subschemes points are determined through a groebner basis calculation. For schemes or subschemes with dimension greater than 1 points are determined through enumeration up to the specified bound.

Over a finite field, all points are returned. Over an infinite field, all points satisfying the bound are returned. For a zero-dimensional subscheme, all points are returned regardless of whether the field is infinite or not.

For number fields, this uses the Doyle-Krumm algorithm 4 (algorithm 5 for imaginary quadratic) for computing algebraic numbers up to a given height [DK2013].

The algorithm requires floating point arithmetic, so the user is allowed to specify the precision for such calculations. Additionally, due to floating point issues, points slightly larger than the bound may be returned. This can be controlled by lowering the tolerance.

INPUT: keyword arguments:

- `bound` – real number (default: 0). The bound for the height of the coordinates. Only used for subschemes with dimension at least 1.
- `zero_tolerance` – positive real number (default: 10^(-10)). For numerically inexact fields, points are on the subscheme if they satisfy the equations to within tolerance.
- `tolerance` – a rational number in (0,1] used in Doyle-Krumm algorithm-4 for enumeration over number fields
- `precision` – the precision to use for computing the elements of bounded height of number fields

OUTPUT: list of rational points of a affine scheme

Warning

For numerically inexact fields such as ComplexField or RealField the list of points returned is very likely to be incomplete. It may also contain repeated points due to tolerance.

EXAMPLES: The bug reported at #11526 is fixed:

```
sage: A2 = AffineSpace(ZZ, 2)
sage: F = GF(3)
sage: A2(F).points()
[(0, 0), (0, 1), (0, 2), (1, 0), (1, 1), (1, 2), (2, 0), (2, 1), (2, 2)]
```

```
>>> from sage.all import *
>>> A2 = AffineSpace(ZZ, Integer(2))
>>> F = GF(Integer(3))
>>> A2(F).points()
[(0, 0), (0, 1), (0, 2), (1, 0), (1, 1), (1, 2), (2, 0), (2, 1), (2, 2)]
```

```
sage: A.<x,y> = ZZ[]
sage: I = A.ideal(x^2 - y^2 - 1)
sage: V = AffineSpace(ZZ, 2)
sage: X = V.subscheme(I)
sage: M = X(ZZ)
sage: M.points(bound=1)
[(-1, 0), (1, 0)]
```

```
>>> from sage.all import *
>>> A = ZZ['x, y']; (x, y,) = A._first_ngens(2)
>>> I = A.ideal(x**Integer(2) - y**Integer(2) - Integer(1))
>>> V = AffineSpace(ZZ, Integer(2))
>>> X = V.subscheme(I)
>>> M = X(ZZ)
>>> M.points(bound=Integer(1))
[(-1, 0), (1, 0)]
```

```
sage: u = QQ['u'].0
sage: K.<v> = NumberField(u^2 + 3)                                    #␣
↪needs sage.rings.number_field
sage: A.<x,y> = AffineSpace(K, 2)                                     #␣
```

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```
↪needs sage.rings.number_field
sage: len(A(K).points(bound=2))                                                 #␣
↪needs sage.rings.number_field
1849
```

```
>>> from sage.all import *
>>> u = QQ['u'].gen(0)
>>> K = NumberField(u**Integer(2) + Integer(3), names=('v',)); (v,) = K._
↪first_ngens(1)# needs sage.rings.number_field
>>> A = AffineSpace(K, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)# needs sage.rings.number_field
>>> len(A(K).points(bound=Integer(2)))                                          ␣
↪     # needs sage.rings.number_field
1849
```

```
sage: A.<x,y> = AffineSpace(QQ, 2)
sage: E = A.subscheme([x^2 + y^2 - 1, y^2 - x^3 + x^2 + x - 1])
sage: E(A.base_ring()).points()                                                 #␣
↪needs sage.libs.singular
[(-1, 0), (0, -1), (0, 1), (1, 0)]
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> E = A.subscheme([x**Integer(2) + y**Integer(2) - Integer(1),␣
↪y**Integer(2) - x**Integer(3) + x**Integer(2) + x - Integer(1)])
>>> E(A.base_ring()).points()                                                   #␣
↪needs sage.libs.singular
[(-1, 0), (0, -1), (0, 1), (1, 0)]
```

```
sage: A.<x,y> = AffineSpace(CC, 2)                                              #␣
↪needs sage.rings.real_mpfr
sage: E = A.subscheme([y^3 - x^3 - x^2, x*y])
sage: E(A.base_ring()).points()                                                 #␣
↪needs sage.libs.singular sage.rings.real_mpfr
verbose 0 (...: affine_homset.py, points)
Warning: computations in the numerical fields are inexact;points
may be computed partially or incorrectly.
[(-1.00000000000000, 0.000000000000000),
 (0.000000000000000, 0.000000000000000)]
```

```
>>> from sage.all import *
>>> A = AffineSpace(CC, Integer(2), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)# needs sage.rings.real_mpfr
>>> E = A.subscheme([y**Integer(3) - x**Integer(3) - x**Integer(2), x*y])
>>> E(A.base_ring()).points()                                                   #␣
↪needs sage.libs.singular sage.rings.real_mpfr
verbose 0 (...: affine_homset.py, points)
Warning: computations in the numerical fields are inexact;points
may be computed partially or incorrectly.
[(-1.00000000000000, 0.000000000000000),
```

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```
 (0.000000000000000, 0.000000000000000)]
```

```
sage: A.<x1,x2> = AffineSpace(CDF, 2)                                    #␣
↪needs sage.rings.complex_double
sage: E = A.subscheme([x1^2 + x2^2 + x1*x2, x1 + x2])                    #␣
↪needs sage.libs.singular sage.rings.complex_double
sage: E(A.base_ring()).points()                                          #␣
↪needs sage.libs.singular sage.rings.complex_double
verbose 0 (...: affine_homset.py, points)
Warning: computations in the numerical fields are inexact;points
may be computed partially or incorrectly.
[(0.0, 0.0)]
```

```
>>> from sage.all import *
>>> A = AffineSpace(CDF, Integer(2), names=('x1', 'x2',)); (x1, x2,) = A._
↪first_ngens(2)# needs sage.rings.complex_double
>>> E = A.subscheme([x1**Integer(2) + x2**Integer(2) + x1*x2, x1 + x2])  ␣
↪                # needs sage.libs.singular sage.rings.complex_double
>>> E(A.base_ring()).points()                                            #␣
↪needs sage.libs.singular sage.rings.complex_double
verbose 0 (...: affine_homset.py, points)
Warning: computations in the numerical fields are inexact;points
may be computed partially or incorrectly.
[(0.0, 0.0)]
```

class sage.schemes.affine.affine_homset.**SchemeHomset_points_spec**(*X*, *Y*, *category=None*, *check=True*, *base=None*)

Bases: *SchemeHomset_generic*

Set of rational points of an affine variety.

INPUT:

See *SchemeHomset_generic*.

EXAMPLES:

```
sage: from sage.schemes.affine.affine_homset import SchemeHomset_points_spec
sage: SchemeHomset_points_spec(Spec(QQ), Spec(QQ))
Set of rational points of Spectrum of Rational Field
```

```
>>> from sage.all import *
>>> from sage.schemes.affine.affine_homset import SchemeHomset_points_spec
>>> SchemeHomset_points_spec(Spec(QQ), Spec(QQ))
Set of rational points of Spectrum of Rational Field
```

class sage.schemes.affine.affine_homset.**SchemeHomset_polynomial_affine_space**(*X*, *Y*, *category=None*, *check=True*, *base=None*)

Bases: *SchemeHomset_generic*

Set of morphisms between affine spaces defined by polynomials.

EXAMPLES:

```
sage: A.<x,y> = AffineSpace(2, QQ)
sage: Hom(A, A)
Set of morphisms
  From: Affine Space of dimension 2 over Rational Field
  To:   Affine Space of dimension 2 over Rational Field
```

```
>>> from sage.all import *
>>> A = AffineSpace(Integer(2), QQ, names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> Hom(A, A)
Set of morphisms
  From: Affine Space of dimension 2 over Rational Field
  To:   Affine Space of dimension 2 over Rational Field
```

identity()

The identity morphism of this homset.

EXAMPLES:

```
sage: A.<x,y> = AffineSpace(2, QQ)
sage: I = A.identity_morphism()
sage: I.parent()
Set of morphisms
  From: Affine Space of dimension 2 over Rational Field
  To:   Affine Space of dimension 2 over Rational Field
sage: _.identity() == I
True
```

```
>>> from sage.all import *
>>> A = AffineSpace(Integer(2), QQ, names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> I = A.identity_morphism()
>>> I.parent()
Set of morphisms
  From: Affine Space of dimension 2 over Rational Field
  To:   Affine Space of dimension 2 over Rational Field
>>> _.identity() == I
True
```

CHAPTER

FOURTEEN

PROJECTIVE SCHEMES

14.1 Projective n space over a ring

EXAMPLES:

We construct projective space over various rings of various dimensions.

The simplest projective space:

```
sage: ProjectiveSpace(0)
Projective Space of dimension 0 over Integer Ring
```

```
>>> from sage.all import *
>>> ProjectiveSpace(Integer(0))
Projective Space of dimension 0 over Integer Ring
```

A slightly bigger projective space over $\mathbf{Q}$:

```
sage: X = ProjectiveSpace(1000, QQ); X
Projective Space of dimension 1000 over Rational Field
sage: X.dimension()
1000
```

```
>>> from sage.all import *
>>> X = ProjectiveSpace(Integer(1000), QQ); X
Projective Space of dimension 1000 over Rational Field
>>> X.dimension()
1000
```

We can use "over" notation to create projective spaces over various base rings.

```
sage: X = ProjectiveSpace(5)/QQ; X
Projective Space of dimension 5 over Rational Field
sage: X/CC                                                                  #␣
↪needs sage.rings.real_mpfr
Projective Space of dimension 5 over Complex Field with 53 bits of precision
```

```
>>> from sage.all import *
>>> X = ProjectiveSpace(Integer(5))/QQ; X
Projective Space of dimension 5 over Rational Field
>>> X/CC                                                                    #␣
```

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```
↪needs sage.rings.real_mpfr
Projective Space of dimension 5 over Complex Field with 53 bits of precision
```

The third argument specifies the printing names of the generators of the homogeneous coordinate ring. Using the method `objgens()` you can obtain both the space and the generators as ready to use variables.

```
sage: P2, vars = ProjectiveSpace(10, QQ, 't').objgens()
sage: vars
(t0, t1, t2, t3, t4, t5, t6, t7, t8, t9, t10)
```

```
>>> from sage.all import *
>>> P2, vars = ProjectiveSpace(Integer(10), QQ, 't').objgens()
>>> vars
(t0, t1, t2, t3, t4, t5, t6, t7, t8, t9, t10)
```

You can alternatively use the special syntax with < and >.

```
sage: P2.<x,y,z> = ProjectiveSpace(2, QQ)
sage: P2
Projective Space of dimension 2 over Rational Field
sage: P2.coordinate_ring()
Multivariate Polynomial Ring in x, y, z over Rational Field
```

```
>>> from sage.all import *
>>> P2 = ProjectiveSpace(Integer(2), QQ, names=('x', 'y', 'z',)); (x, y, z,) = P2._
↪first_ngens(3)
>>> P2
Projective Space of dimension 2 over Rational Field
>>> P2.coordinate_ring()
Multivariate Polynomial Ring in x, y, z over Rational Field
```

The first of the three lines above is just equivalent to the two lines:

```
sage: P2 = ProjectiveSpace(2, QQ, 'xyz')
sage: x,y,z = P2.gens()
```

```
>>> from sage.all import *
>>> P2 = ProjectiveSpace(Integer(2), QQ, 'xyz')
>>> x,y,z = P2.gens()
```

For example, we use x, y, z to define the intersection of two lines.

```
sage: V = P2.subscheme([x + y + z, x + y - z]); V
Closed subscheme of Projective Space of dimension 2 over Rational Field defined by:
  x + y + z,
  x + y - z
sage: V.dimension()                                                    #␣
↪needs sage.libs.singular
0
```

```
>>> from sage.all import *
>>> V = P2.subscheme([x + y + z, x + y - z]); V
```

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```
Closed subscheme of Projective Space of dimension 2 over Rational Field defined by:
  x + y + z,
  x + y - z
>>> V.dimension()                                                              #␣
↪needs sage.libs.singular
0
```

AUTHORS:

- Ben Hutz: (June 2012): support for rings
- Ben Hutz (9/2014): added support for Cartesian products
- Rebecca Lauren Miller (March 2016) : added point_transformation_matrix

sage.schemes.projective.projective_space.**ProjectiveSpace**(*n*, *R=None*, *names=None*)

Return projective space of dimension `n` over the ring `R`.

EXAMPLES: The dimension and ring can be given in either order.

```
sage: ProjectiveSpace(3, QQ)
Projective Space of dimension 3 over Rational Field
sage: ProjectiveSpace(5, QQ)
Projective Space of dimension 5 over Rational Field
sage: P = ProjectiveSpace(2, QQ, names='XYZ'); P
Projective Space of dimension 2 over Rational Field
sage: P.coordinate_ring()
Multivariate Polynomial Ring in X, Y, Z over Rational Field
```

```
>>> from sage.all import *
>>> ProjectiveSpace(Integer(3), QQ)
Projective Space of dimension 3 over Rational Field
>>> ProjectiveSpace(Integer(5), QQ)
Projective Space of dimension 5 over Rational Field
>>> P = ProjectiveSpace(Integer(2), QQ, names='XYZ'); P
Projective Space of dimension 2 over Rational Field
>>> P.coordinate_ring()
Multivariate Polynomial Ring in X, Y, Z over Rational Field
```

The divide operator does base extension.

```
sage: ProjectiveSpace(5)/GF(17)
Projective Space of dimension 5 over Finite Field of size 17
```

```
>>> from sage.all import *
>>> ProjectiveSpace(Integer(5))/GF(Integer(17))
Projective Space of dimension 5 over Finite Field of size 17
```

The default base ring is **Z**.

```
sage: ProjectiveSpace(5)
Projective Space of dimension 5 over Integer Ring
```

```
>>> from sage.all import *
>>> ProjectiveSpace(Integer(5))
Projective Space of dimension 5 over Integer Ring
```

There is also a projective space associated each polynomial ring.

```
sage: R = GF(7)['x,y,z']
sage: P = ProjectiveSpace(R); P
Projective Space of dimension 2 over Finite Field of size 7
sage: P.coordinate_ring()
Multivariate Polynomial Ring in x, y, z over Finite Field of size 7
sage: P.coordinate_ring() is R
True
```

```
>>> from sage.all import *
>>> R = GF(Integer(7))['x,y,z']
>>> P = ProjectiveSpace(R); P
Projective Space of dimension 2 over Finite Field of size 7
>>> P.coordinate_ring()
Multivariate Polynomial Ring in x, y, z over Finite Field of size 7
>>> P.coordinate_ring() is R
True
```

```
sage: ProjectiveSpace(3, Zp(5), 'y')                                    #␣
↪needs sage.rings.padics
Projective Space of dimension 3 over 5-adic Ring with capped relative precision 20
```

```
>>> from sage.all import *
>>> ProjectiveSpace(Integer(3), Zp(Integer(5)), 'y')                     ␣
↪              # needs sage.rings.padics
Projective Space of dimension 3 over 5-adic Ring with capped relative precision 20
```

```
sage: ProjectiveSpace(2, QQ, 'x,y,z')
Projective Space of dimension 2 over Rational Field
```

```
>>> from sage.all import *
>>> ProjectiveSpace(Integer(2), QQ, 'x,y,z')
Projective Space of dimension 2 over Rational Field
```

```
sage: PS.<x,y> = ProjectiveSpace(1, CC); PS                             #␣
↪needs sage.rings.real_mpfr
Projective Space of dimension 1 over Complex Field with 53 bits of precision
```

```
>>> from sage.all import *
>>> PS = ProjectiveSpace(Integer(1), CC, names=('x', 'y',)); (x, y,) = PS._first_
↪ngens(2); PS                                    # needs sage.rings.real_mpfr
Projective Space of dimension 1 over Complex Field with 53 bits of precision
```

```
sage: R.<x,y,z> = QQ[]
sage: ProjectiveSpace(R).variable_names()
('x', 'y', 'z')
```

```
>>> from sage.all import *
>>> R = QQ['x, y, z']; (x, y, z,) = R._first_ngens(3)
>>> ProjectiveSpace(R).variable_names()
('x', 'y', 'z')
```

Projective spaces are not cached, i.e., there can be several with the same base ring and dimension (to facilitate gluing constructions).

```
sage: R.<x> = QQ[]
sage: ProjectiveSpace(R)
Projective Space of dimension 0 over Rational Field
```

```
>>> from sage.all import *
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> ProjectiveSpace(R)
Projective Space of dimension 0 over Rational Field
```

class sage.schemes.projective.projective_space.**ProjectiveSpace_field**(*n*, *R=Integer Ring*, *names=None*)

Bases: *ProjectiveSpace_ring*

curve(*F*)

Return a curve defined by `F` in this projective space.

INPUT:

- `F` – a polynomial, or a list or tuple of polynomials in the coordinate ring of this projective space

EXAMPLES:

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: P.curve([y^2 - x*z])                                                  #␣
↪needs sage.schemes
Projective Plane Curve over Rational Field defined by y^2 - x*z
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> P.curve([y**Integer(2) - x*z])                                          ␣
↪      # needs sage.schemes
Projective Plane Curve over Rational Field defined by y^2 - x*z
```

line_through(*p*, *q*)

Return the line through `p` and `q`.

INPUT:

- `p`, `q` – distinct rational points of the projective space

EXAMPLES:

```
sage: P3.<x0,x1,x2,x3> = ProjectiveSpace(3, QQ)
sage: p1 = P3(1, 2, 3, 4)
sage: p2 = P3(4, 3, 2, 1)
sage: P3.line_through(p1, p2)                                               #␣
```

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```
↪needs sage.libs.singular sage.schemes
Projective Curve over Rational Field defined by
  -5/4*x0 + 5/2*x1 - 5/4*x2,        -5/2*x0 + 15/4*x1 - 5/4*x3,
  -5/4*x0 + 15/4*x2 - 5/2*x3,       -5/4*x1 + 5/2*x2 - 5/4*x3
sage: p3 = P3(2,4,6,8)
sage: P3.line_through(p1, p3)
Traceback (most recent call last):
...
ValueError: not distinct points
```

```
>>> from sage.all import *
>>> P3 = ProjectiveSpace(Integer(3), QQ, names=('x0', 'x1', 'x2', 'x3',));␣
↪(x0, x1, x2, x3,) = P3._first_ngens(4)
>>> p1 = P3(Integer(1), Integer(2), Integer(3), Integer(4))
>>> p2 = P3(Integer(4), Integer(3), Integer(2), Integer(1))
>>> P3.line_through(p1, p2)                                                    #␣
↪needs sage.libs.singular sage.schemes
Projective Curve over Rational Field defined by
  -5/4*x0 + 5/2*x1 - 5/4*x2,        -5/2*x0 + 15/4*x1 - 5/4*x3,
  -5/4*x0 + 15/4*x2 - 5/2*x3,       -5/4*x1 + 5/2*x2 - 5/4*x3
>>> p3 = P3(Integer(2),Integer(4),Integer(6),Integer(8))
>>> P3.line_through(p1, p3)
Traceback (most recent call last):
...
ValueError: not distinct points
```

subscheme_from_Chow_form(*Ch*, *dim*)

Return the subscheme defined by the Chow equations associated to the Chow form `Ch`.

These equations define the subscheme set-theoretically, but only for smooth subschemes and hypersurfaces do they define the subscheme as a scheme.

ALGORITHM:

The Chow form is a polynomial in the Plucker coordinates. The Plucker coordinates are the bracket polynomials. We first re-write the Chow form in terms of the dual Plucker coordinates. Then we expand $Ch(span(p, L)$ for a generic point p and a generic linear subspace L. The coefficients as polynomials in the coordinates of p are the equations defining the subscheme. [DalbecSturmfels].

INPUT:

- `Ch` – a homogeneous polynomial
- `dim` – the dimension of the associated scheme

OUTPUT: a projective subscheme

EXAMPLES:

```
sage: P = ProjectiveSpace(QQ, 4, 'z')
sage: R.<x0,x1,x2,x3,x4> = PolynomialRing(QQ)
sage: H = x1^2 + x2^2 + 5*x3*x4
sage: P.subscheme_from_Chow_form(H, 3)                                      #␣
↪needs sage.modules
Closed subscheme of Projective Space of dimension 4 over Rational Field␣
```

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```
↪defined by:
  -5*z0*z1 + z2^2 + z3^2
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(4), 'z')
>>> R = PolynomialRing(QQ, names=('x0', 'x1', 'x2', 'x3', 'x4',)); (x0, x1,␣
↪x2, x3, x4,) = R._first_ngens(5)
>>> H = x1**Integer(2) + x2**Integer(2) + Integer(5)*x3*x4
>>> P.subscheme_from_Chow_form(H, Integer(3))                                  ␣
↪     # needs sage.modules
Closed subscheme of Projective Space of dimension 4 over Rational Field␣
↪defined by:
  -5*z0*z1 + z2^2 + z3^2
```

```
sage: P = ProjectiveSpace(QQ, 3, 'z')
sage: R.<x0,x1,x2,x3,x4,x5> = PolynomialRing(QQ)
sage: H = x1 - x2 - x3 + x5 + 2*x0
sage: P.subscheme_from_Chow_form(H, 1)                                      #␣
↪needs sage.modules
Closed subscheme of Projective Space of dimension 3 over Rational Field
defined by:
  -z1 + z3,
  z0 + z2 + z3,
  -z1 - 2*z3,
  -z0 - z1 + 2*z2
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(3), 'z')
>>> R = PolynomialRing(QQ, names=('x0', 'x1', 'x2', 'x3', 'x4', 'x5',)); (x0,␣
↪x1, x2, x3, x4, x5,) = R._first_ngens(6)
>>> H = x1 - x2 - x3 + x5 + Integer(2)*x0
>>> P.subscheme_from_Chow_form(H, Integer(1))                                  ␣
↪     # needs sage.modules
Closed subscheme of Projective Space of dimension 3 over Rational Field
defined by:
  -z1 + z3,
  z0 + z2 + z3,
  -z1 - 2*z3,
  -z0 - z1 + 2*z2
```

```
sage: # needs sage.libs.singular
sage: P.<x0,x1,x2,x3> = ProjectiveSpace(GF(7), 3)
sage: X = P.subscheme([x3^2 + x1*x2, x2 - x0])
sage: Ch = X.Chow_form(); Ch
t0^2 - 2*t0*t3 + t3^2 - t2*t4 - t4*t5
sage: Y = P.subscheme_from_Chow_form(Ch, 1); Y
Closed subscheme of Projective Space of dimension 3
 over Finite Field of size 7 defined by:
  x1*x2 + x3^2,
  -x0*x2 + x2^2,
  -x0*x1 - x1*x2 - 2*x3^2,
```

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```
  x0^2 - x0*x2,
  x0*x1 + x3^2,
  -2*x0*x3 + 2*x2*x3,
  2*x0*x3 - 2*x2*x3,
  x0^2 - 2*x0*x2 + x2^2
sage: I = Y.defining_ideal()
sage: I.saturation(I.ring().ideal(list(I.ring().gens())))[0]
Ideal (x0 - x2, x1*x2 + x3^2) of Multivariate Polynomial Ring
 in x0, x1, x2, x3 over Finite Field of size 7
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> P = ProjectiveSpace(GF(Integer(7)), Integer(3), names=('x0', 'x1', 'x2',
↪'x3',)); (x0, x1, x2, x3,) = P._first_ngens(4)
>>> X = P.subscheme([x3**Integer(2) + x1*x2, x2 - x0])
>>> Ch = X.Chow_form(); Ch
t0^2 - 2*t0*t3 + t3^2 - t2*t4 - t4*t5
>>> Y = P.subscheme_from_Chow_form(Ch, Integer(1)); Y
Closed subscheme of Projective Space of dimension 3
 over Finite Field of size 7 defined by:
  x1*x2 + x3^2,
  -x0*x2 + x2^2,
  -x0*x1 - x1*x2 - 2*x3^2,
  x0^2 - x0*x2,
  x0*x1 + x3^2,
  -2*x0*x3 + 2*x2*x3,
  2*x0*x3 - 2*x2*x3,
  x0^2 - 2*x0*x2 + x2^2
>>> I = Y.defining_ideal()
>>> I.saturation(I.ring().ideal(list(I.ring().gens())))[Integer(0)]
Ideal (x0 - x2, x1*x2 + x3^2) of Multivariate Polynomial Ring
 in x0, x1, x2, x3 over Finite Field of size 7
```

class sage.schemes.projective.projective_space.**ProjectiveSpace_finite_field**(*n*, *R=Integer Ring*, *names=None*)

Bases: *ProjectiveSpace_field*

rational_points(*F=None*)

Return the list of `F`-rational points on this projective space, where `F` is a given finite field, or the base ring of this space.

EXAMPLES:

```
sage: P = ProjectiveSpace(1, GF(3))
sage: P.rational_points()
[(0 : 1), (1 : 1), (2 : 1), (1 : 0)]
sage: sorted(P.rational_points(GF(3^2, 'b')), key=str)                    #␣
↪needs sage.rings.finite_rings
[(0 : 1), (1 : 0), (1 : 1), (2 : 1),
 (2*b + 1 : 1), (2*b + 2 : 1), (2*b : 1),
 (b + 1 : 1), (b + 2 : 1), (b : 1)]
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(Integer(1), GF(Integer(3)))
>>> P.rational_points()
[(0 : 1), (1 : 1), (2 : 1), (1 : 0)]
>>> sorted(P.rational_points(GF(Integer(3)**Integer(2), 'b')), key=str)
↪               # needs sage.rings.finite_rings
[(0 : 1), (1 : 0), (1 : 1), (2 : 1),
 (2*b + 1 : 1), (2*b + 2 : 1), (2*b : 1),
 (b + 1 : 1), (b + 2 : 1), (b : 1)]
```

rational_points_dictionary()

Return dictionary of points.

OUTPUT: dictionary

EXAMPLES:

```
sage: P1 = ProjectiveSpace(GF(7), 1, 'x')
sage: P1.rational_points_dictionary()
{(0 : 1): 0,
 (1 : 0): 7,
 (1 : 1): 1,
 (2 : 1): 2,
 (3 : 1): 3,
 (4 : 1): 4,
 (5 : 1): 5,
 (6 : 1): 6}
```

```
>>> from sage.all import *
>>> P1 = ProjectiveSpace(GF(Integer(7)), Integer(1), 'x')
>>> P1.rational_points_dictionary()
{(0 : 1): 0,
 (1 : 0): 7,
 (1 : 1): 1,
 (2 : 1): 2,
 (3 : 1): 3,
 (4 : 1): 4,
 (5 : 1): 5,
 (6 : 1): 6}
```

class sage.schemes.projective.projective_space.**ProjectiveSpace_rational_field**(*n*, *R=Integer Ring*, *names=None*)

Bases: *ProjectiveSpace_field*

rational_points(*bound=0*)

Return the projective points $(x_0 : \cdots : x_n)$ over $\mathbf{Q}$ with $|x_i| \leq$ bound.

ALGORITHM:

The very simple algorithm works as follows: every point $(x_0 : \cdots : x_n)$ in projective space has a unique largest index i for which x_i is not zero. The algorithm then iterates downward on this index. We normalize by choosing x_i positive. Then, the points $x_0, \ldots, x_{i-1}$ are the points of affine i-space that are relatively prime to x_i. We access these by using the Tuples method.

INPUT:

- bound – integer

EXAMPLES:

```
sage: PP = ProjectiveSpace(0, QQ)
sage: PP.rational_points(1)
[(1)]
sage: PP = ProjectiveSpace(1, QQ)
sage: PP.rational_points(2)
[(-2 : 1), (-1 : 1), (0 : 1), (1 : 1), (2 : 1), (-1/2 : 1), (1/2 : 1), (1 :␣
↪0)]
sage: PP = ProjectiveSpace(2, QQ)
sage: PP.rational_points(2)
[(-2 : -2 : 1), (-1 : -2 : 1), (0 : -2 : 1), (1 : -2 : 1), (2 : -2 : 1),
 (-2 : -1 : 1), (-1 : -1 : 1), (0 : -1 : 1), (1 : -1 : 1), (2 : -1 : 1),
 (-2 : 0 : 1), (-1 : 0 : 1), (0 : 0 : 1), (1 : 0 : 1), (2 : 0 : 1), (-2 : 1 :␣
↪1),
 (-1 : 1 : 1), (0 : 1 : 1), (1 : 1 : 1), (2 : 1 : 1), (-2 : 2 : 1),
 (-1 : 2 : 1), (0 : 2 : 1), (1 : 2 : 1), (2 : 2 : 1), (-1/2 : -1 : 1),
 (1/2 : -1 : 1), (-1 : -1/2 : 1), (-1/2 : -1/2 : 1), (0 : -1/2 : 1),
 (1/2 : -1/2 : 1), (1 : -1/2 : 1), (-1/2 : 0 : 1), (1/2 : 0 : 1), (-1 : 1/2 :␣
↪1),
 (-1/2 : 1/2 : 1), (0 : 1/2 : 1), (1/2 : 1/2 : 1), (1 : 1/2 : 1), (-1/2 : 1 :␣
↪1),
 (1/2 : 1 : 1), (-2 : 1 : 0), (-1 : 1 : 0), (0 : 1 : 0), (1 : 1 : 0),
 (2 : 1 : 0), (-1/2 : 1 : 0), (1/2 : 1 : 0), (1 : 0 : 0)]
```

```
>>> from sage.all import *
>>> PP = ProjectiveSpace(Integer(0), QQ)
>>> PP.rational_points(Integer(1))
[(1)]
>>> PP = ProjectiveSpace(Integer(1), QQ)
>>> PP.rational_points(Integer(2))
[(-2 : 1), (-1 : 1), (0 : 1), (1 : 1), (2 : 1), (-1/2 : 1), (1/2 : 1), (1 :␣
↪0)]
>>> PP = ProjectiveSpace(Integer(2), QQ)
>>> PP.rational_points(Integer(2))
[(-2 : -2 : 1), (-1 : -2 : 1), (0 : -2 : 1), (1 : -2 : 1), (2 : -2 : 1),
 (-2 : -1 : 1), (-1 : -1 : 1), (0 : -1 : 1), (1 : -1 : 1), (2 : -1 : 1),
 (-2 : 0 : 1), (-1 : 0 : 1), (0 : 0 : 1), (1 : 0 : 1), (2 : 0 : 1), (-2 : 1 :␣
↪1),
 (-1 : 1 : 1), (0 : 1 : 1), (1 : 1 : 1), (2 : 1 : 1), (-2 : 2 : 1),
 (-1 : 2 : 1), (0 : 2 : 1), (1 : 2 : 1), (2 : 2 : 1), (-1/2 : -1 : 1),
 (1/2 : -1 : 1), (-1 : -1/2 : 1), (-1/2 : -1/2 : 1), (0 : -1/2 : 1),
 (1/2 : -1/2 : 1), (1 : -1/2 : 1), (-1/2 : 0 : 1), (1/2 : 0 : 1), (-1 : 1/2 :␣
↪1),
 (-1/2 : 1/2 : 1), (0 : 1/2 : 1), (1/2 : 1/2 : 1), (1 : 1/2 : 1), (-1/2 : 1 :␣
↪1),
 (1/2 : 1 : 1), (-2 : 1 : 0), (-1 : 1 : 0), (0 : 1 : 0), (1 : 1 : 0),
 (2 : 1 : 0), (-1/2 : 1 : 0), (1/2 : 1 : 0), (1 : 0 : 0)]
```

AUTHORS:

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class sage.schemes.projective.projective_space.**ProjectiveSpace_ring**(*n*, *R=Integer Ring*, *names=None*)

Bases: UniqueRepresentation, *AmbientSpace*

Projective space of dimension n over the ring R.

EXAMPLES:

```
sage: X.<x,y,z,w> = ProjectiveSpace(3, QQ)
sage: X.base_scheme()
Spectrum of Rational Field
sage: X.base_ring()
Rational Field
sage: X.structure_morphism()
Scheme morphism:
  From: Projective Space of dimension 3 over Rational Field
  To:   Spectrum of Rational Field
  Defn: Structure map
sage: X.coordinate_ring()
Multivariate Polynomial Ring in x, y, z, w over Rational Field
```

```
>>> from sage.all import *
>>> X = ProjectiveSpace(Integer(3), QQ, names=('x', 'y', 'z', 'w',)); (x, y, z, w,
↪) = X._first_ngens(4)
>>> X.base_scheme()
Spectrum of Rational Field
>>> X.base_ring()
Rational Field
>>> X.structure_morphism()
Scheme morphism:
  From: Projective Space of dimension 3 over Rational Field
  To:   Spectrum of Rational Field
  Defn: Structure map
>>> X.coordinate_ring()
Multivariate Polynomial Ring in x, y, z, w over Rational Field
```

Loading and saving:

```
sage: loads(X.dumps()) == X
True
sage: P = ProjectiveSpace(ZZ, 1, 'x')
sage: loads(P.dumps()) is P
True
```

```
>>> from sage.all import *
>>> loads(X.dumps()) == X
True
>>> P = ProjectiveSpace(ZZ, Integer(1), 'x')
>>> loads(P.dumps()) is P
True
```

Equality and hashing:

```
sage: ProjectiveSpace(QQ, 3, 'a') == ProjectiveSpace(ZZ, 3, 'a')
False
sage: ProjectiveSpace(ZZ, 1, 'a') == ProjectiveSpace(ZZ, 0, 'a')
False
sage: ProjectiveSpace(ZZ, 2, 'a') == AffineSpace(ZZ, 2, 'a')
False

sage: ProjectiveSpace(QQ, 3, 'a') != ProjectiveSpace(ZZ, 3, 'a')
True
sage: ProjectiveSpace(ZZ, 1, 'a') != ProjectiveSpace(ZZ, 0, 'a')
True
sage: ProjectiveSpace(ZZ, 2, 'a') != AffineSpace(ZZ, 2, 'a')
True

sage: hash(ProjectiveSpace(QQ, 3, 'a')) == hash(ProjectiveSpace(ZZ, 3, 'a'))
False
sage: hash(ProjectiveSpace(ZZ, 1, 'a')) == hash(ProjectiveSpace(ZZ, 0, 'a'))
False
sage: hash(ProjectiveSpace(ZZ, 2, 'a')) == hash(AffineSpace(ZZ, 2, 'a'))
False
```

```
>>> from sage.all import *
>>> ProjectiveSpace(QQ, Integer(3), 'a') == ProjectiveSpace(ZZ, Integer(3), 'a')
False
>>> ProjectiveSpace(ZZ, Integer(1), 'a') == ProjectiveSpace(ZZ, Integer(0), 'a')
False
>>> ProjectiveSpace(ZZ, Integer(2), 'a') == AffineSpace(ZZ, Integer(2), 'a')
False

>>> ProjectiveSpace(QQ, Integer(3), 'a') != ProjectiveSpace(ZZ, Integer(3), 'a')
True
>>> ProjectiveSpace(ZZ, Integer(1), 'a') != ProjectiveSpace(ZZ, Integer(0), 'a')
True
>>> ProjectiveSpace(ZZ, Integer(2), 'a') != AffineSpace(ZZ, Integer(2), 'a')
True

>>> hash(ProjectiveSpace(QQ, Integer(3), 'a')) == hash(ProjectiveSpace(ZZ,␣
↪Integer(3), 'a'))
False
>>> hash(ProjectiveSpace(ZZ, Integer(1), 'a')) == hash(ProjectiveSpace(ZZ,␣
↪Integer(0), 'a'))
False
>>> hash(ProjectiveSpace(ZZ, Integer(2), 'a')) == hash(AffineSpace(ZZ, Integer(2),
↪ 'a'))
False
```

Lattes_map(E, m)

Given an elliptic curve `E` and an integer `m` return the Lattes map associated to multiplication by m.

In other words, the rational map on the quotient $E/\{\pm 1\} \cong \mathbb{P}^1$ associated to $[m] : E \to E$.

INPUT:

- `E` – an elliptic curve

- `m` – integer

OUTPUT: a dynamical system on this projective space

EXAMPLES:

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: E = EllipticCurve(QQ,[-1, 0])                                    #␣
↪needs sage.schemes
sage: P.Lattes_map(E, 2)                                               #␣
↪needs sage.schemes
Dynamical System of Projective Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x : y) to
        (1/4*x^4 + 1/2*x^2*y^2 + 1/4*y^4 : x^3*y - x*y^3)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> E = EllipticCurve(QQ,[-Integer(1), Integer(0)])                     ␣
↪              # needs sage.schemes
>>> P.Lattes_map(E, Integer(2))                                         ␣
↪     # needs sage.schemes
Dynamical System of Projective Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x : y) to
        (1/4*x^4 + 1/2*x^2*y^2 + 1/4*y^4 : x^3*y - x*y^3)
```

affine_patch(*i*, *AA=None*)

Return the i-th affine patch of this projective space.

This is an ambient affine space $\mathbb{A}^n_R$, where R is the base ring of `self`, whose "projective embedding" map is 1 in the i-th factor.

INPUT:

- `i` – integer between 0 and dimension of `self`, inclusive
- `AA` – (default: `None`) ambient affine space, this is constructed if it is not given

OUTPUT: an ambient affine space with fixed projective_embedding map

EXAMPLES:

```
sage: PP = ProjectiveSpace(5) / QQ
sage: AA = PP.affine_patch(2)
sage: AA
Affine Space of dimension 5 over Rational Field
sage: AA.projective_embedding()
Scheme morphism:
  From: Affine Space of dimension 5 over Rational Field
  To:   Projective Space of dimension 5 over Rational Field
  Defn: Defined on coordinates by sending (x0, x1, x3, x4, x5) to
        (x0 : x1 : 1 : x3 : x4 : x5)
sage: AA.projective_embedding(0)
Scheme morphism:
  From: Affine Space of dimension 5 over Rational Field
  To:   Projective Space of dimension 5 over Rational Field
```

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```
  Defn: Defined on coordinates by sending (x0, x1, x3, x4, x5) to
        (1 : x0 : x1 : x3 : x4 : x5)
```

```
>>> from sage.all import *
>>> PP = ProjectiveSpace(Integer(5)) / QQ
>>> AA = PP.affine_patch(Integer(2))
>>> AA
Affine Space of dimension 5 over Rational Field
>>> AA.projective_embedding()
Scheme morphism:
  From: Affine Space of dimension 5 over Rational Field
  To:   Projective Space of dimension 5 over Rational Field
  Defn: Defined on coordinates by sending (x0, x1, x3, x4, x5) to
        (x0 : x1 : 1 : x3 : x4 : x5)
>>> AA.projective_embedding(Integer(0))
Scheme morphism:
  From: Affine Space of dimension 5 over Rational Field
  To:   Projective Space of dimension 5 over Rational Field
  Defn: Defined on coordinates by sending (x0, x1, x3, x4, x5) to
        (1 : x0 : x1 : x3 : x4 : x5)
```

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: P.affine_patch(0).projective_embedding(0).codomain() == P
True
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> P.affine_patch(Integer(0)).projective_embedding(Integer(0)).codomain() ==␣
↪P
True
```

cartesian_product(*other*)

Return the Cartesian product of this projective space and `other`.

INPUT:

- `other` – a projective space with the same base ring as this space

OUTPUT: a Cartesian product of projective spaces

EXAMPLES:

```
sage: P1 = ProjectiveSpace(QQ, 1, 'x')
sage: P2 = ProjectiveSpace(QQ, 2, 'y')
sage: PP = P1.cartesian_product(P2); PP
Product of projective spaces P^1 x P^2 over Rational Field
sage: PP.gens()
(x0, x1, y0, y1, y2)
```

```
>>> from sage.all import *
>>> P1 = ProjectiveSpace(QQ, Integer(1), 'x')
>>> P2 = ProjectiveSpace(QQ, Integer(2), 'y')
```

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```
>>> PP = P1.cartesian_product(P2); PP
Product of projective spaces P^1 x P^2 over Rational Field
>>> PP.gens()
(x0, x1, y0, y1, y2)
```

change_ring(*R*)

Return a projective space over ring `R`.

INPUT:

- `R` – commutative ring or morphism

OUTPUT: projective space over `R`

Note

There is no need to have any relation between `R` and the base ring of this space, if you want to have such a relation, use `self.base_extend(R)` instead.

EXAMPLES:

```
sage: P.<x, y, z> = ProjectiveSpace(2, ZZ)
sage: PQ = P.change_ring(QQ); PQ
Projective Space of dimension 2 over Rational Field
sage: PQ.change_ring(GF(5))
Projective Space of dimension 2 over Finite Field of size 5
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(Integer(2), ZZ, names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> PQ = P.change_ring(QQ); PQ
Projective Space of dimension 2 over Rational Field
>>> PQ.change_ring(GF(Integer(5)))
Projective Space of dimension 2 over Finite Field of size 5
```

```
sage: K.<w> = QuadraticField(2)                                                #␣
↪needs sage.rings.number_field
sage: P = ProjectiveSpace(K, 2, 't')                                           #␣
↪needs sage.rings.number_field
sage: P.change_ring(K.embeddings(QQbar)[0])                                    #␣
↪needs sage.rings.number_field
Projective Space of dimension 2 over Algebraic Field
```

```
>>> from sage.all import *
>>> K = QuadraticField(Integer(2), names=('w',)); (w,) = K._first_ngens(1)#␣
↪needs sage.rings.number_field
>>> P = ProjectiveSpace(K, Integer(2), 't')                                    ␣
↪     # needs sage.rings.number_field
>>> P.change_ring(K.embeddings(QQbar)[Integer(0)])                             ␣
↪     # needs sage.rings.number_field
Projective Space of dimension 2 over Algebraic Field
```

chebyshev_polynomial(*n*, *kind='first'*, *monic=False*)

Generates an endomorphism of this projective line by a Chebyshev polynomial.

Chebyshev polynomials are a sequence of recursively defined orthogonal polynomials. Chebyshev of the first kind are defined as $T_0(x) = 1$, $T_1(x) = x$, and $T_{n+1}(x) = 2xT_n(x) - T_{n-1}(x)$. Chebyshev of the second kind are defined as $U_0(x) = 1$, $U_1(x) = 2x$, and $U_{n+1}(x) = 2xU_n(x) - U_{n-1}(x)$.

INPUT:

- `n` – nonnegative integer
- `kind` – `'first'` (default) or `'second'` specifying which kind of Chebyshev the user would like to generate
- `monic` – boolean (default: `False`) specifying if the polynomial defining the system should be monic or not

OUTPUT: `DynamicalSystem_projective`

EXAMPLES:

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: P.chebyshev_polynomial(5, 'first')                                    #␣
↪needs sage.symbolic
Dynamical System of Projective Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x : y) to
        (16*x^5 - 20*x^3*y^2 + 5*x*y^4 : y^5)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> P.chebyshev_polynomial(Integer(5), 'first')                             ␣
↪     # needs sage.symbolic
Dynamical System of Projective Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x : y) to
        (16*x^5 - 20*x^3*y^2 + 5*x*y^4 : y^5)
```

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: P.chebyshev_polynomial(3, 'second')                                   #␣
↪needs sage.symbolic
Dynamical System of Projective Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x : y) to
        (8*x^3 - 4*x*y^2 : y^3)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> P.chebyshev_polynomial(Integer(3), 'second')                            ␣
↪     # needs sage.symbolic
Dynamical System of Projective Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x : y) to
        (8*x^3 - 4*x*y^2 : y^3)
```

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: P.chebyshev_polynomial(3, 2)                                          #␣
```

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```
↪needs sage.symbolic
Traceback (most recent call last):
...
ValueError: keyword 'kind' must have a value of either 'first' or 'second'
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> P.chebyshev_polynomial(Integer(3), Integer(2))                          ␣
↪              # needs sage.symbolic
Traceback (most recent call last):
...
ValueError: keyword 'kind' must have a value of either 'first' or 'second'
```

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: P.chebyshev_polynomial(-4, 'second')
Traceback (most recent call last):
...
ValueError: first parameter 'n' must be a nonnegative integer
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> P.chebyshev_polynomial(-Integer(4), 'second')
Traceback (most recent call last):
...
ValueError: first parameter 'n' must be a nonnegative integer
```

```
sage: P = ProjectiveSpace(QQ, 2, 'x')
sage: P.chebyshev_polynomial(2)
Traceback (most recent call last):
...
TypeError: projective space must be of dimension 1
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), 'x')
>>> P.chebyshev_polynomial(Integer(2))
Traceback (most recent call last):
...
TypeError: projective space must be of dimension 1
```

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: P.chebyshev_polynomial(3, monic=True)                                #␣
↪needs sage.symbolic
Dynamical System of Projective Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x : y) to
        (x^3 - 3*x*y^2 : y^3)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
```

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```
↪first_ngens(2)
>>> P.chebyshev_polynomial(Integer(3), monic=True)                    ␣
↪     # needs sage.symbolic
Dynamical System of Projective Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x : y) to
        (x^3 - 3*x*y^2 : y^3)
```

```
sage: F.<t> = FunctionField(QQ)
sage: P.<y,z> = ProjectiveSpace(F, 1)
sage: P.chebyshev_polynomial(4, monic=True)                           #␣
↪needs sage.symbolic
Dynamical System of Projective Space of dimension 1
 over Rational function field in t over Rational Field
  Defn: Defined on coordinates by sending (y : z) to
        (y^4 + (-4)*y^2*z^2 + 2*z^4 : z^4)
```

```
>>> from sage.all import *
>>> F = FunctionField(QQ, names=('t',)); (t,) = F._first_ngens(1)
>>> P = ProjectiveSpace(F, Integer(1), names=('y', 'z',)); (y, z,) = P._first_
↪ngens(2)
>>> P.chebyshev_polynomial(Integer(4), monic=True)                    ␣
↪     # needs sage.symbolic
Dynamical System of Projective Space of dimension 1
 over Rational function field in t over Rational Field
  Defn: Defined on coordinates by sending (y : z) to
        (y^4 + (-4)*y^2*z^2 + 2*z^4 : z^4)
```

coordinate_ring()

Return the coordinate ring of this scheme.

EXAMPLES:

```
sage: ProjectiveSpace(3, GF(19^2,'alpha'), 'abcd').coordinate_ring()      #␣
↪needs sage.rings.finite_rings
Multivariate Polynomial Ring in a, b, c, d over Finite Field in alpha of size␣
↪19^2
```

```
>>> from sage.all import *
>>> ProjectiveSpace(Integer(3), GF(Integer(19)**Integer(2),'alpha'), 'abcd').
↪coordinate_ring()        # needs sage.rings.finite_rings
Multivariate Polynomial Ring in a, b, c, d over Finite Field in alpha of size␣
↪19^2
```

```
sage: ProjectiveSpace(3).coordinate_ring()
Multivariate Polynomial Ring in x0, x1, x2, x3 over Integer Ring
```

```
>>> from sage.all import *
>>> ProjectiveSpace(Integer(3)).coordinate_ring()
Multivariate Polynomial Ring in x0, x1, x2, x3 over Integer Ring
```

```
sage: ProjectiveSpace(2, QQ, ['alpha', 'beta', 'gamma']).coordinate_ring()
Multivariate Polynomial Ring in alpha, beta, gamma over Rational Field
```

```
>>> from sage.all import *
>>> ProjectiveSpace(Integer(2), QQ, ['alpha', 'beta', 'gamma']).coordinate_
↪ring()
Multivariate Polynomial Ring in alpha, beta, gamma over Rational Field
```

hyperplane_transformation_matrix(*plane_1*, *plane_2*)

Return a PGL element sending `plane_1` to `plane_2`.

`plane_1` and `plane_2` must be hyperplanes (subschemes of codimension 1, each defined by a single linear homogeneous equation).

INPUT:

- `plane_1`, `plane_2` – hyperplanes of this projective space

OUTPUT: an element of PGL

EXAMPLES:

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: plane1 = P.subscheme(x)
sage: plane2 = P.subscheme(y)
sage: m = P.hyperplane_transformation_matrix(plane1, plane2); m              #␣
↪needs sage.modules
[0 1]
[1 0]
sage: plane2(m*P((0,1)))                                                     #␣
↪needs sage.modules
(1 : 0)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> plane1 = P.subscheme(x)
>>> plane2 = P.subscheme(y)
>>> m = P.hyperplane_transformation_matrix(plane1, plane2); m               #␣
↪needs sage.modules
[0 1]
[1 0]
>>> plane2(m*P((Integer(0),Integer(1))))                                      ␣
↪              # needs sage.modules
(1 : 0)
```

```
sage: P.<x,y,z,w> = ProjectiveSpace(QQ, 3)
sage: plane1 = P.subscheme(x + 2*y + z)
sage: plane2 = P.subscheme(2*x + y + z)
sage: P.hyperplane_transformation_matrix(plane1, plane2)                     #␣
↪needs sage.modules
[1 0 0 0]
[0 4 0 0]
[0 0 2 0]
[0 0 0 1]
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(3), names=('x', 'y', 'z', 'w',)); (x, y,␣
↪z, w,) = P._first_ngens(4)
>>> plane1 = P.subscheme(x + Integer(2)*y + z)
>>> plane2 = P.subscheme(Integer(2)*x + y + z)
>>> P.hyperplane_transformation_matrix(plane1, plane2)                    #␣
↪needs sage.modules
[1 0 0 0]
[0 4 0 0]
[0 0 2 0]
[0 0 0 1]
```

```
sage: P.<x,y> = ProjectiveSpace(ZZ, 1)
sage: plane1 = P.subscheme(x + y)
sage: plane2 = P.subscheme(y)
sage: P.hyperplane_transformation_matrix(plane1, plane2)                  #␣
↪needs sage.modules
[-1  0]
[ 1  1]
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(ZZ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> plane1 = P.subscheme(x + y)
>>> plane2 = P.subscheme(y)
>>> P.hyperplane_transformation_matrix(plane1, plane2)                    #␣
↪needs sage.modules
[-1  0]
[ 1  1]
```

```
sage: # needs sage.rings.number_field
sage: K.<v> = CyclotomicField(3)
sage: P.<x,y,z> = ProjectiveSpace(K, 2)
sage: plane1 = P.subscheme(x - 2*v*y + z)
sage: plane2 = P.subscheme(x + v*y + v*z)
sage: m = P.hyperplane_transformation_matrix(plane1, plane2); m            #␣
↪needs sage.modules
[   v    0    0]
[   0 -2*v    0]
[   0    0    1]
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> K = CyclotomicField(Integer(3), names=('v',)); (v,) = K._first_ngens(1)
>>> P = ProjectiveSpace(K, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> plane1 = P.subscheme(x - Integer(2)*v*y + z)
>>> plane2 = P.subscheme(x + v*y + v*z)
>>> m = P.hyperplane_transformation_matrix(plane1, plane2); m             #␣
↪needs sage.modules
[   v    0    0]
[   0 -2*v    0]
```

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```
[   0    0    1]
```

```
sage: # needs sage.rings.number_field
sage: R.<x> = QQ[]
sage: K.<k> = NumberField(x^2 + 1)
sage: P.<x,y,z,w> = ProjectiveSpace(K, 3)
sage: plane1 = P.subscheme(k*x + 2*k*y + z)
sage: plane2 = P.subscheme(7*k*x + y + 9*z)
sage: m = P.hyperplane_transformation_matrix(plane1, plane2); m             #␣
↪needs sage.modules
[   1    0    0    0]
[   0 14*k    0    0]
[   0    0  7/9    0]
[   0    0    0    1]
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> K = NumberField(x**Integer(2) + Integer(1), names=('k',)); (k,) = K._
↪first_ngens(1)
>>> P = ProjectiveSpace(K, Integer(3), names=('x', 'y', 'z', 'w',)); (x, y, z,
↪ w,) = P._first_ngens(4)
>>> plane1 = P.subscheme(k*x + Integer(2)*k*y + z)
>>> plane2 = P.subscheme(Integer(7)*k*x + y + Integer(9)*z)
>>> m = P.hyperplane_transformation_matrix(plane1, plane2); m             #␣
↪needs sage.modules
[   1    0    0    0]
[   0 14*k    0    0]
[   0    0  7/9    0]
[   0    0    0    1]
```

```
sage: # needs sage.rings.number_field
sage: K.<v> = CyclotomicField(3)
sage: R.<t> = K[]
sage: F.<w> = K.extension(t^5 + 2)
sage: G.<u> = F.absolute_field()
sage: P.<x,y,z> = ProjectiveSpace(G, 2)
sage: plane1 = P.subscheme(x - 2*u*y + z)
sage: plane2 = P.subscheme(x + u*y + z)
sage: m = P.hyperplane_transformation_matrix(plane1, plane2)                #␣
↪needs sage.modules
sage: plane2(m*P((2*u, 1, 0)))                                              #␣
↪needs sage.modules
(-u : 1 : 0)
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> K = CyclotomicField(Integer(3), names=('v',)); (v,) = K._first_ngens(1)
>>> R = K['t']; (t,) = R._first_ngens(1)
>>> F = K.extension(t**Integer(5) + Integer(2), names=('w',)); (w,) = F._
↪first_ngens(1)
```

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```
>>> G = F.absolute_field(names=('u',)); (u,) = G._first_ngens(1)
>>> P = ProjectiveSpace(G, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> plane1 = P.subscheme(x - Integer(2)*u*y + z)
>>> plane2 = P.subscheme(x + u*y + z)
>>> m = P.hyperplane_transformation_matrix(plane1, plane2)                #␣
↪needs sage.modules
>>> plane2(m*P((Integer(2)*u, Integer(1), Integer(0))))                    ␣
↪                        # needs sage.modules
(-u : 1 : 0)
```

```
sage: P.<x,y,z> = ProjectiveSpace(FiniteField(2), 2)
sage: plane1 = P.subscheme(x + y + z)
sage: plane2 = P.subscheme(z)
sage: P.hyperplane_transformation_matrix(plane1, plane2)                   #␣
↪needs sage.modules
[1 0 0]
[1 1 0]
[1 1 1]
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(FiniteField(Integer(2)), Integer(2), names=('x', 'y',
↪'z',)); (x, y, z,) = P._first_ngens(3)
>>> plane1 = P.subscheme(x + y + z)
>>> plane2 = P.subscheme(z)
>>> P.hyperplane_transformation_matrix(plane1, plane2)                     #␣
↪needs sage.modules
[1 0 0]
[1 1 0]
[1 1 1]
```

```
sage: R.<t> = QQ[]
sage: P.<x,y,z> = ProjectiveSpace(R, 2)
sage: plane1 = P.subscheme(x + 9*t*y + z)
sage: plane2 = P.subscheme(x + z)
sage: P.hyperplane_transformation_matrix(plane1, plane2)                   #␣
↪needs sage.modules
[  1 9*t   0]
[  1   0   0]
[  0   0   1]
```

```
>>> from sage.all import *
>>> R = QQ['t']; (t,) = R._first_ngens(1)
>>> P = ProjectiveSpace(R, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> plane1 = P.subscheme(x + Integer(9)*t*y + z)
>>> plane2 = P.subscheme(x + z)
>>> P.hyperplane_transformation_matrix(plane1, plane2)                     #␣
↪needs sage.modules
[  1 9*t   0]
[  1   0   0]
```

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```
[  0   0   1]
```

is_linearly_independent(*points*, *n=None*)

Return whether the set of points is linearly independent.

Alternatively, specify `n` to check if every subset of size `n` is linearly independent.

INPUT:

- `points` – list of points in this projective space
- `n` – (optional) positive integer less than or equal to the length of `points`. Specifies the size of the subsets to check for linear independence.

OUTPUT: `True` if `points` is linearly independent, `False` otherwise

EXAMPLES:

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: points = [P((1, 0, 1)), P((1, 2, 1)), P((1, 3, 4))]
sage: P.is_linearly_independent(points)                                     #␣
↪needs sage.modules
True
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> points = [P((Integer(1), Integer(0), Integer(1))), P((Integer(1),␣
↪Integer(2), Integer(1))), P((Integer(1), Integer(3), Integer(4)))]
>>> P.is_linearly_independent(points)                                       #␣
↪needs sage.modules
True
```

```
sage: P.<x,y,z> = ProjectiveSpace(GF(5), 2)
sage: points = [P((1, 0, 1)), P((1, 2, 1)), P((1, 3, 4)), P((0, 0, 1))]
sage: P.is_linearly_independent(points, 2)                                  #␣
↪needs sage.modules
True
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(GF(Integer(5)), Integer(2), names=('x', 'y', 'z',));␣
↪(x, y, z,) = P._first_ngens(3)
>>> points = [P((Integer(1), Integer(0), Integer(1))), P((Integer(1),␣
↪Integer(2), Integer(1))), P((Integer(1), Integer(3), Integer(4))),␣
↪P((Integer(0), Integer(0), Integer(1)))]
>>> P.is_linearly_independent(points, Integer(2))                                ␣
↪     # needs sage.modules
True
```

```
sage: R.<c> = QQ[]
sage: P.<x,y,z> = ProjectiveSpace(R, 2)
sage: points = [P((c, 0, 1)), P((0, c, 1)), P((1, 0, 4)), P((0, 0, 1))]
sage: P.is_linearly_independent(points, 3)                                  #␣
```

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```
↪needs sage.modules
False
```

```
>>> from sage.all import *
>>> R = QQ['c']; (c,) = R._first_ngens(1)
>>> P = ProjectiveSpace(R, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> points = [P((c, Integer(0), Integer(1))), P((Integer(0), c, Integer(1))),␣
↪P((Integer(1), Integer(0), Integer(4))), P((Integer(0), Integer(0),␣
↪Integer(1)))]
>>> P.is_linearly_independent(points, Integer(3))                              ␣
↪     # needs sage.modules
False
```

```
sage: R.<c> = QQ[]
sage: P.<x,y,z> = ProjectiveSpace(FractionField(R), 2)
sage: points = [P((c, 0, 1)), P((0, c, 1)), P((1, 3, 4)), P((0, 0, 1))]
sage: P.is_linearly_independent(points, 3)                                  #␣
↪needs sage.modules
True
```

```
>>> from sage.all import *
>>> R = QQ['c']; (c,) = R._first_ngens(1)
>>> P = ProjectiveSpace(FractionField(R), Integer(2), names=('x', 'y', 'z',));
↪ (x, y, z,) = P._first_ngens(3)
>>> points = [P((c, Integer(0), Integer(1))), P((Integer(0), c, Integer(1))),␣
↪P((Integer(1), Integer(3), Integer(4))), P((Integer(0), Integer(0),␣
↪Integer(1)))]
>>> P.is_linearly_independent(points, Integer(3))                              ␣
↪     # needs sage.modules
True
```

```
sage: # needs sage.rings.number_field
sage: K.<k> = CyclotomicField(3)
sage: P.<x,y,z> = ProjectiveSpace(K, 2)
sage: points = [P((k, k^2, 1)), P((0, k, 1)), P((1, 0, 4)), P((0, 0, 1))]
sage: P.is_linearly_independent(points, 3)                                  #␣
↪needs sage.modules
True
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> K = CyclotomicField(Integer(3), names=('k',)); (k,) = K._first_ngens(1)
>>> P = ProjectiveSpace(K, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> points = [P((k, k**Integer(2), Integer(1))), P((Integer(0), k,␣
↪Integer(1))), P((Integer(1), Integer(0), Integer(4))), P((Integer(0),␣
↪Integer(0), Integer(1)))]
>>> P.is_linearly_independent(points, Integer(3))                              ␣
↪     # needs sage.modules
True
```

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: points = [P((1, 0)), P((1, 1))]
sage: P.is_linearly_independent(points)                                    #␣
↪needs sage.modules
True
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> points = [P((Integer(1), Integer(0))), P((Integer(1), Integer(1)))]
>>> P.is_linearly_independent(points)                                      #␣
↪needs sage.modules
True
```

is_projective()

Return that this ambient space is projective n-space.

EXAMPLES:

```
sage: ProjectiveSpace(3,QQ).is_projective()
True
```

```
>>> from sage.all import *
>>> ProjectiveSpace(Integer(3),QQ).is_projective()
True
```

ngens()

Return the number of generators of this projective space.

This is the number of variables in the coordinate ring of `self`.

EXAMPLES:

```
sage: ProjectiveSpace(3, QQ).ngens()
4
sage: ProjectiveSpace(7, ZZ).ngens()
8
```

```
>>> from sage.all import *
>>> ProjectiveSpace(Integer(3), QQ).ngens()
4
>>> ProjectiveSpace(Integer(7), ZZ).ngens()
8
```

point(*v*, *check=True*)

Create a point on this projective space.

INPUT:

- `v` – anything that defines a point
- `check` – boolean (default: `True`); whether to check the defining data for consistency

OUTPUT: a point of this projective space

EXAMPLES:

```
sage: P2 = ProjectiveSpace(QQ, 2)
sage: P2.point([4,5])
(4 : 5 : 1)
```

```
>>> from sage.all import *
>>> P2 = ProjectiveSpace(QQ, Integer(2))
>>> P2.point([Integer(4),Integer(5)])
(4 : 5 : 1)
```

```
sage: P = ProjectiveSpace(QQ, 1)
sage: P.point(infinity)
(1 : 0)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1))
>>> P.point(infinity)
(1 : 0)
```

```
sage: P = ProjectiveSpace(QQ, 2)
sage: P.point(infinity)
Traceback (most recent call last):
...
ValueError: +Infinity not well defined in dimension > 1
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2))
>>> P.point(infinity)
Traceback (most recent call last):
...
ValueError: +Infinity not well defined in dimension > 1
```

```
sage: P = ProjectiveSpace(ZZ, 2)
sage: P.point([infinity])
Traceback (most recent call last):
 ...
ValueError: [+Infinity] not well defined in dimension > 1
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(ZZ, Integer(2))
>>> P.point([infinity])
Traceback (most recent call last):
 ...
ValueError: [+Infinity] not well defined in dimension > 1
```

point_transformation_matrix(*points_source*, *points_target*, *normalize=True*)

Returns a unique element of PGL that transforms one set of points to another.

Given a projective space of dimension n and a set of n+2 source points and a set of n+2 target points in the same projective space, such that no n+1 points of each set are linearly dependent find the unique element of PGL that translates the source points to the target points.

Warning

over non-exact rings such as the ComplexField, the returned matrix could be very far from correct.

INPUT:

- `points_source` – points in source projective space
- `points_target` – points in target projective space
- `normalize` – boolean (default: `True`); if the returned matrix should be normalized. Only works over exact rings. If the base ring is a field, the matrix is normalized so that the last nonzero entry in the last row is 1. If the base ring is a ring, then the matrix is normalized so that the entries are elements of the base ring.

OUTPUT: transformation matrix - element of PGL

ALGORITHM:

See [Hutz2007], Proposition 2.16 for details.

EXAMPLES:

```
sage: P1.<a,b,c> = ProjectiveSpace(QQ, 2)
sage: points_source = [P1([1, 4, 1]), P1([1, 2, 2]), P1([3, 5, 1]), P1([1, -1,
↪ 1])]
sage: points_target = [P1([5, -2, 7]), P1([3, -2, 3]), P1([6, -5, 9]), P1([3,␣
↪6, 7])]
sage: m = P1.point_transformation_matrix(points_source, points_target); m   #␣
↪needs sage.modules
[ -13/59 -128/59  -25/59]
[538/177    8/59  26/177]
[ -45/59 -196/59       1]
sage: [m*points_source[i] == points_target[i] for i in range(4)]            #␣
↪needs sage.modules
[True, True, True, True]
```

```
>>> from sage.all import *
>>> P1 = ProjectiveSpace(QQ, Integer(2), names=('a', 'b', 'c',)); (a, b, c,)␣
↪= P1._first_ngens(3)
>>> points_source = [P1([Integer(1), Integer(4), Integer(1)]), P1([Integer(1),
↪ Integer(2), Integer(2)]), P1([Integer(3), Integer(5), Integer(1)]),␣
↪P1([Integer(1), -Integer(1), Integer(1)])]
>>> points_target = [P1([Integer(5), -Integer(2), Integer(7)]),␣
↪P1([Integer(3), -Integer(2), Integer(3)]), P1([Integer(6), -Integer(5),␣
↪Integer(9)]), P1([Integer(3), Integer(6), Integer(7)])]
>>> m = P1.point_transformation_matrix(points_source, points_target); m   #␣
↪needs sage.modules
[ -13/59 -128/59  -25/59]
[538/177    8/59  26/177]
[ -45/59 -196/59       1]
>>> [m*points_source[i] == points_target[i] for i in range(Integer(4))]      ␣
↪     # needs sage.modules
[True, True, True, True]
```

```
sage: P.<a,b> = ProjectiveSpace(GF(13),  1)
sage: points_source = [P([-6, 7]), P([1, 4]), P([3, 2])]
sage: points_target = [P([-1, 2]), P([0, 2]), P([-1, 6])]
sage: P.point_transformation_matrix(points_source, points_target)           #␣
↪needs sage.modules
[10  4]
[10  1]
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(GF(Integer(13)),  Integer(1), names=('a', 'b',)); (a,␣
↪b,) = P._first_ngens(2)
>>> points_source = [P([-Integer(6), Integer(7)]), P([Integer(1),␣
↪Integer(4)]), P([Integer(3), Integer(2)])]
>>> points_target = [P([-Integer(1), Integer(2)]), P([Integer(0),␣
↪Integer(2)]), P([-Integer(1), Integer(6)])]
>>> P.point_transformation_matrix(points_source, points_target)           #␣
↪needs sage.modules
[10  4]
[10  1]
```

```
sage: P.<a,b> = ProjectiveSpace(QQ, 1)
sage: points_source = [P([-6, -4]), P([1, 4]), P([3, 2])]
sage: points_target = [P([-1, 2]), P([0, 2]), P([-7, -3])]
sage: P.point_transformation_matrix(points_source, points_target)           #␣
↪needs sage.modules
Traceback (most recent call last):
...
ValueError: source points not independent
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('a', 'b',)); (a, b,) = P._
↪first_ngens(2)
>>> points_source = [P([-Integer(6), -Integer(4)]), P([Integer(1),␣
↪Integer(4)]), P([Integer(3), Integer(2)])]
>>> points_target = [P([-Integer(1), Integer(2)]), P([Integer(0),␣
↪Integer(2)]), P([-Integer(7), -Integer(3)])]
>>> P.point_transformation_matrix(points_source, points_target)           #␣
↪needs sage.modules
Traceback (most recent call last):
...
ValueError: source points not independent
```

```
sage: R.<t> = FunctionField(QQ)
sage: P.<a,b> = ProjectiveSpace(R, 1)
sage: points_source = [P([-6*t, 7]), P([1, 4]), P([3, 2])]
sage: points_target = [P([-1, 2*t]), P([0, 2]), P([-1, 6])]
sage: P.point_transformation_matrix(points_source, points_target)           #␣
↪needs sage.modules
[             (1/3*t + 7/12)/(t^2 - 53/24*t)       (-1/12*t - 7/48)/(t^2 - 53/
↪24*t)]
[(-2/3*t^2 - 7/36*t - 35/12)/(t^2 - 53/24*t)                                 ␣
↪    1]
```

```
>>> from sage.all import *
>>> R = FunctionField(QQ, names=('t',)); (t,) = R._first_ngens(1)
>>> P = ProjectiveSpace(R, Integer(1), names=('a', 'b',)); (a, b,) = P._first_
↪ngens(2)
>>> points_source = [P([-Integer(6)*t, Integer(7)]), P([Integer(1),␣
↪Integer(4)]), P([Integer(3), Integer(2)])]
>>> points_target = [P([-Integer(1), Integer(2)*t]), P([Integer(0),␣
↪Integer(2)]), P([-Integer(1), Integer(6)])]
>>> P.point_transformation_matrix(points_source, points_target)           #␣
↪needs sage.modules
[             (1/3*t + 7/12)/(t^2 - 53/24*t)       (-1/12*t - 7/48)/(t^2 - 53/
↪24*t)]
[(-2/3*t^2 - 7/36*t - 35/12)/(t^2 - 53/24*t)                              ␣
↪    1]
```

```
sage: P1.<a,b,c> = ProjectiveSpace(RR, 2)
sage: points_source = [P1([1, 4, 1]), P1([1, 2, 2]), P1([3, 5, 1]), P1([1, -1,
↪ 1])]
sage: points_target = [P1([5, -2, 7]), P1([3, -2, 3]), P1([6, -5, 9]), P1([3,␣
↪6, 7])]
sage: P1.point_transformation_matrix(points_source,        # abs tol 1e-13  #␣
↪needs sage.modules
....:                                 points_target)
[-0.0619047619047597  -0.609523809523810  -0.119047619047621]
[  0.853968253968253  0.0380952380952380  0.0412698412698421]
[ -0.214285714285712  -0.933333333333333   0.280952380952379]
```

```
>>> from sage.all import *
>>> P1 = ProjectiveSpace(RR, Integer(2), names=('a', 'b', 'c',)); (a, b, c,)␣
↪= P1._first_ngens(3)
>>> points_source = [P1([Integer(1), Integer(4), Integer(1)]), P1([Integer(1),
↪ Integer(2), Integer(2)]), P1([Integer(3), Integer(5), Integer(1)]),␣
↪P1([Integer(1), -Integer(1), Integer(1)])]
>>> points_target = [P1([Integer(5), -Integer(2), Integer(7)]),␣
↪P1([Integer(3), -Integer(2), Integer(3)]), P1([Integer(6), -Integer(5),␣
↪Integer(9)]), P1([Integer(3), Integer(6), Integer(7)])]
>>> P1.point_transformation_matrix(points_source,        # abs tol 1e-13  #␣
↪needs sage.modules
...                                 points_target)
[-0.0619047619047597  -0.609523809523810  -0.119047619047621]
[  0.853968253968253  0.0380952380952380  0.0412698412698421]
[ -0.214285714285712  -0.933333333333333   0.280952380952379]
```

```
sage: P1.<a,b,c> = ProjectiveSpace(ZZ, 2)
sage: points_source = [P1([1, 4, 1]), P1([1, 2, 2]), P1([3, 5, 1]), P1([1, -1,
↪ 1])]
sage: points_target = [P1([5, -2, 7]), P1([3, -2, 3]), P1([6, -5, 9]), P1([3,␣
↪6, 7])]
sage: P1.point_transformation_matrix(points_source, points_target)           #␣
↪needs sage.modules
[ -39 -384  -75]
[ 538   24   26]
```

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```
[-135 -588  177]
```

```
>>> from sage.all import *
>>> P1 = ProjectiveSpace(ZZ, Integer(2), names=('a', 'b', 'c',)); (a, b, c,)␣
↪= P1._first_ngens(3)
>>> points_source = [P1([Integer(1), Integer(4), Integer(1)]), P1([Integer(1),
↪ Integer(2), Integer(2)]), P1([Integer(3), Integer(5), Integer(1)]),␣
↪P1([Integer(1), -Integer(1), Integer(1)])]
>>> points_target = [P1([Integer(5), -Integer(2), Integer(7)]),␣
↪P1([Integer(3), -Integer(2), Integer(3)]), P1([Integer(6), -Integer(5),␣
↪Integer(9)]), P1([Integer(3), Integer(6), Integer(7)])]
>>> P1.point_transformation_matrix(points_source, points_target)          #␣
↪needs sage.modules
[ -39 -384  -75]
[ 538   24   26]
[-135 -588  177]
```

```
sage: P1.<a,b,c> = ProjectiveSpace(ZZ, 2)
sage: points_source = [P1([1, 4, 1]), P1([1, 2, 2]), P1([3, 5, 1]), P1([1, -1,
↪ 1])]
sage: points_target = [P1([5, -2, 7]), P1([3, -2, 3]), P1([6, -5, 9]), P1([3,␣
↪6, 7])]
sage: P1.point_transformation_matrix(points_source, points_target,          #␣
↪needs sage.modules
....:                                 normalize=False)
[-13/30 -64/15   -5/6]
[269/45   4/15  13/45]
[  -3/2 -98/15  59/30]
```

```
>>> from sage.all import *
>>> P1 = ProjectiveSpace(ZZ, Integer(2), names=('a', 'b', 'c',)); (a, b, c,)␣
↪= P1._first_ngens(3)
>>> points_source = [P1([Integer(1), Integer(4), Integer(1)]), P1([Integer(1),
↪ Integer(2), Integer(2)]), P1([Integer(3), Integer(5), Integer(1)]),␣
↪P1([Integer(1), -Integer(1), Integer(1)])]
>>> points_target = [P1([Integer(5), -Integer(2), Integer(7)]),␣
↪P1([Integer(3), -Integer(2), Integer(3)]), P1([Integer(6), -Integer(5),␣
↪Integer(9)]), P1([Integer(3), Integer(6), Integer(7)])]
>>> P1.point_transformation_matrix(points_source, points_target,          #␣
↪needs sage.modules
...                                 normalize=False)
[-13/30 -64/15   -5/6]
[269/45   4/15  13/45]
[  -3/2 -98/15  59/30]
```

```
sage: R.<t> = ZZ[]
sage: P.<a,b> = ProjectiveSpace(R, 1)
sage: points_source = [P([-6*t, 7]), P([1, 4]), P([3, 2])]
sage: points_target = [P([-1, 2*t]), P([0, 2]), P([-1, 6])]
sage: P.point_transformation_matrix(points_source, points_target)          #␣
↪needs sage.modules
```

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```
[         -48*t - 84           12*t + 21]
[96*t^2 + 28*t + 420    -144*t^2 + 318*t]
```

```
>>> from sage.all import *
>>> R = ZZ['t']; (t,) = R._first_ngens(1)
>>> P = ProjectiveSpace(R, Integer(1), names=('a', 'b',)); (a, b,) = P._first_
↪ngens(2)
>>> points_source = [P([-Integer(6)*t, Integer(7)]), P([Integer(1),␣
↪Integer(4)]), P([Integer(3), Integer(2)])]
>>> points_target = [P([-Integer(1), Integer(2)*t]), P([Integer(0),␣
↪Integer(2)]), P([-Integer(1), Integer(6)])]
>>> P.point_transformation_matrix(points_source, points_target)           #␣
↪needs sage.modules
[         -48*t - 84           12*t + 21]
[96*t^2 + 28*t + 420    -144*t^2 + 318*t]
```

points_of_bounded_height(***kwds*)

Return an iterator of the points in `self` of absolute multiplicative height of at most the given bound.

ALGORITHM:

This is an implementation of Algorithm 6 in [Krumm2016].

INPUT: keyword arguments:

- `bound` – a real number
- `precision` – (default: 53) a positive integer

OUTPUT: an iterator of points of bounded height

EXAMPLES:

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: sorted(list(P.points_of_bounded_height(bound=2)))
[(-2 : 1), (-1 : 1), (-1/2 : 1), (0 : 1),
 (1/2 : 1), (1 : 0), (1 : 1), (2 : 1)]
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> sorted(list(P.points_of_bounded_height(bound=Integer(2))))
[(-2 : 1), (-1 : 1), (-1/2 : 1), (0 : 1),
 (1/2 : 1), (1 : 0), (1 : 1), (2 : 1)]
```

```
sage: u = QQ['u'].0
sage: P.<x,y,z> = ProjectiveSpace(NumberField(u^2 - 2, 'v'), 2)            #␣
↪needs sage.rings.number_field
sage: len(list(P.points_of_bounded_height(bound=2)))                       #␣
↪needs sage.rings.number_field
265
```

```
>>> from sage.all import *
>>> u = QQ['u'].gen(0)
```

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```
>>> P = ProjectiveSpace(NumberField(u**Integer(2) - Integer(2), 'v'),␣
↪Integer(2), names=('x', 'y', 'z',)); (x, y, z,) = P._first_ngens(3)# needs␣
↪sage.rings.number_field
>>> len(list(P.points_of_bounded_height(bound=Integer(2))))                    ␣
↪     # needs sage.rings.number_field
265
```

```
sage: # needs sage.rings.number_field
sage: CF.<a> = CyclotomicField(3)
sage: R.<x> = CF[]
sage: L.<l> = CF.extension(x^3 + 2)
sage: Q.<x,y> = ProjectiveSpace(L, 1)
sage: sorted(list(Q.points_of_bounded_height(bound=1)))
[(0 : 1), (1 : 0), (a + 1 : 1), (a : 1),
 (-1 : 1), (-a - 1 : 1), (-a : 1), (1 : 1)]
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> CF = CyclotomicField(Integer(3), names=('a',)); (a,) = CF._first_ngens(1)
>>> R = CF['x']; (x,) = R._first_ngens(1)
>>> L = CF.extension(x**Integer(3) + Integer(2), names=('l',)); (l,) = L._
↪first_ngens(1)
>>> Q = ProjectiveSpace(L, Integer(1), names=('x', 'y',)); (x, y,) = Q._first_
↪ngens(2)
>>> sorted(list(Q.points_of_bounded_height(bound=Integer(1))))
[(0 : 1), (1 : 0), (a + 1 : 1), (a : 1),
 (-1 : 1), (-a - 1 : 1), (-a : 1), (1 : 1)]
```

```
sage: # needs sage.rings.number_field
sage: R.<x> = QQ[]
sage: F.<a> = NumberField(x^4 - 8*x^2 + 3)
sage: P.<x,y,z> = ProjectiveSpace(F, 2)
sage: all(exp(p.global_height()) <= 1                                       #␣
↪needs sage.symbolic
....:     for p in P.points_of_bounded_height(bound=1))
True
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> F = NumberField(x**Integer(4) - Integer(8)*x**Integer(2) + Integer(3),␣
↪names=('a',)); (a,) = F._first_ngens(1)
>>> P = ProjectiveSpace(F, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> all(exp(p.global_height()) <= Integer(1)                                  ␣
↪     # needs sage.symbolic
...     for p in P.points_of_bounded_height(bound=Integer(1)))
True
```

```
sage: K.<a> = CyclotomicField(3)                                            #␣
↪needs sage.rings.number_field
```

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```
sage: P.<x,y,z> = ProjectiveSpace(K, 2)                                    #␣
↪needs sage.rings.number_field
sage: len(list(P.points_of_bounded_height(bound=1)))                       #␣
↪needs sage.rings.number_field
57
```

```
>>> from sage.all import *
>>> K = CyclotomicField(Integer(3), names=('a',)); (a,) = K._first_ngens(1)#␣
↪needs sage.rings.number_field
>>> P = ProjectiveSpace(K, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)# needs sage.rings.number_field
>>> len(list(P.points_of_bounded_height(bound=Integer(1))))                 ␣
↪     # needs sage.rings.number_field
57
```

```
sage: u = QQ['u'].0
sage: K.<k> = NumberField(u^2 - 2)                                         #␣
↪needs sage.rings.number_field
sage: P.<x,y> = ProjectiveSpace(K, 1)                                      #␣
↪needs sage.rings.number_field
sage: len(list(P.points_of_bounded_height(bound=2)))                       #␣
↪needs sage.rings.number_field
24
```

```
>>> from sage.all import *
>>> u = QQ['u'].gen(0)
>>> K = NumberField(u**Integer(2) - Integer(2), names=('k',)); (k,) = K._
↪first_ngens(1)# needs sage.rings.number_field
>>> P = ProjectiveSpace(K, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)# needs sage.rings.number_field
>>> len(list(P.points_of_bounded_height(bound=Integer(2))))                 ␣
↪     # needs sage.rings.number_field
24
```

```
sage: R.<x> = QQ[]
sage: K.<k> = NumberField(x^4 - 8*x^2 + 3)                                 #␣
↪needs sage.rings.number_field
sage: P.<x,y> = ProjectiveSpace(K, 1)                                      #␣
↪needs sage.rings.number_field
sage: len(list(P.points_of_bounded_height(bound=2)))                       #␣
↪needs sage.rings.number_field
108
```

```
>>> from sage.all import *
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> K = NumberField(x**Integer(4) - Integer(8)*x**Integer(2) + Integer(3),␣
↪names=('k',)); (k,) = K._first_ngens(1)# needs sage.rings.number_field
>>> P = ProjectiveSpace(K, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)# needs sage.rings.number_field
>>> len(list(P.points_of_bounded_height(bound=Integer(2))))                 ␣
↪     # needs sage.rings.number_field
```

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```
108
```

```
sage: # needs sage.rings.number_field
sage: R.<x> = QQ[]
sage: K.<v> = NumberField(x^5 + x^3 + 1)
sage: P.<x,y,z> = ProjectiveSpace(K, 2)
sage: L = P.points_of_bounded_height(bound=1.2)
sage: len(list(L))
109
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> K = NumberField(x**Integer(5) + x**Integer(3) + Integer(1), names=('v',));
 ↪ (v,) = K._first_ngens(1)
>>> P = ProjectiveSpace(K, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> L = P.points_of_bounded_height(bound=RealNumber('1.2'))
>>> len(list(L))
109
```

```
sage: # needs sage.rings.number_field
sage: K.<v> = QuadraticField(2)
sage: P.<x,y> = ProjectiveSpace(K, 1)
sage: sorted(list(P.points_of_bounded_height(bound=2)))
[(-v - 2 : 1), (-v - 1 : 1), (-2 : 1), (-1/2*v - 1 : 1), (-v : 1), (-1 : 1),
 (-1/2*v : 1), (v - 2 : 1), (-1/2 : 1), (-v + 1 : 1), (1/2*v - 1 : 1), (0 :␣
↪1),
 (-1/2*v + 1 : 1), (v - 1 : 1), (1/2 : 1), (-v + 2 : 1), (1/2*v : 1), (1 : 0),
 (1 : 1), (v : 1), (1/2*v + 1 : 1), (2 : 1), (v + 1 : 1), (v + 2 : 1)]
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> K = QuadraticField(Integer(2), names=('v',)); (v,) = K._first_ngens(1)
>>> P = ProjectiveSpace(K, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> sorted(list(P.points_of_bounded_height(bound=Integer(2))))
[(-v - 2 : 1), (-v - 1 : 1), (-2 : 1), (-1/2*v - 1 : 1), (-v : 1), (-1 : 1),
 (-1/2*v : 1), (v - 2 : 1), (-1/2 : 1), (-v + 1 : 1), (1/2*v - 1 : 1), (0 :␣
↪1),
 (-1/2*v + 1 : 1), (v - 1 : 1), (1/2 : 1), (-v + 2 : 1), (1/2*v : 1), (1 : 0),
 (1 : 1), (v : 1), (1/2*v + 1 : 1), (2 : 1), (v + 1 : 1), (v + 2 : 1)]
```

```
sage: # needs sage.rings.number_field
sage: R.<x> = QQ[]
sage: K.<a> = NumberField(3*x^2 + 1)
sage: P.<z,w> = ProjectiveSpace(K, 1)
sage: sorted(list(P.points_of_bounded_height(bound=1)))
[(-1 : 1), (-3/2*a - 1/2 : 1), (3/2*a - 1/2 : 1), (0 : 1),
 (-3/2*a + 1/2 : 1), (3/2*a + 1/2 : 1), (1 : 0), (1 : 1)]
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> K = NumberField(Integer(3)*x**Integer(2) + Integer(1), names=('a',)); (a,
↪) = K._first_ngens(1)
>>> P = ProjectiveSpace(K, Integer(1), names=('z', 'w',)); (z, w,) = P._first_
↪ngens(2)
>>> sorted(list(P.points_of_bounded_height(bound=Integer(1))))
[(-1 : 1), (-3/2*a - 1/2 : 1), (3/2*a - 1/2 : 1), (0 : 1),
 (-3/2*a + 1/2 : 1), (3/2*a + 1/2 : 1), (1 : 0), (1 : 1)]
```

```
sage: # needs sage.rings.number_field
sage: R.<x> = QQ[]
sage: K.<a> = NumberField(3*x^2 + 1)
sage: O = K.maximal_order()
sage: P.<z,w> = ProjectiveSpace(O, 1)
sage: len(sorted(list(P.points_of_bounded_height(bound=2))))
44
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> K = NumberField(Integer(3)*x**Integer(2) + Integer(1), names=('a',)); (a,
↪) = K._first_ngens(1)
>>> O = K.maximal_order()
>>> P = ProjectiveSpace(O, Integer(1), names=('z', 'w',)); (z, w,) = P._first_
↪ngens(2)
>>> len(sorted(list(P.points_of_bounded_height(bound=Integer(2)))))
44
```

```
sage: # needs sage.rings.number_field
sage: R.<x> = QQ[]
sage: K.<a> = NumberField(x^3 - 7)
sage: O = K.maximal_order()
sage: P.<z,w> = ProjectiveSpace(O, 1)
sage: len(sorted(list(P.points_of_bounded_height(bound=2))))
28
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> K = NumberField(x**Integer(3) - Integer(7), names=('a',)); (a,) = K._
↪first_ngens(1)
>>> O = K.maximal_order()
>>> P = ProjectiveSpace(O, Integer(1), names=('z', 'w',)); (z, w,) = P._first_
↪ngens(2)
>>> len(sorted(list(P.points_of_bounded_height(bound=Integer(2)))))
28
```

```
sage: P.<w,z> = ProjectiveSpace(ZZ, 1)
sage: sorted(list(P.points_of_bounded_height(bound=2)))
```

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```
[(-2 : -1), (-2 : 1), (-1 : -2), (-1 : -1),
 (-1 : 0), (-1 : 1), (-1 : 2), (0 : -1)]
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(ZZ, Integer(1), names=('w', 'z',)); (w, z,) = P._
↪first_ngens(2)
>>> sorted(list(P.points_of_bounded_height(bound=Integer(2))))
[(-2 : -1), (-2 : 1), (-1 : -2), (-1 : -1),
 (-1 : 0), (-1 : 1), (-1 : 2), (0 : -1)]
```

```
sage: R.<x> = QQ[]
sage: P.<z,w> = ProjectiveSpace(R, 1)
sage: P.points_of_bounded_height(bound=2)
Traceback (most recent call last):
...
NotImplementedError: self must be a projective space over
a number field or a ring of integers
```

```
>>> from sage.all import *
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> P = ProjectiveSpace(R, Integer(1), names=('z', 'w',)); (z, w,) = P._first_
↪ngens(2)
>>> P.points_of_bounded_height(bound=Integer(2))
Traceback (most recent call last):
...
NotImplementedError: self must be a projective space over
a number field or a ring of integers
```

```
sage: # needs sage.rings.number_field
sage: K.<i> = NumberField(x^2 + 1)
sage: PK.<t> = K[]
sage: L.<a> = K.extension(t^4  - i)
sage: P.<z,w> = ProjectiveSpace(L, 1)
sage: sorted(list(P.points_of_bounded_height(bound=1)))
[(0 : 1), (1 : 0), (a : 1), (a^2 : 1), (a^3 : 1), (i : 1),
 (i*a : 1), (i*a^2 : 1), (i*a^3 : 1), (-1 : 1), (-a : 1), (-a^2 : 1),
 (-a^3 : 1), (-i : 1), (-i*a : 1), (-i*a^2 : 1), (-i*a^3 : 1), (1 : 1)]
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> K = NumberField(x**Integer(2) + Integer(1), names=('i',)); (i,) = K._
↪first_ngens(1)
>>> PK = K['t']; (t,) = PK._first_ngens(1)
>>> L = K.extension(t**Integer(4)  - i, names=('a',)); (a,) = L._first_
↪ngens(1)
>>> P = ProjectiveSpace(L, Integer(1), names=('z', 'w',)); (z, w,) = P._first_
↪ngens(2)
>>> sorted(list(P.points_of_bounded_height(bound=Integer(1))))
[(0 : 1), (1 : 0), (a : 1), (a^2 : 1), (a^3 : 1), (i : 1),
 (i*a : 1), (i*a^2 : 1), (i*a^3 : 1), (-1 : 1), (-a : 1), (-a^2 : 1),
 (-a^3 : 1), (-i : 1), (-i*a : 1), (-i*a^2 : 1), (-i*a^3 : 1), (1 : 1)]
```

subscheme(*X*)

Return the closed subscheme defined by X.

INPUT:

- X – list or tuple of equations

EXAMPLES:

```
sage: A.<x,y,z> = ProjectiveSpace(2, QQ)
sage: X = A.subscheme([x*z^2, y^2*z, x*y^2]); X
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  x*z^2,
  y^2*z,
  x*y^2
sage: X.defining_polynomials ()
(x*z^2, y^2*z, x*y^2)
sage: I = X.defining_ideal(); I
Ideal (x*z^2, y^2*z, x*y^2) of Multivariate Polynomial Ring in x, y, z
 over Rational Field
sage: I.groebner_basis()                                                    #␣
↪needs sage.libs.singular
[x*y^2, y^2*z,  x*z^2]
sage: X.dimension()                                                         #␣
↪needs sage.libs.singular
0
sage: X.base_ring()
Rational Field
sage: X.base_scheme()
Spectrum of Rational Field
sage: X.structure_morphism()
Scheme morphism:
  From: Closed subscheme of Projective Space of dimension 2
        over Rational Field defined by: x*z^2, y^2*z, x*y^2
  To:   Spectrum of Rational Field
  Defn: Structure map
```

```
>>> from sage.all import *
>>> A = ProjectiveSpace(Integer(2), QQ, names=('x', 'y', 'z',)); (x, y, z,) =␣
↪A._first_ngens(3)
>>> X = A.subscheme([x*z**Integer(2), y**Integer(2)*z, x*y**Integer(2)]); X
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  x*z^2,
  y^2*z,
  x*y^2
>>> X.defining_polynomials ()
(x*z^2, y^2*z, x*y^2)
>>> I = X.defining_ideal(); I
Ideal (x*z^2, y^2*z, x*y^2) of Multivariate Polynomial Ring in x, y, z
 over Rational Field
>>> I.groebner_basis()                                                      #␣
↪needs sage.libs.singular
```

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```
[x*y^2, y^2*z,  x*z^2]
>>> X.dimension()                                                    #␣
↪needs sage.libs.singular
0
>>> X.base_ring()
Rational Field
>>> X.base_scheme()
Spectrum of Rational Field
>>> X.structure_morphism()
Scheme morphism:
  From: Closed subscheme of Projective Space of dimension 2
        over Rational Field defined by: x*z^2, y^2*z, x*y^2
  To:   Spectrum of Rational Field
  Defn: Structure map
```

veronese_embedding(*d*, *CS=None*, *order='lex'*)

Return the degree `d` Veronese embedding from this projective space.

INPUT:

- `d` – positive integer
- `CS` – (default: `None`) a projective ambient space to embed into. If this projective space has dimension N, the dimension of `CS` must be $\binom{N+d}{d} - 1$. This is constructed if not specified.
- `order` – string (default: `'lex'`); a monomial order to use to arrange the monomials defining the embedding. The monomials will be arranged from greatest to least with respect to this order.

OUTPUT: a scheme morphism from this projective space to `CS`

EXAMPLES:

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: vd = P.veronese_embedding(4, order='invlex')                    #␣
↪needs sage.combinat
sage: vd                                                              #␣
↪needs sage.combinat
Scheme morphism:
  From: Projective Space of dimension 1 over Rational Field
  To:   Projective Space of dimension 4 over Rational Field
  Defn: Defined on coordinates by sending (x : y) to
        (y^4 : x*y^3 : x^2*y^2 : x^3*y : x^4)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> vd = P.veronese_embedding(Integer(4), order='invlex')                ␣
↪     # needs sage.combinat
>>> vd                                                                 #␣
↪needs sage.combinat
Scheme morphism:
  From: Projective Space of dimension 1 over Rational Field
  To:   Projective Space of dimension 4 over Rational Field
  Defn: Defined on coordinates by sending (x : y) to
        (y^4 : x*y^3 : x^2*y^2 : x^3*y : x^4)
```

Veronese surface:

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: Q.<q,r,s,t,u,v> = ProjectiveSpace(QQ, 5)
sage: vd = P.veronese_embedding(2, Q)                                    #␣
↪needs sage.combinat
sage: vd                                                                 #␣
↪needs sage.combinat
Scheme morphism:
  From: Projective Space of dimension 2 over Rational Field
  To:   Projective Space of dimension 5 over Rational Field
  Defn: Defined on coordinates by sending (x : y : z) to
        (x^2 : x*y : x*z : y^2 : y*z : z^2)
sage: vd(P.subscheme([]))                                                #␣
↪needs sage.combinat sage.libs.singular
Closed subscheme of Projective Space of dimension 5 over Rational Field
 defined by:
  -u^2 + t*v,
  -s*u + r*v,
  -s*t + r*u,
  -s^2 + q*v,
  -r*s + q*u,
  -r^2 + q*t
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> Q = ProjectiveSpace(QQ, Integer(5), names=('q', 'r', 's', 't', 'u', 'v',
↪)); (q, r, s, t, u, v,) = Q._first_ngens(6)
>>> vd = P.veronese_embedding(Integer(2), Q)                                 ␣
↪     # needs sage.combinat
>>> vd                                                                    #␣
↪needs sage.combinat
Scheme morphism:
  From: Projective Space of dimension 2 over Rational Field
  To:   Projective Space of dimension 5 over Rational Field
  Defn: Defined on coordinates by sending (x : y : z) to
        (x^2 : x*y : x*z : y^2 : y*z : z^2)
>>> vd(P.subscheme([]))                                                   #␣
↪needs sage.combinat sage.libs.singular
Closed subscheme of Projective Space of dimension 5 over Rational Field
 defined by:
  -u^2 + t*v,
  -s*u + r*v,
  -s*t + r*u,
  -s^2 + q*v,
  -r*s + q*u,
  -r^2 + q*t
```

sage.schemes.projective.projective_space.**is_ProjectiveSpace**(*x*)

Return `True` if `x` is a projective space.

In other words, if `x` is an ambient space $\mathbb{P}^n_R$, where R is a ring and $n \geq 0$ is an integer.

EXAMPLES:

```
sage: from sage.schemes.projective.projective_space import is_ProjectiveSpace
sage: is_ProjectiveSpace(ProjectiveSpace(5, names='x'))
doctest:warning...
DeprecationWarning: The function is_ProjectiveSpace is deprecated; use
↪'isinstance(..., ProjectiveSpace_ring)' instead.
See https://github.com/sagemath/sage/issues/38022 for details.
True
sage: is_ProjectiveSpace(ProjectiveSpace(5, GF(9, 'alpha'), names='x'))         #␣
↪needs sage.rings.finite_rings
True
sage: is_ProjectiveSpace(Spec(ZZ))
False
```

```
>>> from sage.all import *
>>> from sage.schemes.projective.projective_space import is_ProjectiveSpace
>>> is_ProjectiveSpace(ProjectiveSpace(Integer(5), names='x'))
doctest:warning...
DeprecationWarning: The function is_ProjectiveSpace is deprecated; use
↪'isinstance(..., ProjectiveSpace_ring)' instead.
See https://github.com/sagemath/sage/issues/38022 for details.
True
>>> is_ProjectiveSpace(ProjectiveSpace(Integer(5), GF(Integer(9), 'alpha'), names=
↪'x'))          # needs sage.rings.finite_rings
True
>>> is_ProjectiveSpace(Spec(ZZ))
False
```

14.2 Morphisms on projective schemes

This module defines morphisms from projective schemes. A morphism from a projective scheme to a projective scheme is defined by homogeneous polynomials of the same degree that define what the morphism does on points in the ambient projective space. A morphism from a projective scheme to an affine scheme is determined by rational function, that is, quotients of homogeneous polynomials of the same degree.

EXAMPLES:

```
sage: P2.<x0,x1,x2> = ProjectiveSpace(QQ, 2)
sage: A2.<x,y> = AffineSpace(QQ, 2)
sage: P2.hom([x0, x1, x1 + x2], P2)
Scheme endomorphism of Projective Space of dimension 2 over Rational Field
  Defn: Defined on coordinates by sending (x0 : x1 : x2) to (x0 : x1 : x1 + x2)
sage: P2.hom([x1/x0, (x1 + x2)/x0], A2)
Scheme morphism:
  From: Projective Space of dimension 2 over Rational Field
  To:   Affine Space of dimension 2 over Rational Field
  Defn: Defined on coordinates by sending (x0 : x1 : x2) to (x1/x0, (x1 + x2)/x0)
```

```
>>> from sage.all import *
>>> P2 = ProjectiveSpace(QQ, Integer(2), names=('x0', 'x1', 'x2',)); (x0, x1, x2,) =␣
↪P2._first_ngens(3)
>>> A2 = AffineSpace(QQ, Integer(2), names=('x', 'y',)); (x, y,) = A2._first_ngens(2)
>>> P2.hom([x0, x1, x1 + x2], P2)
```

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```
Scheme endomorphism of Projective Space of dimension 2 over Rational Field
  Defn: Defined on coordinates by sending (x0 : x1 : x2) to (x0 : x1 : x1 + x2)
>>> P2.hom([x1/x0, (x1 + x2)/x0], A2)
Scheme morphism:
  From: Projective Space of dimension 2 over Rational Field
  To:   Affine Space of dimension 2 over Rational Field
  Defn: Defined on coordinates by sending (x0 : x1 : x2) to (x1/x0, (x1 + x2)/x0)
```

AUTHORS:

- David Kohel, William Stein: initial version
- William Stein (2006-02-11): fixed bug where P(0,0,0) was allowed as a projective point
- Volker Braun (2011-08-08): renamed classes, more documentation, misc cleanups
- Ben Hutz (2013-03): iteration functionality and new directory structure for affine/projective, height functionality
- Brian Stout, Ben Hutz (2013-11): added minimal model functionality
- Dillon Rose (2014-01): speed enhancements
- Ben Hutz (2015-11): iteration of subschemes
- Kwankyu Lee (2020-02): added indeterminacy_locus() and image()
- Kwankyu Lee (2022-05): added graph(), projective_degrees(), and degree()

class sage.schemes.projective.projective_morphism.**SchemeMorphism_polynomial_projective_space**(*parent*, *polys*, *check=Tru*

Bases: *SchemeMorphism_polynomial*

A morphism of schemes determined by rational functions that define what the morphism does on points in the ambient projective space.

EXAMPLES:

```
sage: R.<x,y> = QQ[]
sage: P1 = ProjectiveSpace(R)
sage: H = P1.Hom(P1)
sage: H([y,2*x])
Scheme endomorphism of Projective Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x : y) to
        (y : 2*x)
```

```
>>> from sage.all import *
>>> R = QQ['x, y']; (x, y,) = R._first_ngens(2)
>>> P1 = ProjectiveSpace(R)
>>> H = P1.Hom(P1)
>>> H([y,Integer(2)*x])
Scheme endomorphism of Projective Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x : y) to
        (y : 2*x)
```

An example of a morphism between projective plane curves (see Issue #10297):

```
sage: # needs sage.schemes
sage: P2.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: f = x^3 + y^3 + 60*z^3
sage: g = y^2*z - (x^3 - 6400*z^3/3)
sage: C = Curve(f)
sage: E = Curve(g)
sage: xbar,ybar,zbar = C.coordinate_ring().gens()
sage: H = C.Hom(E)
sage: H([zbar, xbar - ybar, -(xbar+ybar)/80])
Scheme morphism:
  From: Projective Plane Curve over Rational Field defined by x^3 + y^3 + 60*z^3
  To:   Projective Plane Curve over Rational Field defined by -x^3 + y^2*z + 6400/
↪3*z^3
  Defn: Defined on coordinates by sending (x : y : z) to
        (z : x - y : -1/80*x - 1/80*y)
```

```
>>> from sage.all import *
>>> # needs sage.schemes
>>> P2 = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) = P2.
↪_first_ngens(3)
>>> f = x**Integer(3) + y**Integer(3) + Integer(60)*z**Integer(3)
>>> g = y**Integer(2)*z - (x**Integer(3) - Integer(6400)*z**Integer(3)/Integer(3))
>>> C = Curve(f)
>>> E = Curve(g)
>>> xbar,ybar,zbar = C.coordinate_ring().gens()
>>> H = C.Hom(E)
>>> H([zbar, xbar - ybar, -(xbar+ybar)/Integer(80)])
Scheme morphism:
  From: Projective Plane Curve over Rational Field defined by x^3 + y^3 + 60*z^3
  To:   Projective Plane Curve over Rational Field defined by -x^3 + y^2*z + 6400/
↪3*z^3
  Defn: Defined on coordinates by sending (x : y : z) to
        (z : x - y : -1/80*x - 1/80*y)
```

A more complicated example:

```
sage: P2.<x,y,z> = ProjectiveSpace(2, QQ)
sage: P1 = P2.subscheme(x - y)
sage: H12 = P1.Hom(P2)
sage: H12([x^2, x*z, z^2])
Scheme morphism:
  From: Closed subscheme of Projective Space of dimension 2 over Rational Field
        defined by: x - y
  To:   Projective Space of dimension 2 over Rational Field
  Defn: Defined on coordinates by sending (x : y : z) to (x^2 : x*z : z^2)
```

```
>>> from sage.all import *
>>> P2 = ProjectiveSpace(Integer(2), QQ, names=('x', 'y', 'z',)); (x, y, z,) = P2.
↪_first_ngens(3)
>>> P1 = P2.subscheme(x - y)
>>> H12 = P1.Hom(P2)
>>> H12([x**Integer(2), x*z, z**Integer(2)])
```

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```
Scheme morphism:
  From: Closed subscheme of Projective Space of dimension 2 over Rational Field
        defined by: x - y
  To:   Projective Space of dimension 2 over Rational Field
  Defn: Defined on coordinates by sending (x : y : z) to (x^2 : x*z : z^2)
```

We illustrate some error checking:

```
sage: R.<x,y> = QQ[]
sage: P1 = ProjectiveSpace(R)
sage: H = P1.Hom(P1)
sage: f = H([x - y, x*y])
Traceback (most recent call last):
...
ValueError: polys (=[x - y, x*y]) must be of the same degree

sage: H([x - 1, x*y + x])
Traceback (most recent call last):
...
ValueError: polys (=[x - 1, x*y + x]) must be homogeneous

sage: H([exp(x), exp(y)])                                                    #␣
↪needs sage.symbolic
Traceback (most recent call last):
...
TypeError: polys (=[e^x, e^y]) must be elements of
Multivariate Polynomial Ring in x, y over Rational Field
```

```
>>> from sage.all import *
>>> R = QQ['x, y']; (x, y,) = R._first_ngens(2)
>>> P1 = ProjectiveSpace(R)
>>> H = P1.Hom(P1)
>>> f = H([x - y, x*y])
Traceback (most recent call last):
...
ValueError: polys (=[x - y, x*y]) must be of the same degree

>>> H([x - Integer(1), x*y + x])
Traceback (most recent call last):
...
ValueError: polys (=[x - 1, x*y + x]) must be homogeneous

>>> H([exp(x), exp(y)])                                                      #␣
↪needs sage.symbolic
Traceback (most recent call last):
...
TypeError: polys (=[e^x, e^y]) must be elements of
Multivariate Polynomial Ring in x, y over Rational Field
```

We can also compute the forward image of subschemes through elimination. In particular, let $X = V(h_1, \ldots, h_t)$ and define the ideal $I = (h_1, \ldots, h_t, y_0 - f_0(\bar{x}), \ldots, y_n - f_n(\bar{x}))$. Then the elimination ideal $I_{n+1} = I \cap K[y_0, \ldots, y_n]$ is a homogeneous ideal and $f(X) = V(I_{n+1})$:

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: H = End(P)
sage: f = H([(x-2*y)^2, (x-2*z)^2, x^2])
sage: X = P.subscheme(y-z)
sage: f(f(f(X)))                                                              #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 2 over Rational Field
 defined by:
  y - z
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) = P._
↪first_ngens(3)
>>> H = End(P)
>>> f = H([(x-Integer(2)*y)**Integer(2), (x-Integer(2)*z)**Integer(2),␣
↪x**Integer(2)])
>>> X = P.subscheme(y-z)
>>> f(f(f(X)))                                                                #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 2 over Rational Field
 defined by:
  y - z
```

```
sage: P.<x,y,z,w> = ProjectiveSpace(QQ, 3)
sage: H = End(P)
sage: f = H([(x-2*y)^2, (x-2*z)^2, (x-2*w)^2, x^2])
sage: f(P.subscheme([x,y,z]))                                                 #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 3 over Rational Field
 defined by:
  w,
  y,
  x
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(3), names=('x', 'y', 'z', 'w',)); (x, y, z, w,
↪) = P._first_ngens(4)
>>> H = End(P)
>>> f = H([(x-Integer(2)*y)**Integer(2), (x-Integer(2)*z)**Integer(2), (x-
↪Integer(2)*w)**Integer(2), x**Integer(2)])
>>> f(P.subscheme([x,y,z]))                                                   #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 3 over Rational Field
 defined by:
  w,
  y,
  x
```

as_dynamical_system()

Return this endomorphism as a DynamicalSystem_projective.

OUTPUT: DynamicalSystem_projective

EXAMPLES:

```
sage: P.<x,y,z> = ProjectiveSpace(ZZ, 2)
sage: H = End(P)
sage: f = H([x^2, y^2, z^2])
sage: type(f.as_dynamical_system())                                             #␣
↪needs sage.schemes
<class 'sage.dynamics.arithmetic_dynamics.projective_ds.DynamicalSystem_
↪projective'>
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(ZZ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> H = End(P)
>>> f = H([x**Integer(2), y**Integer(2), z**Integer(2)])
>>> type(f.as_dynamical_system())                                               #␣
↪needs sage.schemes
<class 'sage.dynamics.arithmetic_dynamics.projective_ds.DynamicalSystem_
↪projective'>
```

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: H = End(P)
sage: f = H([x^2 - y^2, y^2])
sage: type(f.as_dynamical_system())                                             #␣
↪needs sage.schemes
<class 'sage.dynamics.arithmetic_dynamics.projective_ds.DynamicalSystem_
↪projective_field'>
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> H = End(P)
>>> f = H([x**Integer(2) - y**Integer(2), y**Integer(2)])
>>> type(f.as_dynamical_system())                                               #␣
↪needs sage.schemes
<class 'sage.dynamics.arithmetic_dynamics.projective_ds.DynamicalSystem_
↪projective_field'>
```

```
sage: P.<x,y> = ProjectiveSpace(GF(5), 1)
sage: H = End(P)
sage: f = H([x^2, y^2])
sage: type(f.as_dynamical_system())                                             #␣
↪needs sage.schemes
<class 'sage.dynamics.arithmetic_dynamics.projective_ds.DynamicalSystem_
↪projective_finite_field'>
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(GF(Integer(5)), Integer(1), names=('x', 'y',)); (x, y,
↪) = P._first_ngens(2)
>>> H = End(P)
>>> f = H([x**Integer(2), y**Integer(2)])
>>> type(f.as_dynamical_system())                                               #␣
```

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```
↪needs sage.schemes
<class 'sage.dynamics.arithmetic_dynamics.projective_ds.DynamicalSystem_
↪projective_finite_field'>
```

```
sage: P.<x,y> = ProjectiveSpace(RR, 1)
sage: f = DynamicalSystem([x^2 + y^2, y^2], P)                          #␣
↪needs sage.schemes
sage: g = f.as_dynamical_system()                                       #␣
↪needs sage.schemes
sage: g is f                                                            #␣
↪needs sage.schemes
True
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(RR, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> f = DynamicalSystem([x**Integer(2) + y**Integer(2), y**Integer(2)], P)  ␣
↪                           # needs sage.schemes
>>> g = f.as_dynamical_system()                                         #␣
↪needs sage.schemes
>>> g is f                                                              #␣
↪needs sage.schemes
True
```

degree()

Return the degree of this map.

The degree is defined as the degree of the homogeneous polynomials that are the coordinates of this map.

OUTPUT: positive integer

EXAMPLES:

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: H = Hom(P, P)
sage: f = H([x^2 + y^2, y^2])
sage: f.degree()
2
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> H = Hom(P, P)
>>> f = H([x**Integer(2) + y**Integer(2), y**Integer(2)])
>>> f.degree()
2
```

```
sage: # needs sage.rings.real_mpfr
sage: P.<x,y,z> = ProjectiveSpace(CC, 2)
sage: H = Hom(P, P)
sage: f = H([x^3 + y^3, y^2*z, z*x*y])
sage: f.degree()
3
```

```
>>> from sage.all import *
>>> # needs sage.rings.real_mpfr
>>> P = ProjectiveSpace(CC, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> H = Hom(P, P)
>>> f = H([x**Integer(3) + y**Integer(3), y**Integer(2)*z, z*x*y])
>>> f.degree()
3
```

```
sage: R.<t> = PolynomialRing(QQ)
sage: P.<x,y,z> = ProjectiveSpace(R, 2)
sage: H = Hom(P, P)
sage: f = H([x^2 + t*y^2, (2-t)*y^2, z^2])
sage: f.degree()
2
```

```
>>> from sage.all import *
>>> R = PolynomialRing(QQ, names=('t',)); (t,) = R._first_ngens(1)
>>> P = ProjectiveSpace(R, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> H = Hom(P, P)
>>> f = H([x**Integer(2) + t*y**Integer(2), (Integer(2)-t)*y**Integer(2),␣
↪z**Integer(2)])
>>> f.degree()
2
```

```
sage: P.<x,y,z> = ProjectiveSpace(ZZ, 2)
sage: X = P.subscheme(x^2 - y^2)
sage: H = Hom(X, X)
sage: f = H([x^2, y^2, z^2])
sage: f.degree()
2
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(ZZ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> X = P.subscheme(x**Integer(2) - y**Integer(2))
>>> H = Hom(X, X)
>>> f = H([x**Integer(2), y**Integer(2), z**Integer(2)])
>>> f.degree()
2
```

dehomogenize(*n*)

Return the standard dehomogenization at the `n[0]` coordinate for the domain and the `n[1]` coordinate for the codomain.

Note that the new function is defined over the fraction field of the base ring of this map.

INPUT:

- `n` – tuple of nonnegative integers; if `n` is an integer, then the two values of the tuple are assumed to be the same

OUTPUT: `SchemeMorphism_polynomial_affine_space`

EXAMPLES:

```
sage: P.<x,y> = ProjectiveSpace(ZZ, 1)
sage: H = Hom(P, P)
sage: f = H([x^2 + y^2, y^2])
sage: f.dehomogenize(0)
Scheme endomorphism of Affine Space of dimension 1 over Integer Ring
  Defn: Defined on coordinates by sending (y) to (y^2/(y^2 + 1))
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(ZZ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> H = Hom(P, P)
>>> f = H([x**Integer(2) + y**Integer(2), y**Integer(2)])
>>> f.dehomogenize(Integer(0))
Scheme endomorphism of Affine Space of dimension 1 over Integer Ring
  Defn: Defined on coordinates by sending (y) to (y^2/(y^2 + 1))
```

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: H = Hom(P, P)
sage: f = H([x^2 - y^2, y^2])
sage: f.dehomogenize((0,1))
Scheme morphism:
  From: Affine Space of dimension 1 over Rational Field
  To:   Affine Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (y) to ((-y^2 + 1)/y^2)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> H = Hom(P, P)
>>> f = H([x**Integer(2) - y**Integer(2), y**Integer(2)])
>>> f.dehomogenize((Integer(0),Integer(1)))
Scheme morphism:
  From: Affine Space of dimension 1 over Rational Field
  To:   Affine Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (y) to ((-y^2 + 1)/y^2)
```

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: H = Hom(P, P)
sage: f = H([x^2 + y^2, y^2 - z^2, 2*z^2])
sage: f.dehomogenize(2)
Scheme endomorphism of Affine Space of dimension 2 over Rational Field
  Defn: Defined on coordinates by sending (x, y) to
        (1/2*x^2 + 1/2*y^2, 1/2*y^2 - 1/2)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> H = Hom(P, P)
>>> f = H([x**Integer(2) + y**Integer(2), y**Integer(2) - z**Integer(2),␣
↪Integer(2)*z**Integer(2)])
```

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```
>>> f.dehomogenize(Integer(2))
Scheme endomorphism of Affine Space of dimension 2 over Rational Field
  Defn: Defined on coordinates by sending (x, y) to
        (1/2*x^2 + 1/2*y^2, 1/2*y^2 - 1/2)
```

```
sage: R.<t> = PolynomialRing(QQ)
sage: P.<x,y,z> = ProjectiveSpace(FractionField(R),2)
sage: H = Hom(P,P)
sage: f = H([x^2 + t*y^2, t*y^2 - z^2, t*z^2])
sage: f.dehomogenize(2)
Scheme endomorphism of Affine Space of dimension 2 over Fraction Field
 of Univariate Polynomial Ring in t over Rational Field
  Defn: Defined on coordinates by sending (x, y) to
        (1/t*x^2 + y^2, y^2 - 1/t)
```

```
>>> from sage.all import *
>>> R = PolynomialRing(QQ, names=('t',)); (t,) = R._first_ngens(1)
>>> P = ProjectiveSpace(FractionField(R),Integer(2), names=('x', 'y', 'z',));␣
↪(x, y, z,) = P._first_ngens(3)
>>> H = Hom(P,P)
>>> f = H([x**Integer(2) + t*y**Integer(2), t*y**Integer(2) - z**Integer(2),␣
↪t*z**Integer(2)])
>>> f.dehomogenize(Integer(2))
Scheme endomorphism of Affine Space of dimension 2 over Fraction Field
 of Univariate Polynomial Ring in t over Rational Field
  Defn: Defined on coordinates by sending (x, y) to
        (1/t*x^2 + y^2, y^2 - 1/t)
```

```
sage: P.<x,y,z> = ProjectiveSpace(ZZ, 2)
sage: X = P.subscheme(x^2 - y^2)
sage: H = Hom(X, X)
sage: f = H([x^2, y^2, x*z])
sage: f.dehomogenize(2)                                                    #␣
↪needs sage.libs.singular
Scheme endomorphism of Closed subscheme of Affine Space of dimension 2
 over Integer Ring defined by: x^2 - y^2
  Defn: Defined on coordinates by sending (x, y) to (x, y^2/x)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(ZZ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> X = P.subscheme(x**Integer(2) - y**Integer(2))
>>> H = Hom(X, X)
>>> f = H([x**Integer(2), y**Integer(2), x*z])
>>> f.dehomogenize(Integer(2))                                                ␣
↪     # needs sage.libs.singular
Scheme endomorphism of Closed subscheme of Affine Space of dimension 2
 over Integer Ring defined by: x^2 - y^2
  Defn: Defined on coordinates by sending (x, y) to (x, y^2/x)
```

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: H = End(P)
sage: f = H([x^2 - 2*x*y, y^2])
sage: f.dehomogenize(0).homogenize(0) == f
True
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> H = End(P)
>>> f = H([x**Integer(2) - Integer(2)*x*y, y**Integer(2)])
>>> f.dehomogenize(Integer(0)).homogenize(Integer(0)) == f
True
```

```
sage: # needs sage.rings.number_field
sage: K.<w> = QuadraticField(3)
sage: O = K.ring_of_integers()
sage: P.<x,y> = ProjectiveSpace(O, 1)
sage: H = End(P)
sage: f = H([x^2 - O(w)*y^2, y^2])
sage: f.dehomogenize(1)
Scheme endomorphism of Affine Space of dimension 1 over
 Maximal Order generated by w in Number Field in w with defining polynomial x^
↪2 - 3
  with w = 1.732050807568878?
  Defn: Defined on coordinates by sending (x) to (x^2 - w)
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> K = QuadraticField(Integer(3), names=('w',)); (w,) = K._first_ngens(1)
>>> O = K.ring_of_integers()
>>> P = ProjectiveSpace(O, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> H = End(P)
>>> f = H([x**Integer(2) - O(w)*y**Integer(2), y**Integer(2)])
>>> f.dehomogenize(Integer(1))
Scheme endomorphism of Affine Space of dimension 1 over
 Maximal Order generated by w in Number Field in w with defining polynomial x^
↪2 - 3
  with w = 1.732050807568878?
  Defn: Defined on coordinates by sending (x) to (x^2 - w)
```

```
sage: P1.<x,y> = ProjectiveSpace(QQ, 1)
sage: P2.<u,v,w> = ProjectiveSpace(QQ, 2)
sage: H = Hom(P2, P1)
sage: f = H([u*w, v^2 + w^2])
sage: f.dehomogenize((2,1))
Scheme morphism:
  From: Affine Space of dimension 2 over Rational Field
  To:   Affine Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (u, v) to (u/(v^2 + 1))
```

```
>>> from sage.all import *
>>> P1 = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P1._
↪first_ngens(2)
>>> P2 = ProjectiveSpace(QQ, Integer(2), names=('u', 'v', 'w',)); (u, v, w,)␣
↪= P2._first_ngens(3)
>>> H = Hom(P2, P1)
>>> f = H([u*w, v**Integer(2) + w**Integer(2)])
>>> f.dehomogenize((Integer(2),Integer(1)))
Scheme morphism:
  From: Affine Space of dimension 2 over Rational Field
  To:   Affine Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (u, v) to (u/(v^2 + 1))
```

global_height(*prec=None*)

Return the global height of the coefficients as a projective point.

INPUT:

- `prec` – desired floating point precision (default: default RealField precision)

OUTPUT: a real number

EXAMPLES:

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: H = Hom(P, P)
sage: f = H([1/1331*x^2 + 1/4000*y^2, 210*x*y]);
sage: f.global_height()                                                    #␣
↪needs sage.symbolic
20.8348429892146
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> H = Hom(P, P)
>>> f = H([Integer(1)/Integer(1331)*x**Integer(2) + Integer(1)/
↪Integer(4000)*y**Integer(2), Integer(210)*x*y]);
>>> f.global_height()                                                      #␣
↪needs sage.symbolic
20.8348429892146
```

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: H = Hom(P, P)
sage: f = H([1/1331*x^2 + 1/4000*y^2, 210*x*y]);
sage: f.global_height(prec=11)                                             #␣
↪needs sage.symbolic
20.8
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> H = Hom(P, P)
>>> f = H([Integer(1)/Integer(1331)*x**Integer(2) + Integer(1)/
↪Integer(4000)*y**Integer(2), Integer(210)*x*y]);
```

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```
>>> f.global_height(prec=Integer(11))                                          ␣
↪     # needs sage.symbolic
20.8
```

```
sage: P.<x,y,z> = ProjectiveSpace(ZZ, 2)
sage: H = Hom(P, P)
sage: f = H([4*x^2 + 100*y^2, 210*x*y, 10000*z^2]);
sage: f.global_height()                                                       #␣
↪needs sage.symbolic
8.51719319141624
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(ZZ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> H = Hom(P, P)
>>> f = H([Integer(4)*x**Integer(2) + Integer(100)*y**Integer(2),␣
↪Integer(210)*x*y, Integer(10000)*z**Integer(2)]);
>>> f.global_height()                                                          #␣
↪needs sage.symbolic
8.51719319141624
```

```
sage: # needs sage.rings.number_field
sage: R.<z> = PolynomialRing(QQ)
sage: K.<w> = NumberField(z^2 - 2)
sage: O = K.maximal_order()
sage: P.<x,y> = ProjectiveSpace(O, 1)
sage: H = Hom(P, P)
sage: f = H([2*x^2 + 3*O(w)*y^2, O(w)*y^2])
sage: f.global_height()
1.09861228866811
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = PolynomialRing(QQ, names=('z',)); (z,) = R._first_ngens(1)
>>> K = NumberField(z**Integer(2) - Integer(2), names=('w',)); (w,) = K._
↪first_ngens(1)
>>> O = K.maximal_order()
>>> P = ProjectiveSpace(O, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> H = Hom(P, P)
>>> f = H([Integer(2)*x**Integer(2) + Integer(3)*O(w)*y**Integer(2),␣
↪O(w)*y**Integer(2)])
>>> f.global_height()
1.09861228866811
```

```
sage: # needs sage.rings.number_field sage.symbolic
sage: P.<x,y> = ProjectiveSpace(QQbar, 1)
sage: P2.<u,v,w> = ProjectiveSpace(QQbar, 2)
sage: H = Hom(P, P2)
sage: f = H([x^2 + QQbar(I)*x*y + 3*y^2, y^2, QQbar(sqrt(5))*x*y])
sage: f.global_height()
```

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```
1.09861228866811
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field sage.symbolic
>>> P = ProjectiveSpace(QQbar, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> P2 = ProjectiveSpace(QQbar, Integer(2), names=('u', 'v', 'w',)); (u, v, w,
↪) = P2._first_ngens(3)
>>> H = Hom(P, P2)
>>> f = H([x**Integer(2) + QQbar(I)*x*y + Integer(3)*y**Integer(2),␣
↪y**Integer(2), QQbar(sqrt(Integer(5)))*x*y])
>>> f.global_height()
1.09861228866811
```

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: A.<z,w> = ProjectiveSpace(QQ, 1)
sage: H = Hom(P, A)
sage: f = H([1/1331*x^2 + 4000*y*z, y^2])
sage: f.global_height()                                                    #␣
↪needs sage.symbolic
15.4877354584971
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> A = ProjectiveSpace(QQ, Integer(1), names=('z', 'w',)); (z, w,) = A._
↪first_ngens(2)
>>> H = Hom(P, A)
>>> f = H([Integer(1)/Integer(1331)*x**Integer(2) + Integer(4000)*y*z,␣
↪y**Integer(2)])
>>> f.global_height()                                                      #␣
↪needs sage.symbolic
15.4877354584971
```

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: f = DynamicalSystem([1/25*x^2 + 25/3*x*y + y^2, 1*y^2])
sage: exp(f.global_height())                                               #␣
↪needs sage.symbolic
625.000000000000
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> f = DynamicalSystem([Integer(1)/Integer(25)*x**Integer(2) + Integer(25)/
↪Integer(3)*x*y + y**Integer(2), Integer(1)*y**Integer(2)])
>>> exp(f.global_height())                                                 #␣
↪needs sage.symbolic
625.000000000000
```

Scaling should not change the result:

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: f = DynamicalSystem([1/25*x^2 + 25/3*x*y + y^2, 1*y^2])
sage: f.global_height()                                                    #␣
↪needs sage.symbolic
6.43775164973640
sage: c = 10000
sage: f.scale_by(c)
sage: f.global_height()                                                    #␣
↪needs sage.symbolic
6.43775164973640
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> f = DynamicalSystem([Integer(1)/Integer(25)*x**Integer(2) + Integer(25)/
↪Integer(3)*x*y + y**Integer(2), Integer(1)*y**Integer(2)])
>>> f.global_height()                                                      #␣
↪needs sage.symbolic
6.43775164973640
>>> c = Integer(10000)
>>> f.scale_by(c)
>>> f.global_height()                                                      #␣
↪needs sage.symbolic
6.43775164973640
```

is_morphism()

Return `True` if this map is a morphism.

The map is a morphism if and only if the ideal generated by the defining polynomials is the unit ideal (no common zeros of the defining polynomials).

OUTPUT: boolean

EXAMPLES:

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: H = Hom(P, P)
sage: f = H([x^2 + y^2, y^2])
sage: f.is_morphism()                                                      #␣
↪needs sage.libs.singular
True
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> H = Hom(P, P)
>>> f = H([x**Integer(2) + y**Integer(2), y**Integer(2)])
>>> f.is_morphism()                                                        #␣
↪needs sage.libs.singular
True
```

```
sage: P.<x,y,z> = ProjectiveSpace(RR, 2)
sage: H = Hom(P, P)
```

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```
sage: f = H([x*z - y*z, x^2 - y^2, z^2])
sage: f.is_morphism()                                                       #␣
↪needs sage.libs.singular
False
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(RR, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> H = Hom(P, P)
>>> f = H([x*z - y*z, x**Integer(2) - y**Integer(2), z**Integer(2)])
>>> f.is_morphism()                                                         #␣
↪needs sage.libs.singular
False
```

```
sage: R.<t> = PolynomialRing(GF(5))
sage: P.<x,y,z> = ProjectiveSpace(R, 2)
sage: H = Hom(P, P)
sage: f = H([x*z - t*y^2, x^2 - y^2, t*z^2])
sage: f.is_morphism()                                                       #␣
↪needs sage.libs.singular
True
```

```
>>> from sage.all import *
>>> R = PolynomialRing(GF(Integer(5)), names=('t',)); (t,) = R._first_ngens(1)
>>> P = ProjectiveSpace(R, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> H = Hom(P, P)
>>> f = H([x*z - t*y**Integer(2), x**Integer(2) - y**Integer(2),␣
↪t*z**Integer(2)])
>>> f.is_morphism()                                                         #␣
↪needs sage.libs.singular
True
```

Map that is not morphism on projective space, but is over a subscheme:

```
sage: P.<x,y,z> = ProjectiveSpace(RR, 2)
sage: X = P.subscheme([x*y + y*z])
sage: H = Hom(X, X)
sage: f = H([x*z - y*z, x^2 - y^2, z^2])
sage: f.is_morphism()                                                       #␣
↪needs sage.libs.singular
True
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(RR, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> X = P.subscheme([x*y + y*z])
>>> H = Hom(X, X)
>>> f = H([x*z - y*z, x**Integer(2) - y**Integer(2), z**Integer(2)])
>>> f.is_morphism()                                                         #␣
↪needs sage.libs.singular
```

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```
True
```

local_height(*v*, *prec=None*)

Return the maximum of the local height of the coefficients in any of the coordinate functions of this map.

INPUT:

- `v` – a prime or prime ideal of the base ring
- `prec` – desired floating point precision (default: default RealField precision)

OUTPUT: a real number

EXAMPLES:

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: H = Hom(P, P)
sage: f = H([1/1331*x^2 + 1/4000*y^2, 210*x*y])
sage: f.local_height(1331)                                                  #␣
↪needs sage.rings.real_mpfr
7.19368581839511
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> H = Hom(P, P)
>>> f = H([Integer(1)/Integer(1331)*x**Integer(2) + Integer(1)/
↪Integer(4000)*y**Integer(2), Integer(210)*x*y])
>>> f.local_height(Integer(1331))                                           ␣
↪     # needs sage.rings.real_mpfr
7.19368581839511
```

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: H = Hom(P, P)
sage: f = H([1/1331*x^2 + 1/4000*y^2, 210*x*y])
sage: f.local_height(1331, prec=2)                                          #␣
↪needs sage.rings.real_mpfr
8.0
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> H = Hom(P, P)
>>> f = H([Integer(1)/Integer(1331)*x**Integer(2) + Integer(1)/
↪Integer(4000)*y**Integer(2), Integer(210)*x*y])
>>> f.local_height(Integer(1331), prec=Integer(2))                          ␣
↪              # needs sage.rings.real_mpfr
8.0
```

This function does not automatically normalize:

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: H = Hom(P, P)
sage: f = H([4*x^2 + 3/100*y^2, 8/210*x*y, 1/10000*z^2])
```

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```
sage: f.local_height(2)                                                    #␣
↪needs sage.rings.real_mpfr
2.77258872223978
sage: f.normalize_coordinates()                                            #␣
↪needs sage.libs.singular
sage: f.local_height(2)                                                    #␣
↪needs sage.libs.singular
0.000000000000000
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> H = Hom(P, P)
>>> f = H([Integer(4)*x**Integer(2) + Integer(3)/Integer(100)*y**Integer(2),␣
↪Integer(8)/Integer(210)*x*y, Integer(1)/Integer(10000)*z**Integer(2)])
>>> f.local_height(Integer(2))                                                ␣
↪     # needs sage.rings.real_mpfr
2.77258872223978
>>> f.normalize_coordinates()                                              #␣
↪needs sage.libs.singular
>>> f.local_height(Integer(2))                                                ␣
↪     # needs sage.libs.singular
0.000000000000000
```

```
sage: # needs sage.rings.number_field
sage: R.<z> = PolynomialRing(QQ)
sage: K.<w> = NumberField(z^2 - 2)
sage: P.<x,y> = ProjectiveSpace(K, 1)
sage: H = Hom(P, P)
sage: f = H([2*x^2 + w/3*y^2, 1/w*y^2])
sage: f.local_height(K.ideal(3))
1.09861228866811
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = PolynomialRing(QQ, names=('z',)); (z,) = R._first_ngens(1)
>>> K = NumberField(z**Integer(2) - Integer(2), names=('w',)); (w,) = K._
↪first_ngens(1)
>>> P = ProjectiveSpace(K, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> H = Hom(P, P)
>>> f = H([Integer(2)*x**Integer(2) + w/Integer(3)*y**Integer(2), Integer(1)/
↪w*y**Integer(2)])
>>> f.local_height(K.ideal(Integer(3)))
1.09861228866811
```

local_height_arch(*i*, *prec=None*)

Return the maximum of the local height at the `i`-th infinite place of the coefficients in any of the coordinate functions of this map.

INPUT:

- `i` – integer

- `prec` – desired floating point precision (default: default RealField precision)

OUTPUT: a real number

EXAMPLES:

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: H = Hom(P, P)
sage: f = H([1/1331*x^2 + 1/4000*y^2, 210*x*y])
sage: f.local_height_arch(0)                                                #␣
↪needs sage.rings.real_mpfr
5.34710753071747
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> H = Hom(P, P)
>>> f = H([Integer(1)/Integer(1331)*x**Integer(2) + Integer(1)/
↪Integer(4000)*y**Integer(2), Integer(210)*x*y])
>>> f.local_height_arch(Integer(0))                                         ␣
↪     # needs sage.rings.real_mpfr
5.34710753071747
```

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: H = Hom(P, P)
sage: f = H([1/1331*x^2 + 1/4000*y^2, 210*x*y])
sage: f.local_height_arch(0, prec=5)                                        #␣
↪needs sage.rings.real_mpfr
5.2
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> H = Hom(P, P)
>>> f = H([Integer(1)/Integer(1331)*x**Integer(2) + Integer(1)/
↪Integer(4000)*y**Integer(2), Integer(210)*x*y])
>>> f.local_height_arch(Integer(0), prec=Integer(5))                        ␣
↪              # needs sage.rings.real_mpfr
5.2
```

```
sage: # needs sage.rings.number_field
sage: R.<z> = PolynomialRing(QQ)
sage: K.<w> = NumberField(z^2 - 2)
sage: P.<x,y> = ProjectiveSpace(K, 1)
sage: H = Hom(P, P)
sage: f = H([2*x^2 + w/3*y^2, 1/w*y^2])
sage: f.local_height_arch(1)
0.69314718055994530941723212145820
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = PolynomialRing(QQ, names=('z',)); (z,) = R._first_ngens(1)
>>> K = NumberField(z**Integer(2) - Integer(2), names=('w',)); (w,) = K._
```

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```
↪first_ngens(1)
>>> P = ProjectiveSpace(K, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> H = Hom(P, P)
>>> f = H([Integer(2)*x**Integer(2) + w/Integer(3)*y**Integer(2), Integer(1)/
↪w*y**Integer(2)])
>>> f.local_height_arch(Integer(1))
0.69314718055994530941723212145 82
```

normalize_coordinates(***kwds*)

Ensures that this morphism has integral coefficients. If the coordinate ring has a GCD, then it ensures that the coefficients have no common factor.

It also makes the leading coefficients of the first polynomial positive (if positive has meaning in the coordinate ring). This is done in place.

When `ideal` or `valuation` is specified, normalization occurs with respect to the absolute value defined by the `ideal` or `valuation`. That is, the coefficients are scaled such that one coefficient has absolute value 1 while the others have absolute value less than or equal to 1. Only supported when the base ring is a number field.

INPUT: keyword arguments:

- `ideal` – (optional) a prime ideal of the base ring of this morphism
- `valuation` – (optional) a valuation of the base ring of this morphism

OUTPUT: none

EXAMPLES:

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: H = Hom(P, P)
sage: f = H([5/4*x^3, 5*x*y^2])
sage: f.normalize_coordinates(); f
Scheme endomorphism of Projective Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x : y) to (x^2 : 4*y^2)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> H = Hom(P, P)
>>> f = H([Integer(5)/Integer(4)*x**Integer(3), Integer(5)*x*y**Integer(2)])
>>> f.normalize_coordinates(); f
Scheme endomorphism of Projective Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x : y) to (x^2 : 4*y^2)
```

```
sage: P.<x,y,z> = ProjectiveSpace(GF(7), 2)
sage: X = P.subscheme(x^2 - y^2)
sage: H = Hom(X, X)
sage: f = H([x^3 + x*y^2, x*y^2, x*z^2])
sage: f.normalize_coordinates(); f                                          #␣
↪needs sage.libs.singular
Scheme endomorphism of Closed subscheme of Projective Space of dimension 2
```

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```
 over Finite Field of size 7 defined by: x^2 - y^2
  Defn: Defined on coordinates by sending (x : y : z) to (2*y^2 : y^2 : z^2)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(GF(Integer(7)), Integer(2), names=('x', 'y', 'z',));␣
↪(x, y, z,) = P._first_ngens(3)
>>> X = P.subscheme(x**Integer(2) - y**Integer(2))
>>> H = Hom(X, X)
>>> f = H([x**Integer(3) + x*y**Integer(2), x*y**Integer(2), x*z**Integer(2)])
>>> f.normalize_coordinates(); f                                                #␣
↪needs sage.libs.singular
Scheme endomorphism of Closed subscheme of Projective Space of dimension 2
 over Finite Field of size 7 defined by: x^2 - y^2
  Defn: Defined on coordinates by sending (x : y : z) to (2*y^2 : y^2 : z^2)
```

```
sage: R.<a,b> = QQ[]
sage: P.<x,y,z> = ProjectiveSpace(R, 2)
sage: H = End(P)
sage: f = H([a*(x*z + y^2)*x^2, a*b*(x*z + y^2)*y^2, a*(x*z + y^2)*z^2])
sage: f.normalize_coordinates(); f
Scheme endomorphism of Projective Space of dimension 2 over
 Multivariate Polynomial Ring in a, b over Rational Field
  Defn: Defined on coordinates by sending (x : y : z) to (x^2 : b*y^2 : z^2)
```

```
>>> from sage.all import *
>>> R = QQ['a, b']; (a, b,) = R._first_ngens(2)
>>> P = ProjectiveSpace(R, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> H = End(P)
>>> f = H([a*(x*z + y**Integer(2))*x**Integer(2), a*b*(x*z +␣
↪y**Integer(2))*y**Integer(2), a*(x*z + y**Integer(2))*z**Integer(2)])
>>> f.normalize_coordinates(); f
Scheme endomorphism of Projective Space of dimension 2 over
 Multivariate Polynomial Ring in a, b over Rational Field
  Defn: Defined on coordinates by sending (x : y : z) to (x^2 : b*y^2 : z^2)
```

```
sage: # needs sage.rings.number_field
sage: K.<w> = QuadraticField(5)
sage: P.<x,y> = ProjectiveSpace(K, 1)
sage: f = DynamicalSystem([w*x^2 + (1/5*w)*y^2, w*y^2])
sage: f.normalize_coordinates(); f
Dynamical System of Projective Space of dimension 1 over Number Field in w
 with defining polynomial x^2 - 5 with w = 2.236067977499790?
  Defn: Defined on coordinates by sending (x : y) to (5*x^2 + y^2 : 5*y^2)
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> K = QuadraticField(Integer(5), names=('w',)); (w,) = K._first_ngens(1)
>>> P = ProjectiveSpace(K, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> f = DynamicalSystem([w*x**Integer(2) + (Integer(1)/
```

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```
↪Integer(5)*w)*y**Integer(2), w*y**Integer(2)])
>>> f.normalize_coordinates(); f
Dynamical System of Projective Space of dimension 1 over Number Field in w
 with defining polynomial x^2 - 5 with w = 2.236067977499790?
  Defn: Defined on coordinates by sending (x : y) to (5*x^2 + y^2 : 5*y^2)
```

```
sage: # needs sage.rings.number_field
sage: R.<t> = PolynomialRing(ZZ)
sage: K.<b> = NumberField(t^3 - 11)
sage: a = 7/(b - 1)
sage: P.<x,y> = ProjectiveSpace(K, 1)
sage: f = DynamicalSystem_projective([a*y^2 - (a*y - x)^2, y^2])
sage: f.normalize_coordinates(); f
Dynamical System of Projective Space of dimension 1 over
 Number Field in b with defining polynomial t^3 - 11
  Defn: Defined on coordinates by sending (x : y) to
        (-100*x^2 + (140*b^2 + 140*b + 140)*x*y + (-77*b^2 - 567*b - 1057)*y^2
         : 100*y^2)
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = PolynomialRing(ZZ, names=('t',)); (t,) = R._first_ngens(1)
>>> K = NumberField(t**Integer(3) - Integer(11), names=('b',)); (b,) = K._
↪first_ngens(1)
>>> a = Integer(7)/(b - Integer(1))
>>> P = ProjectiveSpace(K, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> f = DynamicalSystem_projective([a*y**Integer(2) - (a*y - x)**Integer(2),␣
↪y**Integer(2)])
>>> f.normalize_coordinates(); f
Dynamical System of Projective Space of dimension 1 over
 Number Field in b with defining polynomial t^3 - 11
  Defn: Defined on coordinates by sending (x : y) to
        (-100*x^2 + (140*b^2 + 140*b + 140)*x*y + (-77*b^2 - 567*b - 1057)*y^2
         : 100*y^2)
```

We can used `ideal` to scale with respect to a norm defined by an ideal:

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: f = DynamicalSystem_projective([2*x^3, 2*x^2*y + 4*x*y^2])
sage: f.normalize_coordinates(ideal=2); f
Dynamical System of Projective Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x : y) to (x^3 : x^2*y + 2*x*y^2)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> f = DynamicalSystem_projective([Integer(2)*x**Integer(3),␣
↪Integer(2)*x**Integer(2)*y + Integer(4)*x*y**Integer(2)])
>>> f.normalize_coordinates(ideal=Integer(2)); f
Dynamical System of Projective Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x : y) to (x^3 : x^2*y + 2*x*y^2)
```

```
sage: # needs sage.rings.number_field
sage: R.<w> = QQ[]
sage: A.<a> = NumberField(w^2 + 1)
sage: P.<x,y,z> = ProjectiveSpace(A, 2)
sage: X = P.subscheme(x^2 - y^2)
sage: H = Hom(X, X)
sage: f = H([(a+1)*x^3 + 2*x*y^2, 4*x*y^2, 8*x*z^2])
sage: f.normalize_coordinates(ideal=A.prime_above(2)); f
Scheme endomorphism of Closed subscheme of Projective Space of dimension 2␣
↪over
 Number Field in a with defining polynomial w^2 + 1 defined by: x^2 - y^2
  Defn: Defined on coordinates by sending (x : y : z) to
        ((-a + 2)*x*y^2 : (-2*a + 2)*x*y^2 : (-4*a + 4)*x*z^2)
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = QQ['w']; (w,) = R._first_ngens(1)
>>> A = NumberField(w**Integer(2) + Integer(1), names=('a',)); (a,) = A._
↪first_ngens(1)
>>> P = ProjectiveSpace(A, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> X = P.subscheme(x**Integer(2) - y**Integer(2))
>>> H = Hom(X, X)
>>> f = H([(a+Integer(1))*x**Integer(3) + Integer(2)*x*y**Integer(2),␣
↪Integer(4)*x*y**Integer(2), Integer(8)*x*z**Integer(2)])
>>> f.normalize_coordinates(ideal=A.prime_above(Integer(2))); f
Scheme endomorphism of Closed subscheme of Projective Space of dimension 2␣
↪over
 Number Field in a with defining polynomial w^2 + 1 defined by: x^2 - y^2
  Defn: Defined on coordinates by sending (x : y : z) to
        ((-a + 2)*x*y^2 : (-2*a + 2)*x*y^2 : (-4*a + 4)*x*z^2)
```

We can pass in a valuation to `valuation`:

```
sage: g = H([(a+1)*x^3 + 2*x*y^2, 4*x*y^2, 8*x*z^2])                    #␣
↪needs sage.rings.number_field
sage: g.normalize_coordinates(valuation=A.valuation(A.prime_above(2)))  #␣
↪needs sage.rings.number_field
sage: g == f                                                            #␣
↪needs sage.rings.number_field
True
```

```
>>> from sage.all import *
>>> g = H([(a+Integer(1))*x**Integer(3) + Integer(2)*x*y**Integer(2),␣
↪Integer(4)*x*y**Integer(2), Integer(8)*x*z**Integer(2)])                ␣
↪    # needs sage.rings.number_field
>>> g.normalize_coordinates(valuation=A.valuation(A.prime_above(Integer(2))))␣
↪     # needs sage.rings.number_field
>>> g == f                                                              #␣
↪needs sage.rings.number_field
True
```

```
sage: P.<x,y> = ProjectiveSpace(Qp(3), 1)                                    #␣
↪needs sage.rings.padics
sage: f = DynamicalSystem_projective([3*x^2 + 6*y^2, 9*x*y])                 #␣
↪needs sage.rings.padics
sage: f.normalize_coordinates(); f                                           #␣
↪needs sage.rings.padics
Dynamical System of Projective Space of dimension 1 over
 3-adic Field with capped relative precision 20
  Defn: Defined on coordinates by sending (x : y) to
        (x^2 + (2 + O(3^20))*y^2 : (3 + O(3^21))*x*y)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(Qp(Integer(3)), Integer(1), names=('x', 'y',)); (x, y,
↪) = P._first_ngens(2)# needs sage.rings.padics
>>> f = DynamicalSystem_projective([Integer(3)*x**Integer(2) +␣
↪Integer(6)*y**Integer(2), Integer(9)*x*y])                # needs sage.
↪rings.padics
>>> f.normalize_coordinates(); f                                             #␣
↪needs sage.rings.padics
Dynamical System of Projective Space of dimension 1 over
 3-adic Field with capped relative precision 20
  Defn: Defined on coordinates by sending (x : y) to
        (x^2 + (2 + O(3^20))*y^2 : (3 + O(3^21))*x*y)
```

Check that #35797 is fixed:

```
sage: # needs sage.rings.number_field
sage: R.<x> = QQ[]
sage: K.<a> = NumberField(3*x^2 + 1)
sage: P.<z,w> = ProjectiveSpace(K, 1)
sage: f = DynamicalSystem_projective([a*(z^2 + w^2), z*w])
sage: f.normalize_coordinates(); f
Dynamical System of Projective Space of dimension 1 over
Number Field in a with defining polynomial 3*x^2 + 1
Defn: Defined on coordinates by sending (z : w) to
    ((3/2*a + 1/2)*z^2 + (3/2*a + 1/2)*w^2 : (-3/2*a + 3/2)*z*w)
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> K = NumberField(Integer(3)*x**Integer(2) + Integer(1), names=('a',)); (a,
↪) = K._first_ngens(1)
>>> P = ProjectiveSpace(K, Integer(1), names=('z', 'w',)); (z, w,) = P._first_
↪ngens(2)
>>> f = DynamicalSystem_projective([a*(z**Integer(2) + w**Integer(2)), z*w])
>>> f.normalize_coordinates(); f
Dynamical System of Projective Space of dimension 1 over
Number Field in a with defining polynomial 3*x^2 + 1
Defn: Defined on coordinates by sending (z : w) to
    ((3/2*a + 1/2)*z^2 + (3/2*a + 1/2)*w^2 : (-3/2*a + 3/2)*z*w)
```

```
sage: R.<a,b> = QQ[]
```

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```
sage: P.<x,y,z> = ProjectiveSpace(FractionField(R), 2)
sage: H = End(P)
sage: f = H([a/b*(x*z + y^2)*x^2, a*b*(x*z + y^2)*y^2, a*(x*z + y^2)*z^2])
sage: f.normalize_coordinates(); f
Scheme endomorphism of Projective Space of dimension 2 over Fraction
Field of Multivariate Polynomial Ring in a, b over Rational Field
Defn: Defined on coordinates by sending (x : y : z) to
    (x^2 : (b^2)*y^2 : b*z^2)
```

```
>>> from sage.all import *
>>> R = QQ['a, b']; (a, b,) = R._first_ngens(2)
>>> P = ProjectiveSpace(FractionField(R), Integer(2), names=('x', 'y', 'z',));
↪ (x, y, z,) = P._first_ngens(3)
>>> H = End(P)
>>> f = H([a/b*(x*z + y**Integer(2))*x**Integer(2), a*b*(x*z +␣
↪y**Integer(2))*y**Integer(2), a*(x*z + y**Integer(2))*z**Integer(2)])
>>> f.normalize_coordinates(); f
Scheme endomorphism of Projective Space of dimension 2 over Fraction
Field of Multivariate Polynomial Ring in a, b over Rational Field
Defn: Defined on coordinates by sending (x : y : z) to
    (x^2 : (b^2)*y^2 : b*z^2)
```

scale_by(*t*)

Scale each coordinate by a factor of `t`.

A `TypeError` occurs if the point is not in the coordinate ring of the parent after scaling.

INPUT:

- `t` – a ring element

OUTPUT: none

EXAMPLES:

```
sage: A.<x,y> = ProjectiveSpace(QQ, 1)
sage: H = Hom(A, A)
sage: f = H([x^3 - 2*x*y^2, x^2*y])
sage: f.scale_by(1/x)
sage: f
Scheme endomorphism of Projective Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x : y) to (x^2 - 2*y^2 : x*y)
```

```
>>> from sage.all import *
>>> A = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = A._
↪first_ngens(2)
>>> H = Hom(A, A)
>>> f = H([x**Integer(3) - Integer(2)*x*y**Integer(2), x**Integer(2)*y])
>>> f.scale_by(Integer(1)/x)
>>> f
Scheme endomorphism of Projective Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x : y) to (x^2 - 2*y^2 : x*y)
```

```
sage: R.<t> = PolynomialRing(QQ)
sage: P.<x,y> = ProjectiveSpace(R, 1)
sage: H = Hom(P,P)
sage: f = H([3/5*x^2, 6*y^2])
sage: f.scale_by(5/3*t); f
Scheme endomorphism of Projective Space of dimension 1 over
 Univariate Polynomial Ring in t over Rational Field
  Defn: Defined on coordinates by sending (x : y) to (t*x^2 : 10*t*y^2)
```

```
>>> from sage.all import *
>>> R = PolynomialRing(QQ, names=('t',)); (t,) = R._first_ngens(1)
>>> P = ProjectiveSpace(R, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> H = Hom(P,P)
>>> f = H([Integer(3)/Integer(5)*x**Integer(2), Integer(6)*y**Integer(2)])
>>> f.scale_by(Integer(5)/Integer(3)*t); f
Scheme endomorphism of Projective Space of dimension 1 over
 Univariate Polynomial Ring in t over Rational Field
  Defn: Defined on coordinates by sending (x : y) to (t*x^2 : 10*t*y^2)
```

```
sage: P.<x,y,z> = ProjectiveSpace(GF(7), 2)
sage: X = P.subscheme(x^2 - y^2)
sage: H = Hom(X, X)
sage: f = H([x^2, y^2, z^2])
sage: f.scale_by(x - y); f                                                  #␣
↪needs sage.libs.singular
Scheme endomorphism of Closed subscheme of Projective Space of dimension 2
 over Finite Field of size 7 defined by: x^2 - y^2
  Defn: Defined on coordinates by sending (x : y : z) to
        (x*y^2 - y^3 : x*y^2 - y^3 : x*z^2 - y*z^2)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(GF(Integer(7)), Integer(2), names=('x', 'y', 'z',));␣
↪(x, y, z,) = P._first_ngens(3)
>>> X = P.subscheme(x**Integer(2) - y**Integer(2))
>>> H = Hom(X, X)
>>> f = H([x**Integer(2), y**Integer(2), z**Integer(2)])
>>> f.scale_by(x - y); f                                                    #␣
↪needs sage.libs.singular
Scheme endomorphism of Closed subscheme of Projective Space of dimension 2
 over Finite Field of size 7 defined by: x^2 - y^2
  Defn: Defined on coordinates by sending (x : y : z) to
        (x*y^2 - y^3 : x*y^2 - y^3 : x*z^2 - y*z^2)
```

wronskian_ideal()

Return the ideal generated by the critical point locus.

This is the vanishing of the maximal minors of the Jacobian matrix. Not implemented for subvarieties.

OUTPUT: an ideal in the coordinate ring of the domain of this map

EXAMPLES:

```
sage: # needs sage.rings.number_field
sage: R.<x> = PolynomialRing(QQ)
sage: K.<w> = NumberField(x^2 + 11)
sage: P.<x,y> = ProjectiveSpace(K, 1)
sage: H = End(P)
sage: f = H([x^2 - w*y^2, w*y^2])
sage: f.wronskian_ideal()
Ideal ((4*w)*x*y) of Multivariate Polynomial Ring in x, y
 over Number Field in w with defining polynomial x^2 + 11
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = PolynomialRing(QQ, names=('x',)); (x,) = R._first_ngens(1)
>>> K = NumberField(x**Integer(2) + Integer(11), names=('w',)); (w,) = K._
↪first_ngens(1)
>>> P = ProjectiveSpace(K, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> H = End(P)
>>> f = H([x**Integer(2) - w*y**Integer(2), w*y**Integer(2)])
>>> f.wronskian_ideal()
Ideal ((4*w)*x*y) of Multivariate Polynomial Ring in x, y
 over Number Field in w with defining polynomial x^2 + 11
```

```
sage: # needs sage.rings.number_field
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: P2.<u,v,t> = ProjectiveSpace(K, 2)
sage: H = Hom(P, P2)
sage: f = H([x^2 - 2*y^2, y^2, x*y])
sage: f.wronskian_ideal()
Ideal (4*x*y, 2*x^2 + 4*y^2, -2*y^2) of
 Multivariate Polynomial Ring in x, y over Rational Field
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> P2 = ProjectiveSpace(K, Integer(2), names=('u', 'v', 't',)); (u, v, t,) =␣
↪P2._first_ngens(3)
>>> H = Hom(P, P2)
>>> f = H([x**Integer(2) - Integer(2)*y**Integer(2), y**Integer(2), x*y])
>>> f.wronskian_ideal()
Ideal (4*x*y, 2*x^2 + 4*y^2, -2*y^2) of
 Multivariate Polynomial Ring in x, y over Rational Field
```

class sage.schemes.projective.projective_morphism.**SchemeMorphism_polynomial_projective_space_field**(*po*
en
po
ch

Bases: *SchemeMorphism_polynomial_projective_space*

base_indeterminacy_locus()

Return the base indeterminacy locus of this map.

The base indeterminacy locus is the set of points in projective space at which all of the defining polynomials of the rational map simultaneously vanish.

OUTPUT: a subscheme of the domain of the map

EXAMPLES:

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: H = End(P)
sage: f = H([x*z - y*z, x^2 - y^2, z^2])
sage: f.base_indeterminacy_locus()
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  x*z - y*z,
  x^2 - y^2,
  z^2
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> H = End(P)
>>> f = H([x*z - y*z, x**Integer(2) - y**Integer(2), z**Integer(2)])
>>> f.base_indeterminacy_locus()
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  x*z - y*z,
  x^2 - y^2,
  z^2
```

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: H = End(P)
sage: f = H([x^2, y^2, z^2])
sage: f.base_indeterminacy_locus()
Closed subscheme of Projective Space of dimension 2 over Rational Field
 defined by:
  x^2,
  y^2,
  z^2
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> H = End(P)
>>> f = H([x**Integer(2), y**Integer(2), z**Integer(2)])
>>> f.base_indeterminacy_locus()
Closed subscheme of Projective Space of dimension 2 over Rational Field
 defined by:
  x^2,
  y^2,
  z^2
```

```
sage: P1.<x,y,z> = ProjectiveSpace(RR, 2)
sage: P2.<t,u,v,w> = ProjectiveSpace(RR, 3)
```

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```
sage: H = Hom(P1, P2)
sage: h = H([y^3*z^3, x^3*z^3, y^3*z^3, x^2*y^2*z^2])
sage: h.base_indeterminacy_locus()                                          #␣
↪needs sage.rings.real_mpfr
Closed subscheme of Projective Space of dimension 2 over
 Real Field with 53 bits of precision defined by:
  y^3*z^3,
  x^3*z^3,
  y^3*z^3,
  x^2*y^2*z^2
```

```
>>> from sage.all import *
>>> P1 = ProjectiveSpace(RR, Integer(2), names=('x', 'y', 'z',)); (x, y, z,)␣
↪= P1._first_ngens(3)
>>> P2 = ProjectiveSpace(RR, Integer(3), names=('t', 'u', 'v', 'w',)); (t, u,␣
↪v, w,) = P2._first_ngens(4)
>>> H = Hom(P1, P2)
>>> h = H([y**Integer(3)*z**Integer(3), x**Integer(3)*z**Integer(3),␣
↪y**Integer(3)*z**Integer(3), x**Integer(2)*y**Integer(2)*z**Integer(2)])
>>> h.base_indeterminacy_locus()                                            #␣
↪needs sage.rings.real_mpfr
Closed subscheme of Projective Space of dimension 2 over
 Real Field with 53 bits of precision defined by:
  y^3*z^3,
  x^3*z^3,
  y^3*z^3,
  x^2*y^2*z^2
```

If defining polynomials are not normalized, output scheme will not be normalized:

```
sage: P.<x,y,z> = ProjectiveSpace(QQ,2)
sage: H = End(P)
sage: f = H([x*x^2,x*y^2,x*z^2])
sage: f.base_indeterminacy_locus()
Closed subscheme of Projective Space of dimension 2 over Rational Field
 defined by:
  x^3,
  x*y^2,
  x*z^2
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ,Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> H = End(P)
>>> f = H([x*x**Integer(2),x*y**Integer(2),x*z**Integer(2)])
>>> f.base_indeterminacy_locus()
Closed subscheme of Projective Space of dimension 2 over Rational Field
 defined by:
  x^3,
  x*y^2,
  x*z^2
```

image()

Return the scheme-theoretic image of the morphism.

OUTPUT: a subscheme of the ambient space of the codomain

EXAMPLES:

```
sage: P2.<x0,x1,x2> = ProjectiveSpace(QQ, 2)
sage: f = P2.hom([x0^3, x0^2*x1, x0*x1^2], P2)
sage: f.image()                                                             #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  x1^2 - x0*x2
sage: f = P2.hom([x0 - x1, x0 - x2, x1 - x2], P2)
sage: f.image()                                                             #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  x0 - x1 + x2
```

```
>>> from sage.all import *
>>> P2 = ProjectiveSpace(QQ, Integer(2), names=('x0', 'x1', 'x2',)); (x0, x1,␣
↪x2,) = P2._first_ngens(3)
>>> f = P2.hom([x0**Integer(3), x0**Integer(2)*x1, x0*x1**Integer(2)], P2)
>>> f.image()                                                               #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  x1^2 - x0*x2
>>> f = P2.hom([x0 - x1, x0 - x2, x1 - x2], P2)
>>> f.image()                                                               #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  x0 - x1 + x2
```

```
sage: P2.<x0,x1,x2> = ProjectiveSpace(QQ, 2)
sage: A2.<x,y> = AffineSpace(QQ, 2)
sage: f = P2.hom([1, x0/x1], A2)
sage: f.image()                                                             #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  -x + 1
```

```
>>> from sage.all import *
>>> P2 = ProjectiveSpace(QQ, Integer(2), names=('x0', 'x1', 'x2',)); (x0, x1,␣
↪x2,) = P2._first_ngens(3)
>>> A2 = AffineSpace(QQ, Integer(2), names=('x', 'y',)); (x, y,) = A2._first_
↪ngens(2)
>>> f = P2.hom([Integer(1), x0/x1], A2)
>>> f.image()                                                               #␣
↪needs sage.libs.singular
```

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```
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  -x + 1
```

indeterminacy_locus()

Return the indeterminacy locus of this map as a rational map on the domain.

The indeterminacy locus is the intersection of all the base indeterminacy locuses of maps that define the same rational map as by this map.

OUTPUT: a subscheme of the domain of the map

EXAMPLES:

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: H = End(P)
sage: f = H([x^2, y^2, z^2])
sage: f.indeterminacy_locus()                                                  #␣
↪needs sage.libs.singular
... DeprecationWarning: The meaning of indeterminacy_locus() has changed.
Read the docstring. See https://github.com/sagemath/sage/issues/29145 for␣
↪details.
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  z,
  y,
  x
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> H = End(P)
>>> f = H([x**Integer(2), y**Integer(2), z**Integer(2)])
>>> f.indeterminacy_locus()                                                    #␣
↪needs sage.libs.singular
... DeprecationWarning: The meaning of indeterminacy_locus() has changed.
Read the docstring. See https://github.com/sagemath/sage/issues/29145 for␣
↪details.
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  z,
  y,
  x
```

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: H = End(P)
sage: f = H([x*z - y*z, x^2 - y^2, z^2])
sage: f.indeterminacy_locus()                                                  #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  z,
  x^2 - y^2
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> H = End(P)
>>> f = H([x*z - y*z, x**Integer(2) - y**Integer(2), z**Integer(2)])
>>> f.indeterminacy_locus()                                                    #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  z,
  x^2 - y^2
```

There is related *base_indeterminacy_locus()* method. This computes the indeterminacy locus only from the defining polynomials of the map:

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: H = End(P)
sage: f = H([x*z - y*z, x^2 - y^2, z^2])
sage: f.base_indeterminacy_locus()
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  x*z - y*z,
  x^2 - y^2,
  z^2
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> H = End(P)
>>> f = H([x*z - y*z, x**Integer(2) - y**Integer(2), z**Integer(2)])
>>> f.base_indeterminacy_locus()
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  x*z - y*z,
  x^2 - y^2,
  z^2
```

indeterminacy_points(*F=None*, *base=False*)

Return the points in the indeterminacy locus of this map.

If the dimension of the indeterminacy locus is not zero, an error is raised.

INPUT:

- `F` – a field; if not given, the base ring of the domain is assumed
- `base` – if `True`, the base indeterminacy locus is used

OUTPUT: indeterminacy points of the map defined over `F`

EXAMPLES:

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: H = End(P)
sage: f = H([x*z - y*z, x^2 - y^2, z^2])
```

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```
sage: f.indeterminacy_points()                                                  #␣
↪needs sage.libs.singular
... DeprecationWarning: The meaning of indeterminacy_locus() has changed.
Read the docstring. See https://github.com/sagemath/sage/issues/29145 for␣
↪details.
[(-1 : 1 : 0), (1 : 1 : 0)]
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> H = End(P)
>>> f = H([x*z - y*z, x**Integer(2) - y**Integer(2), z**Integer(2)])
>>> f.indeterminacy_points()                                                    #␣
↪needs sage.libs.singular
... DeprecationWarning: The meaning of indeterminacy_locus() has changed.
Read the docstring. See https://github.com/sagemath/sage/issues/29145 for␣
↪details.
[(-1 : 1 : 0), (1 : 1 : 0)]
```

```
sage: P1.<x,y,z> = ProjectiveSpace(RR, 2)
sage: P2.<t,u,v,w> = ProjectiveSpace(RR, 3)
sage: H = Hom(P1, P2)
sage: h = H([x + y, y, z + y, y])
sage: set_verbose(None)
sage: h.indeterminacy_points(base=True)                                         #␣
↪needs sage.libs.singular
[]
sage: g = H([y^3*z^3, x^3*z^3, y^3*z^3, x^2*y^2*z^2])
sage: g.indeterminacy_points(base=True)                                         #␣
↪needs sage.libs.singular
Traceback (most recent call last):
...
ValueError: indeterminacy scheme is not dimension 0
```

```
>>> from sage.all import *
>>> P1 = ProjectiveSpace(RR, Integer(2), names=('x', 'y', 'z',)); (x, y, z,)␣
↪= P1._first_ngens(3)
>>> P2 = ProjectiveSpace(RR, Integer(3), names=('t', 'u', 'v', 'w',)); (t, u,␣
↪v, w,) = P2._first_ngens(4)
>>> H = Hom(P1, P2)
>>> h = H([x + y, y, z + y, y])
>>> set_verbose(None)
>>> h.indeterminacy_points(base=True)                                           #␣
↪needs sage.libs.singular
[]
>>> g = H([y**Integer(3)*z**Integer(3), x**Integer(3)*z**Integer(3),␣
↪y**Integer(3)*z**Integer(3), x**Integer(2)*y**Integer(2)*z**Integer(2)])
>>> g.indeterminacy_points(base=True)                                           #␣
↪needs sage.libs.singular
Traceback (most recent call last):
...
```

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```
ValueError: indeterminacy scheme is not dimension 0
```

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: H = End(P)
sage: f = H([x^2 + y^2, x*z, x^2 + y^2])
sage: f.indeterminacy_points()                                              #␣
↪needs sage.libs.singular
[(0 : 0 : 1)]

sage: R.<t> = QQ[]
sage: K.<a> = NumberField(t^2 + 1)                                          #␣
↪needs sage.rings.number_field
sage: f.indeterminacy_points(F=K)                                           #␣
↪needs sage.libs.singular sage.rings.number_field
[(-a : 1 : 0), (0 : 0 : 1), (a : 1 : 0)]
sage: set_verbose(None)
sage: f.indeterminacy_points(F=QQbar, base=True)                            #␣
↪needs sage.libs.singular sage.rings.number_field
[(-1*I : 1 : 0), (0 : 0 : 1), (1*I : 1 : 0)]
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> H = End(P)
>>> f = H([x**Integer(2) + y**Integer(2), x*z, x**Integer(2) + y**Integer(2)])
>>> f.indeterminacy_points()                                                #␣
↪needs sage.libs.singular
[(0 : 0 : 1)]

>>> R = QQ['t']; (t,) = R._first_ngens(1)
>>> K = NumberField(t**Integer(2) + Integer(1), names=('a',)); (a,) = K._
↪first_ngens(1)# needs sage.rings.number_field
>>> f.indeterminacy_points(F=K)                                             #␣
↪needs sage.libs.singular sage.rings.number_field
[(-a : 1 : 0), (0 : 0 : 1), (a : 1 : 0)]
>>> set_verbose(None)
>>> f.indeterminacy_points(F=QQbar, base=True)                              #␣
↪needs sage.libs.singular sage.rings.number_field
[(-1*I : 1 : 0), (0 : 0 : 1), (1*I : 1 : 0)]
```

```
sage: set_verbose(None)
sage: K.<t> = FunctionField(QQ)
sage: P.<x,y,z> = ProjectiveSpace(K, 2)
sage: H = End(P)
sage: f = H([x^2 - t^2*y^2, y^2 - z^2, x^2 - t^2*z^2])
sage: f.indeterminacy_points(base=True)                                     #␣
↪needs sage.libs.singular
[(-t : -1 : 1), (-t : 1 : 1), (t : -1 : 1), (t : 1 : 1)]
```

```
>>> from sage.all import *
>>> set_verbose(None)
```

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```
>>> K = FunctionField(QQ, names=('t',)); (t,) = K._first_ngens(1)
>>> P = ProjectiveSpace(K, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> H = End(P)
>>> f = H([x**Integer(2) - t**Integer(2)*y**Integer(2), y**Integer(2) -␣
↪z**Integer(2), x**Integer(2) - t**Integer(2)*z**Integer(2)])
>>> f.indeterminacy_points(base=True)                                    #␣
↪needs sage.libs.singular
[(-t : -1 : 1), (-t : 1 : 1), (t : -1 : 1), (t : 1 : 1)]
```

```
sage: # needs sage.rings.padics
sage: set_verbose(None)
sage: P.<x,y,z> = ProjectiveSpace(Qp(3), 2)
sage: H = End(P)
sage: f = H([x^2 - 7*y^2, y^2 - z^2, x^2 - 7*z^2])
sage: f.indeterminacy_points(base=True)                                   #␣
↪needs sage.libs.singular
[(2 + 3 + 3^2 + 2*3^3 + 2*3^5 + 2*3^6 + 3^8
    + 3^9 + 2*3^11 + 3^15 + 2*3^16 + 3^18 + O(3^20) : 1 + O(3^20) : 1 + O(3^
↪20)),
 (2 + 3 + 3^2 + 2*3^3 + 2*3^5 + 2*3^6 + 3^8 + 3^9 + 2*3^11 + 3^15
    + 2*3^16 + 3^18 + O(3^20) : 2 + 2*3 + 2*3^2 + 2*3^3 + 2*3^4 + 2*3^5
    + 2*3^6 + 2*3^7 + 2*3^8 + 2*3^9 + 2*3^10 + 2*3^11 + 2*3^12 + 2*3^13
    + 2*3^14 + 2*3^15 + 2*3^16 + 2*3^17 + 2*3^18 + 2*3^19 + O(3^20) : 1 + O(3^
↪20)),
 (1 + 3 + 3^2 + 2*3^4 + 2*3^7 + 3^8 + 3^9 + 2*3^10 + 2*3^12 + 2*3^13
    + 2*3^14 + 3^15 + 2*3^17 + 3^18 + 2*3^19 + O(3^20) : 1 + O(3^20) : 1 +␣
↪O(3^20)),
 (1 + 3 + 3^2 + 2*3^4 + 2*3^7 + 3^8 + 3^9 + 2*3^10 + 2*3^12 + 2*3^13
    + 2*3^14 + 3^15 + 2*3^17 + 3^18 + 2*3^19 + O(3^20) : 2 + 2*3 + 2*3^2
    + 2*3^3 + 2*3^4 + 2*3^5 + 2*3^6 + 2*3^7 + 2*3^8 + 2*3^9 + 2*3^10 + 2*3^11
    + 2*3^12 + 2*3^13 + 2*3^14 + 2*3^15 + 2*3^16 + 2*3^17 + 2*3^18 + 2*3^19
    + O(3^20) : 1 + O(3^20))]
```

```
>>> from sage.all import *
>>> # needs sage.rings.padics
>>> set_verbose(None)
>>> P = ProjectiveSpace(Qp(Integer(3)), Integer(2), names=('x', 'y', 'z',));␣
↪(x, y, z,) = P._first_ngens(3)
>>> H = End(P)
>>> f = H([x**Integer(2) - Integer(7)*y**Integer(2), y**Integer(2) -␣
↪z**Integer(2), x**Integer(2) - Integer(7)*z**Integer(2)])
>>> f.indeterminacy_points(base=True)                                    #␣
↪needs sage.libs.singular
[(2 + 3 + 3^2 + 2*3^3 + 2*3^5 + 2*3^6 + 3^8
    + 3^9 + 2*3^11 + 3^15 + 2*3^16 + 3^18 + O(3^20) : 1 + O(3^20) : 1 + O(3^
↪20)),
 (2 + 3 + 3^2 + 2*3^3 + 2*3^5 + 2*3^6 + 3^8 + 3^9 + 2*3^11 + 3^15
    + 2*3^16 + 3^18 + O(3^20) : 2 + 2*3 + 2*3^2 + 2*3^3 + 2*3^4 + 2*3^5
    + 2*3^6 + 2*3^7 + 2*3^8 + 2*3^9 + 2*3^10 + 2*3^11 + 2*3^12 + 2*3^13
    + 2*3^14 + 2*3^15 + 2*3^16 + 2*3^17 + 2*3^18 + 2*3^19 + O(3^20) : 1 + O(3^
```

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```
↪20)),
 (1 + 3 + 3^2 + 2*3^4 + 2*3^7 + 3^8 + 3^9 + 2*3^10 + 2*3^12 + 2*3^13
    + 2*3^14 + 3^15 + 2*3^17 + 3^18 + 2*3^19 + O(3^20) : 1 + O(3^20) : 1 +␣
↪O(3^20)),
 (1 + 3 + 3^2 + 2*3^4 + 2*3^7 + 3^8 + 3^9 + 2*3^10 + 2*3^12 + 2*3^13
    + 2*3^14 + 3^15 + 2*3^17 + 3^18 + 2*3^19 + O(3^20) : 2 + 2*3 + 2*3^2
    + 2*3^3 + 2*3^4 + 2*3^5 + 2*3^6 + 2*3^7 + 2*3^8 + 2*3^9 + 2*3^10 + 2*3^11
    + 2*3^12 + 2*3^13 + 2*3^14 + 2*3^15 + 2*3^16 + 2*3^17 + 2*3^18 + 2*3^19
    + O(3^20) : 1 + O(3^20))]
```

rational_preimages(*Q*, *k=1*)

Determine all of the rational k-th preimages of `Q` by this map.

Given a rational point `Q` in the domain of this map, return all the rational points `P` in the domain with $f^k(P) == Q$. In other words, the set of k-th preimages of `Q`. The map must be defined over a number field and be an endomorphism for $k > 1$.

If `Q` is a subscheme, then return the subscheme that maps to `Q` by this map. In particular, $f^{-k}(V(h_1, \ldots, h_t)) = V(h_1 \circ f^k, \ldots, h_t \circ f^k)$.

INPUT:

- `Q` – a rational point or subscheme in the domain of this map
- `k` – positive integer

OUTPUT: a list of rational points or a subscheme in the domain of this map

EXAMPLES:

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: H = End(P)
sage: f = H([16*x^2 - 29*y^2, 16*y^2])
sage: f.rational_preimages(P(-1, 4))                                          #␣
↪needs sage.libs.singular
[(-5/4 : 1), (5/4 : 1)]
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> H = End(P)
>>> f = H([Integer(16)*x**Integer(2) - Integer(29)*y**Integer(2),␣
↪Integer(16)*y**Integer(2)])
>>> f.rational_preimages(P(-Integer(1), Integer(4)))                          ␣
↪              # needs sage.libs.singular
[(-5/4 : 1), (5/4 : 1)]
```

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: H = End(P)
sage: f = H([76*x^2 - 180*x*y + 45*y^2 + 14*x*z + 45*y*z - 90*z^2,
....:        67*x^2 - 180*x*y - 157*x*z + 90*y*z,
....:        -90*z^2])
sage: f.rational_preimages(P(-9, -4, 1))                                      #␣
↪needs sage.libs.singular
[(0 : 4 : 1)]
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> H = End(P)
>>> f = H([Integer(76)*x**Integer(2) - Integer(180)*x*y +␣
↪Integer(45)*y**Integer(2) + Integer(14)*x*z + Integer(45)*y*z -␣
↪Integer(90)*z**Integer(2),
...         Integer(67)*x**Integer(2) - Integer(180)*x*y - Integer(157)*x*z +␣
↪Integer(90)*y*z,
...         -Integer(90)*z**Integer(2)])
>>> f.rational_preimages(P(-Integer(9), -Integer(4), Integer(1)))           ␣
↪                       # needs sage.libs.singular
[(0 : 4 : 1)]
```

A non-periodic example

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: H = End(P)
sage: f = H([x^2 + y^2, 2*x*y])
sage: f.rational_preimages(P(17, 15))                                    #␣
↪needs sage.libs.singular
[(3/5 : 1), (5/3 : 1)]
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> H = End(P)
>>> f = H([x**Integer(2) + y**Integer(2), Integer(2)*x*y])
>>> f.rational_preimages(P(Integer(17), Integer(15)))                       ␣
↪              # needs sage.libs.singular
[(3/5 : 1), (5/3 : 1)]
```

```
sage: P.<x,y,z,w> = ProjectiveSpace(QQ, 3)
sage: H = End(P)
sage: f = H([x^2 - 2*y*w - 3*w^2, -2*x^2 + y^2 - 2*x*z + 4*y*w + 3*w^2,
....:        x^2 - y^2 + 2*x*z + z^2 - 2*y*w - w^2,
....:        w^2])
sage: f.rational_preimages(P(0, -1, 0, 1))                               #␣
↪needs sage.libs.singular
[]
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(3), names=('x', 'y', 'z', 'w',)); (x, y,␣
↪z, w,) = P._first_ngens(4)
>>> H = End(P)
>>> f = H([x**Integer(2) - Integer(2)*y*w - Integer(3)*w**Integer(2), -
↪Integer(2)*x**Integer(2) + y**Integer(2) - Integer(2)*x*z + Integer(4)*y*w␣
↪+ Integer(3)*w**Integer(2),
...         x**Integer(2) - y**Integer(2) + Integer(2)*x*z + z**Integer(2) -␣
↪Integer(2)*y*w - w**Integer(2),
...         w**Integer(2)])
>>> f.rational_preimages(P(Integer(0), -Integer(1), Integer(0), Integer(1))) ␣
```

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```
↪                                    # needs sage.libs.singular
[]
```

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: H = End(P)
sage: f = H([x^2 + y^2, 2*x*y])
sage: f.rational_preimages([CC.0, 1])                                          #␣
↪needs sage.libs.singular
Traceback (most recent call last):
...
TypeError: point must be in codomain of self
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> H = End(P)
>>> f = H([x**Integer(2) + y**Integer(2), Integer(2)*x*y])
>>> f.rational_preimages([CC.gen(0), Integer(1)])                              ␣
↪          # needs sage.libs.singular
Traceback (most recent call last):
...
TypeError: point must be in codomain of self
```

A number field example

```
sage: # needs sage.rings.number_field
sage: z = QQ['z'].0
sage: K.<a> = NumberField(z^2 - 2)
sage: P.<x,y> = ProjectiveSpace(K, 1)
sage: H = End(P)
sage: f = H([x^2 + y^2, y^2])
sage: f.rational_preimages(P(3, 1))                                            #␣
↪needs sage.libs.singular
[(-a : 1), (a : 1)]
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> z = QQ['z'].gen(0)
>>> K = NumberField(z**Integer(2) - Integer(2), names=('a',)); (a,) = K._
↪first_ngens(1)
>>> P = ProjectiveSpace(K, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> H = End(P)
>>> f = H([x**Integer(2) + y**Integer(2), y**Integer(2)])
>>> f.rational_preimages(P(Integer(3), Integer(1)))                            ␣
↪              # needs sage.libs.singular
[(-a : 1), (a : 1)]
```

```
sage: # needs sage.rings.number_field
sage: z = QQ['z'].0
sage: K.<a> = NumberField(z^2 - 2)
```

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```
sage: P.<x,y,z> = ProjectiveSpace(K, 2)
sage: X = P.subscheme([x^2 - z^2])
sage: H = End(X)
sage: f= H([x^2 - z^2, a*y^2, z^2 - x^2])
sage: f.rational_preimages(X([1, 2, -1]))                                    #␣
↪needs sage.libs.singular
[]
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> z = QQ['z'].gen(0)
>>> K = NumberField(z**Integer(2) - Integer(2), names=('a',)); (a,) = K._
↪first_ngens(1)
>>> P = ProjectiveSpace(K, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> X = P.subscheme([x**Integer(2) - z**Integer(2)])
>>> H = End(X)
>>> f= H([x**Integer(2) - z**Integer(2), a*y**Integer(2), z**Integer(2) -␣
↪x**Integer(2)])
>>> f.rational_preimages(X([Integer(1), Integer(2), -Integer(1)]))           ␣
↪                       # needs sage.libs.singular
[]
```

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: X = P.subscheme([x^2 - z^2])
sage: H = End(X)
sage: f = H([x^2-z^2, y^2, z^2-x^2])
sage: f.rational_preimages(X([0, 1, 0]))                                     #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  x^2 - z^2,
  -x^2 + z^2,
  0,
  -x^2 + z^2
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> X = P.subscheme([x**Integer(2) - z**Integer(2)])
>>> H = End(X)
>>> f = H([x**Integer(2)-z**Integer(2), y**Integer(2), z**Integer(2)-
↪x**Integer(2)])
>>> f.rational_preimages(X([Integer(0), Integer(1), Integer(0)]))           ␣
↪                       # needs sage.libs.singular
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  x^2 - z^2,
  -x^2 + z^2,
  0,
  -x^2 + z^2
```

```
sage: P.<x, y> = ProjectiveSpace(QQ, 1)
sage: H = End(P)
sage: f = H([x^2 - y^2, y^2])
sage: f.rational_preimages(P.subscheme([x]))                                    #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 1 over Rational Field
 defined by: x^2 - y^2
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> H = End(P)
>>> f = H([x**Integer(2) - y**Integer(2), y**Integer(2)])
>>> f.rational_preimages(P.subscheme([x]))                                      #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 1 over Rational Field
 defined by: x^2 - y^2
```

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: H = End(P)
sage: f = H([x^2 - 29/16*y^2, y^2])
sage: f.rational_preimages(P(5/4, 1), k=4)                                      #␣
↪needs sage.libs.singular
[(-3/4 : 1), (3/4 : 1), (-7/4 : 1), (7/4 : 1)]
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> H = End(P)
>>> f = H([x**Integer(2) - Integer(29)/Integer(16)*y**Integer(2),␣
↪y**Integer(2)])
>>> f.rational_preimages(P(Integer(5)/Integer(4), Integer(1)), k=Integer(4)) ␣
↪                                  # needs sage.libs.singular
[(-3/4 : 1), (3/4 : 1), (-7/4 : 1), (7/4 : 1)]
```

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: P2.<u,v,w> = ProjectiveSpace(QQ, 2)
sage: H = Hom(P, P2)
sage: f = H([x^2, y^2, x^2-y^2])
sage: f.rational_preimages(P2(1, 1, 0))                                         #␣
↪needs sage.libs.singular
[(-1 : 1), (1 : 1)]
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> P2 = ProjectiveSpace(QQ, Integer(2), names=('u', 'v', 'w',)); (u, v, w,)␣
↪= P2._first_ngens(3)
>>> H = Hom(P, P2)
>>> f = H([x**Integer(2), y**Integer(2), x**Integer(2)-y**Integer(2)])
>>> f.rational_preimages(P2(Integer(1), Integer(1), Integer(0)))               ␣
```

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```
↪                          # needs sage.libs.singular
[(-1 : 1), (1 : 1)]
```

reduce_base_field()

Return this map defined over the field of definition of the coefficients.

The base field of the map could be strictly larger than the field where all of the coefficients are defined. This function reduces the base field to the minimal possible. This can be done when the base ring is a number field, QQbar, a finite field, or algebraic closure of a finite field.

OUTPUT: a scheme morphism

EXAMPLES:

```
sage: # needs sage.rings.finite_rings
sage: K.<t> = GF(3^4)
sage: P.<x,y> = ProjectiveSpace(K, 1)
sage: P2.<a,b,c> = ProjectiveSpace(K, 2)
sage: H = End(P)
sage: H2 = Hom(P, P2)
sage: H3 = Hom(P2, P)
sage: f = H([x^2 + (2*t^3 + 2*t^2 + 1)*y^2, y^2])
sage: f.reduce_base_field()                                                 #␣
↪needs sage.libs.singular sage.modules
Scheme endomorphism of Projective Space of dimension 1
 over Finite Field in t2 of size 3^2
  Defn: Defined on coordinates by sending (x : y) to (x^2 + t2*y^2 : y^2)
sage: f2 = H2([x^2 + 5*y^2, y^2, 2*x*y])
sage: f2.reduce_base_field()                                                #␣
↪needs sage.libs.singular sage.modules
Scheme morphism:
  From: Projective Space of dimension 1 over Finite Field of size 3
  To:   Projective Space of dimension 2 over Finite Field of size 3
  Defn: Defined on coordinates by sending (x : y) to (x^2 - y^2 : y^2 : -x*y)
sage: f3 = H3([a^2 + t*b^2, c^2])
sage: f3.reduce_base_field()                                                #␣
↪needs sage.libs.singular sage.modules
Scheme morphism:
  From: Projective Space of dimension 2 over Finite Field in t of size 3^4
  To:   Projective Space of dimension 1 over Finite Field in t of size 3^4
  Defn: Defined on coordinates by sending (a : b : c) to (a^2 + t*b^2 : c^2)
```

```
>>> from sage.all import *
>>> # needs sage.rings.finite_rings
>>> K = GF(Integer(3)**Integer(4), names=('t',)); (t,) = K._first_ngens(1)
>>> P = ProjectiveSpace(K, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> P2 = ProjectiveSpace(K, Integer(2), names=('a', 'b', 'c',)); (a, b, c,) =␣
↪P2._first_ngens(3)
>>> H = End(P)
>>> H2 = Hom(P, P2)
>>> H3 = Hom(P2, P)
>>> f = H([x**Integer(2) + (Integer(2)*t**Integer(3) +␣
```

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```
↪Integer(2)*t**Integer(2) + Integer(1))*y**Integer(2), y**Integer(2)])
>>> f.reduce_base_field()                                                #␣
↪needs sage.libs.singular sage.modules
Scheme endomorphism of Projective Space of dimension 1
 over Finite Field in t2 of size 3^2
  Defn: Defined on coordinates by sending (x : y) to (x^2 + t2*y^2 : y^2)
>>> f2 = H2([x**Integer(2) + Integer(5)*y**Integer(2), y**Integer(2),␣
↪Integer(2)*x*y])
>>> f2.reduce_base_field()                                               #␣
↪needs sage.libs.singular sage.modules
Scheme morphism:
  From: Projective Space of dimension 1 over Finite Field of size 3
  To:   Projective Space of dimension 2 over Finite Field of size 3
  Defn: Defined on coordinates by sending (x : y) to (x^2 - y^2 : y^2 : -x*y)
>>> f3 = H3([a**Integer(2) + t*b**Integer(2), c**Integer(2)])
>>> f3.reduce_base_field()                                               #␣
↪needs sage.libs.singular sage.modules
Scheme morphism:
  From: Projective Space of dimension 2 over Finite Field in t of size 3^4
  To:   Projective Space of dimension 1 over Finite Field in t of size 3^4
  Defn: Defined on coordinates by sending (a : b : c) to (a^2 + t*b^2 : c^2)
```

```
sage: # needs sage.rings.number_field
sage: K.<v> = CyclotomicField(4)
sage: P.<x,y> = ProjectiveSpace(K, 1)
sage: H = End(P)
sage: f = H([x^2 + 2*y^2, y^2])
sage: f.reduce_base_field()                                             #␣
↪needs sage.libs.singular
Scheme endomorphism of Projective Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x : y) to (x^2 + 2*y^2 : y^2)
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> K = CyclotomicField(Integer(4), names=('v',)); (v,) = K._first_ngens(1)
>>> P = ProjectiveSpace(K, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> H = End(P)
>>> f = H([x**Integer(2) + Integer(2)*y**Integer(2), y**Integer(2)])
>>> f.reduce_base_field()                                                #␣
↪needs sage.libs.singular
Scheme endomorphism of Projective Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x : y) to (x^2 + 2*y^2 : y^2)
```

```
sage: # needs sage.rings.finite_rings
sage: K.<v> = GF(5)
sage: L = K.algebraic_closure()
sage: P.<x,y> = ProjectiveSpace(L, 1)
sage: H = End(P)
sage: f = H([(L.gen(2))*x^2 + L.gen(4)*y^2, x*y])
sage: f.reduce_base_field()                                             #␣
```

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```
↪needs sage.libs.singular
Scheme endomorphism of Projective Space of dimension 1
 over Finite Field in z4 of size 5^4
  Defn: Defined on coordinates by sending (x : y) to
        ((z4^3 + z4^2 + z4 - 2)*x^2 + z4*y^2 : x*y)
sage: f = DynamicalSystem_projective([L.gen(3)*x^2 + L.gen(2)*y^2, x*y])     #␣
↪needs sage.schemes
sage: f.reduce_base_field()                                                  #␣
↪needs sage.libs.singular sage.schemes
Dynamical System of Projective Space of dimension 1
 over Finite Field in z6 of size 5^6
  Defn: Defined on coordinates by sending (x : y) to
        ((-z6^5 + z6^4 - z6^3 - z6^2 - 2*z6 - 2)*x^2
         + (z6^5 - 2*z6^4 + z6^2 - z6 + 1)*y^2 : x*y)
```

```
>>> from sage.all import *
>>> # needs sage.rings.finite_rings
>>> K = GF(Integer(5), names=('v',)); (v,) = K._first_ngens(1)
>>> L = K.algebraic_closure()
>>> P = ProjectiveSpace(L, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> H = End(P)
>>> f = H([(L.gen(Integer(2)))*x**Integer(2) + L.
↪gen(Integer(4))*y**Integer(2), x*y])
>>> f.reduce_base_field()                                                    #␣
↪needs sage.libs.singular
Scheme endomorphism of Projective Space of dimension 1
 over Finite Field in z4 of size 5^4
  Defn: Defined on coordinates by sending (x : y) to
        ((z4^3 + z4^2 + z4 - 2)*x^2 + z4*y^2 : x*y)
>>> f = DynamicalSystem_projective([L.gen(Integer(3))*x**Integer(2) + L.
↪gen(Integer(2))*y**Integer(2), x*y])     # needs sage.schemes
>>> f.reduce_base_field()                                                    #␣
↪needs sage.libs.singular sage.schemes
Dynamical System of Projective Space of dimension 1
 over Finite Field in z6 of size 5^6
  Defn: Defined on coordinates by sending (x : y) to
        ((-z6^5 + z6^4 - z6^3 - z6^2 - 2*z6 - 2)*x^2
         + (z6^5 - 2*z6^4 + z6^2 - z6 + 1)*y^2 : x*y)
```

class sage.schemes.projective.projective_morphism.**SchemeMorphism_polynomial_projective_space_finite_f**

Bases: *SchemeMorphism_polynomial_projective_space_field*

class sage.schemes.projective.projective_morphism.**SchemeMorphism_polynomial_projective_subscheme_fiel**

Bases: *SchemeMorphism_polynomial_projective_space_field*

Morphisms from subschemes of projective spaces defined over fields.

degree()

Return the degree of this rational map.

EXAMPLES:

```
sage: # needs sage.schemes
sage: k = GF(11)
sage: E = EllipticCurve(k, [1,1])
sage: Q = E(6, 5)
sage: phi = E.scalar_multiplication(2)
sage: mor = phi.as_morphism()
sage: mor.degree()
4
```

```
>>> from sage.all import *
>>> # needs sage.schemes
>>> k = GF(Integer(11))
>>> E = EllipticCurve(k, [Integer(1),Integer(1)])
>>> Q = E(Integer(6), Integer(5))
>>> phi = E.scalar_multiplication(Integer(2))
>>> mor = phi.as_morphism()
>>> mor.degree()
4
```

graph()

Return the graph of this morphism.

The graph is a subscheme of the product of the ambient spaces of the domain and the codomain. If the ambient space of the codomain is an affine space, it is first embedded into a projective space.

EXAMPLES:

We get the standard quadratic curve as the graph of a quadratic function of an affine line.

```
sage: A1.<x> = AffineSpace(1, QQ)
sage: X = A1.subscheme(0)  # affine line
sage: phi = X.hom([x^2], A1)
sage: mor = phi.homogenize(0)                                                  #␣
↪needs sage.libs.singular
sage: G = mor.graph(); G                                                       #␣
↪needs sage.libs.singular
Closed subscheme of Product of projective spaces P^1 x P^1
  over Rational Field defined by: x1^2*x2 - x0^2*x3
sage: G.affine_patch([0, 0])                                                   #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 2
  over Rational Field defined by: x0^2 - x1
```

```
>>> from sage.all import *
>>> A1 = AffineSpace(Integer(1), QQ, names=('x',)); (x,) = A1._first_ngens(1)
>>> X = A1.subscheme(Integer(0))  # affine line
>>> phi = X.hom([x**Integer(2)], A1)
>>> mor = phi.homogenize(Integer(0))                                           ␣
↪     # needs sage.libs.singular
>>> G = mor.graph(); G                                                        #␣
```

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```
↪needs sage.libs.singular
Closed subscheme of Product of projective spaces P^1 x P^1
  over Rational Field defined by: x1^2*x2 - x0^2*x3
>>> G.affine_patch([Integer(0), Integer(0)])                                ␣
↪              # needs sage.libs.singular
Closed subscheme of Affine Space of dimension 2
  over Rational Field defined by: x0^2 - x1
```

image()

Return the scheme-theoretic image of the morphism.

EXAMPLES:

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: P2.<x0,x1,x2> = ProjectiveSpace(QQ, 2)
sage: X = P2.subscheme(0)
sage: f = X.hom([x1,x0], P)
sage: f.image()                                                             #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 1 over Rational Field␣
↪defined by:
  (no polynomials)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> P2 = ProjectiveSpace(QQ, Integer(2), names=('x0', 'x1', 'x2',)); (x0, x1,␣
↪x2,) = P2._first_ngens(3)
>>> X = P2.subscheme(Integer(0))
>>> f = X.hom([x1,x0], P)
>>> f.image()                                                               #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 1 over Rational Field␣
↪defined by:
  (no polynomials)
```

```
sage: P2.<x,y,z> = ProjectiveSpace(QQ,2)
sage: X = P2.subscheme([z^3 - x*y^2 + y^3])
sage: f = X.hom([x*z, x*y, x^2 + y*z], P2)
sage: f.image()                                                             #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  x^6 + 2*x^3*y^3 + x*y^5 + y^6 - x^3*y^2*z - y^5*z
```

```
>>> from sage.all import *
>>> P2 = ProjectiveSpace(QQ,Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P2._first_ngens(3)
>>> X = P2.subscheme([z**Integer(3) - x*y**Integer(2) + y**Integer(3)])
>>> f = X.hom([x*z, x*y, x**Integer(2) + y*z], P2)
>>> f.image()                                                               #␣
↪needs sage.libs.singular
```

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```
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  x^6 + 2*x^3*y^3 + x*y^5 + y^6 - x^3*y^2*z - y^5*z
```

indeterminacy_locus()

Return the indeterminacy locus of this map.

The map defines a rational map on the domain. The output is the subscheme of the domain on which the rational map is not defined by any representative of the rational map. See *representatives()*.

EXAMPLES:

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: P2.<x0,x1,x2> = ProjectiveSpace(QQ, 2)
sage: X = P2.subscheme(0)
sage: f = X.hom([x1,x0], P)
sage: L = f.indeterminacy_locus()                                              #␣
↪needs sage.libs.singular
sage: L.rational_points()                                                      #␣
↪needs sage.libs.singular
[(0 : 0 : 1)]
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> P2 = ProjectiveSpace(QQ, Integer(2), names=('x0', 'x1', 'x2',)); (x0, x1,␣
↪x2,) = P2._first_ngens(3)
>>> X = P2.subscheme(Integer(0))
>>> f = X.hom([x1,x0], P)
>>> L = f.indeterminacy_locus()                                                #␣
↪needs sage.libs.singular
>>> L.rational_points()                                                        #␣
↪needs sage.libs.singular
[(0 : 0 : 1)]
```

```
sage: P2.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: P1.<a,b> = ProjectiveSpace(QQ, 1)
sage: X = P2.subscheme([x^2 - y^2 - y*z])
sage: f = X.hom([x,y], P1)
sage: f.indeterminacy_locus()                                                  #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  z,
  y,
  x
```

```
>>> from sage.all import *
>>> P2 = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,)␣
↪= P2._first_ngens(3)
>>> P1 = ProjectiveSpace(QQ, Integer(1), names=('a', 'b',)); (a, b,) = P1._
↪first_ngens(2)
```

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```
>>> X = P2.subscheme([x**Integer(2) - y**Integer(2) - y*z])
>>> f = X.hom([x,y], P1)
>>> f.indeterminacy_locus()                                                    #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  z,
  y,
  x
```

```
sage: P3.<x,y,z,w> = ProjectiveSpace(QQ, 3)
sage: P2.<a,b,c> = ProjectiveSpace(QQ, 2)
sage: X = P3.subscheme(x^2 - w*y - x*z)
sage: f = X.hom([x*y, y*z, z*x], P2)
sage: L = f.indeterminacy_locus()                                           #␣
↪needs sage.libs.singular
sage: L.dimension()                                                         #␣
↪needs sage.libs.singular
0
sage: L.degree()                                                            #␣
↪needs sage.libs.singular
2
sage: L.rational_points()                                                   #␣
↪needs sage.libs.singular
[(0 : 0 : 0 : 1), (0 : 1 : 0 : 0)]
```

```
>>> from sage.all import *
>>> P3 = ProjectiveSpace(QQ, Integer(3), names=('x', 'y', 'z', 'w',)); (x, y,␣
↪z, w,) = P3._first_ngens(4)
>>> P2 = ProjectiveSpace(QQ, Integer(2), names=('a', 'b', 'c',)); (a, b, c,)␣
↪= P2._first_ngens(3)
>>> X = P3.subscheme(x**Integer(2) - w*y - x*z)
>>> f = X.hom([x*y, y*z, z*x], P2)
>>> L = f.indeterminacy_locus()                                             #␣
↪needs sage.libs.singular
>>> L.dimension()                                                           #␣
↪needs sage.libs.singular
0
>>> L.degree()                                                              #␣
↪needs sage.libs.singular
2
>>> L.rational_points()                                                     #␣
↪needs sage.libs.singular
[(0 : 0 : 0 : 1), (0 : 1 : 0 : 0)]
```

```
sage: P3.<x,y,z,w> = ProjectiveSpace(QQ, 3)
sage: A2.<a,b> = AffineSpace(QQ, 2)
sage: X = P3.subscheme(x^2 - w*y - x*z)
sage: f = X.hom([x/z, y/x], A2)
sage: L = f.indeterminacy_locus()                                           #␣
↪needs sage.libs.singular
```

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```
sage: L.rational_points()                                                   #␣
↪needs sage.libs.singular
[(0 : 0 : 0 : 1), (0 : 1 : 0 : 0)]
```

```
>>> from sage.all import *
>>> P3 = ProjectiveSpace(QQ, Integer(3), names=('x', 'y', 'z', 'w',)); (x, y,␣
↪z, w,) = P3._first_ngens(4)
>>> A2 = AffineSpace(QQ, Integer(2), names=('a', 'b',)); (a, b,) = A2._first_
↪ngens(2)
>>> X = P3.subscheme(x**Integer(2) - w*y - x*z)
>>> f = X.hom([x/z, y/x], A2)
>>> L = f.indeterminacy_locus()                                             #␣
↪needs sage.libs.singular
>>> L.rational_points()                                                     #␣
↪needs sage.libs.singular
[(0 : 0 : 0 : 1), (0 : 1 : 0 : 0)]
```

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: X = P.subscheme(x - y)
sage: H = End(X)
sage: f = H([x^2 - 4*y^2, y^2 - z^2, 4*z^2 - x^2])
sage: Z = f.indeterminacy_locus(); Z                                        #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  z,
  y,
  x
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> X = P.subscheme(x - y)
>>> H = End(X)
>>> f = H([x**Integer(2) - Integer(4)*y**Integer(2), y**Integer(2) -␣
↪z**Integer(2), Integer(4)*z**Integer(2) - x**Integer(2)])
>>> Z = f.indeterminacy_locus(); Z                                          #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  z,
  y,
  x
```

is_morphism()

Return `True` if the map is defined everywhere on the domain.

EXAMPLES:

```
sage: P2.<x,y,z> = ProjectiveSpace(QQ,2)
sage: P1.<a,b> = ProjectiveSpace(QQ, 1)
sage: X = P2.subscheme([x^2 - y^2 - y*z])
```

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```
sage: f = X.hom([x,y], P1)
sage: f.is_morphism()                                                       #␣
↪needs sage.libs.singular
True
```

```
>>> from sage.all import *
>>> P2 = ProjectiveSpace(QQ,Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P2._first_ngens(3)
>>> P1 = ProjectiveSpace(QQ, Integer(1), names=('a', 'b',)); (a, b,) = P1._
↪first_ngens(2)
>>> X = P2.subscheme([x**Integer(2) - y**Integer(2) - y*z])
>>> f = X.hom([x,y], P1)
>>> f.is_morphism()                                                         #␣
↪needs sage.libs.singular
True
```

projective_degrees()

Return the projective degrees of this rational map.

EXAMPLES:

```
sage: # needs sage.schemes
sage: k = GF(11)
sage: E = EllipticCurve(k, [1,1])
sage: Q = E(6, 5)
sage: phi = E.scalar_multiplication(2)
sage: mor = phi.as_morphism()
sage: mor.projective_degrees()
(12, 3)
```

```
>>> from sage.all import *
>>> # needs sage.schemes
>>> k = GF(Integer(11))
>>> E = EllipticCurve(k, [Integer(1),Integer(1)])
>>> Q = E(Integer(6), Integer(5))
>>> phi = E.scalar_multiplication(Integer(2))
>>> mor = phi.as_morphism()
>>> mor.projective_degrees()
(12, 3)
```

representatives()

Return all maps representing the same rational map as by this map.

EXAMPLES:

```
sage: P2.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: X = P2.subscheme(0)
sage: f = X.hom([x^2*y, x^2*z, x*y*z], P2)
sage: f.representatives()                                                   #␣
↪needs sage.libs.singular
[Scheme morphism:
   From: Closed subscheme of Projective Space of dimension 2
```

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```
        over Rational Field defined by: 0
   To:   Projective Space of dimension 2 over Rational Field
   Defn: Defined on coordinates by sending (x : y : z) to (x*y : x*z : y*z)]
```

```
>>> from sage.all import *
>>> P2 = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,)␣
↪= P2._first_ngens(3)
>>> X = P2.subscheme(Integer(0))
>>> f = X.hom([x**Integer(2)*y, x**Integer(2)*z, x*y*z], P2)
>>> f.representatives()                                                    #␣
↪needs sage.libs.singular
[Scheme morphism:
   From: Closed subscheme of Projective Space of dimension 2
         over Rational Field defined by: 0
   To:   Projective Space of dimension 2 over Rational Field
   Defn: Defined on coordinates by sending (x : y : z) to (x*y : x*z : y*z)]
```

```
sage: P2.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: P1.<a,b> = ProjectiveSpace(QQ, 1)
sage: X = P2.subscheme([x^2 - y^2 - y*z])
sage: f = X.hom([x, y], P1)
sage: f.representatives()                                                  #␣
↪needs sage.libs.singular
[Scheme morphism:
   From: Closed subscheme of Projective Space of dimension 2
         over Rational Field defined by: x^2 - y^2 - y*z
   To:   Projective Space of dimension 1 over Rational Field
   Defn: Defined on coordinates by sending (x : y : z) to (y + z : x),
 Scheme morphism:
   From: Closed subscheme of Projective Space of dimension 2
         over Rational Field defined by: x^2 - y^2 - y*z
   To:   Projective Space of dimension 1 over Rational Field
   Defn: Defined on coordinates by sending (x : y : z) to (x : y)]
sage: g = _[0]                                                             #␣
↪needs sage.libs.singular
sage: g.representatives()                                                  #␣
↪needs sage.libs.singular
[Scheme morphism:
   From: Closed subscheme of Projective Space of dimension 2
         over Rational Field defined by: x^2 - y^2 - y*z
   To:   Projective Space of dimension 1 over Rational Field
   Defn: Defined on coordinates by sending (x : y : z) to (y + z : x),
 Scheme morphism:
   From: Closed subscheme of Projective Space of dimension 2
         over Rational Field defined by: x^2 - y^2 - y*z
   To:   Projective Space of dimension 1 over Rational Field
   Defn: Defined on coordinates by sending (x : y : z) to (x : y)]
```

```
>>> from sage.all import *
>>> P2 = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,)␣
↪= P2._first_ngens(3)
```

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```
>>> P1 = ProjectiveSpace(QQ, Integer(1), names=('a', 'b',)); (a, b,) = P1._
↪first_ngens(2)
>>> X = P2.subscheme([x**Integer(2) - y**Integer(2) - y*z])
>>> f = X.hom([x, y], P1)
>>> f.representatives()                                                    #␣
↪needs sage.libs.singular
[Scheme morphism:
   From: Closed subscheme of Projective Space of dimension 2
         over Rational Field defined by: x^2 - y^2 - y*z
   To:   Projective Space of dimension 1 over Rational Field
   Defn: Defined on coordinates by sending (x : y : z) to (y + z : x),
 Scheme morphism:
   From: Closed subscheme of Projective Space of dimension 2
         over Rational Field defined by: x^2 - y^2 - y*z
   To:   Projective Space of dimension 1 over Rational Field
   Defn: Defined on coordinates by sending (x : y : z) to (x : y)]
>>> g = _[Integer(0)]                                                      ␣
↪     # needs sage.libs.singular
>>> g.representatives()                                                    #␣
↪needs sage.libs.singular
[Scheme morphism:
   From: Closed subscheme of Projective Space of dimension 2
         over Rational Field defined by: x^2 - y^2 - y*z
   To:   Projective Space of dimension 1 over Rational Field
   Defn: Defined on coordinates by sending (x : y : z) to (y + z : x),
 Scheme morphism:
   From: Closed subscheme of Projective Space of dimension 2
         over Rational Field defined by: x^2 - y^2 - y*z
   To:   Projective Space of dimension 1 over Rational Field
   Defn: Defined on coordinates by sending (x : y : z) to (x : y)]
```

```
sage: P2.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: X = P2.subscheme([x^2 - y^2 - y*z])
sage: A1.<a> = AffineSpace(QQ, 1)
sage: g = X.hom([y/x], A1)
sage: g.representatives()                                                  #␣
↪needs sage.libs.singular
[Scheme morphism:
   From: Closed subscheme of Projective Space of dimension 2
         over Rational Field defined by: x^2 - y^2 - y*z
   To:   Affine Space of dimension 1 over Rational Field
   Defn: Defined on coordinates by sending (x : y : z) to (x/(y + z)),
 Scheme morphism:
   From: Closed subscheme of Projective Space of dimension 2
         over Rational Field defined by: x^2 - y^2 - y*z
   To:   Affine Space of dimension 1 over Rational Field
   Defn: Defined on coordinates by sending (x : y : z) to (y/x)]
sage: g0, g1 = _                                                           #␣
↪needs sage.libs.singular
sage: emb = A1.projective_embedding(0)
sage: emb*g0                                                               #␣
↪needs sage.libs.singular
```

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```
Scheme morphism:
  From: Closed subscheme of Projective Space of dimension 2
        over Rational Field defined by: x^2 - y^2 - y*z
  To:   Projective Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x : y : z) to (y + z : x)
sage: emb*g1                                                                #␣
↪needs sage.libs.singular
Scheme morphism:
  From: Closed subscheme of Projective Space of dimension 2
        over Rational Field defined by: x^2 - y^2 - y*z
  To:   Projective Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x : y : z) to (x : y)
```

```
>>> from sage.all import *
>>> P2 = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,)␣
↪= P2._first_ngens(3)
>>> X = P2.subscheme([x**Integer(2) - y**Integer(2) - y*z])
>>> A1 = AffineSpace(QQ, Integer(1), names=('a',)); (a,) = A1._first_ngens(1)
>>> g = X.hom([y/x], A1)
>>> g.representatives()                                                     #␣
↪needs sage.libs.singular
[Scheme morphism:
   From: Closed subscheme of Projective Space of dimension 2
         over Rational Field defined by: x^2 - y^2 - y*z
   To:   Affine Space of dimension 1 over Rational Field
   Defn: Defined on coordinates by sending (x : y : z) to (x/(y + z)),
 Scheme morphism:
   From: Closed subscheme of Projective Space of dimension 2
         over Rational Field defined by: x^2 - y^2 - y*z
   To:   Affine Space of dimension 1 over Rational Field
   Defn: Defined on coordinates by sending (x : y : z) to (y/x)]
>>> g0, g1 = _                                                              #␣
↪needs sage.libs.singular
>>> emb = A1.projective_embedding(Integer(0))
>>> emb*g0                                                                  #␣
↪needs sage.libs.singular
Scheme morphism:
  From: Closed subscheme of Projective Space of dimension 2
        over Rational Field defined by: x^2 - y^2 - y*z
  To:   Projective Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x : y : z) to (y + z : x)
>>> emb*g1                                                                  #␣
↪needs sage.libs.singular
Scheme morphism:
  From: Closed subscheme of Projective Space of dimension 2
        over Rational Field defined by: x^2 - y^2 - y*z
  To:   Projective Space of dimension 1 over Rational Field
  Defn: Defined on coordinates by sending (x : y : z) to (x : y)
```

ALGORITHM:

The algorithm is from Proposition 1.1 in [Sim2004].

14.3 Points on projective varieties

This module implements scheme morphism for points on projective varieties.

AUTHORS:

- David Kohel, William Stein (2006): initial version
- William Stein (2006-02-11): fixed bug where P(0,0,0) was allowed as a projective point
- Volker Braun (2011-08-08): Renamed classes, more documentation, misc cleanups
- Ben Hutz (2012-06): added support for projective ring
- Ben Hutz (2013-03): added iteration functionality and new directory structure for affine/projective, height functionality

class sage.schemes.projective.projective_point.**SchemeMorphism_point_abelian_variety_field**(*X*, *v*, *check=True*)

Bases: AdditiveGroupElement, *SchemeMorphism_point_projective_field*

A rational point of an abelian variety over a field.

EXAMPLES:

```
sage: # needs sage.schemes
sage: E = EllipticCurve([0,0,1,-1,0])
sage: origin = E(0)
sage: origin.domain()
Spectrum of Rational Field
sage: origin.codomain()
Elliptic Curve defined by y^2 + y = x^3 - x over Rational Field
```

```
>>> from sage.all import *
>>> # needs sage.schemes
>>> E = EllipticCurve([Integer(0),Integer(0),Integer(1),-Integer(1),Integer(0)])
>>> origin = E(Integer(0))
>>> origin.domain()
Spectrum of Rational Field
>>> origin.codomain()
Elliptic Curve defined by y^2 + y = x^3 - x over Rational Field
```

class sage.schemes.projective.projective_point.**SchemeMorphism_point_projective_field**(*X*, *v*, *check=True*)

Bases: *SchemeMorphism_point_projective_ring*

A rational point of projective space over a field.

INPUT:

- `X` – a homset of a subscheme of an ambient projective space over a field K
- `v` – list or tuple of coordinates in K
- `check` – boolean (default: `True`); whether to check the input for consistency

EXAMPLES:

```
sage: # needs sage.rings.real_mpfr
sage: P = ProjectiveSpace(3, RR)
sage: P(2, 3, 4, 5)
(0.400000000000000 : 0.600000000000000 : 0.800000000000000 : 1.00000000000000)
```

```
>>> from sage.all import *
>>> # needs sage.rings.real_mpfr
>>> P = ProjectiveSpace(Integer(3), RR)
>>> P(Integer(2), Integer(3), Integer(4), Integer(5))
(0.400000000000000 : 0.600000000000000 : 0.800000000000000 : 1.00000000000000)
```

as_subscheme()

Return the subscheme associated with this rational point.

EXAMPLES:

```
sage: P2.<x,y,z> = ProjectiveSpace(QQ,2)
sage: p1 = P2.point([0,0,1]).as_subscheme(); p1
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  x, y
sage: p2 = P2.point([1,1,1]).as_subscheme(); p2
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  x - z, y - z
sage: p1 + p2
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  x - y, y^2 - y*z
```

```
>>> from sage.all import *
>>> P2 = ProjectiveSpace(QQ,Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P2._first_ngens(3)
>>> p1 = P2.point([Integer(0),Integer(0),Integer(1)]).as_subscheme(); p1
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  x, y
>>> p2 = P2.point([Integer(1),Integer(1),Integer(1)]).as_subscheme(); p2
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  x - z, y - z
>>> p1 + p2
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  x - y, y^2 - y*z
```

clear_denominators()

Scale by the least common multiple of the denominators.

OUTPUT: none

EXAMPLES:

```
sage: R.<t> = PolynomialRing(QQ)
sage: P.<x,y,z> = ProjectiveSpace(FractionField(R), 2)
sage: Q = P([t, 3/t^2, 1])
sage: Q.clear_denominators(); Q
(t^3 : 3 : t^2)
```

```
>>> from sage.all import *
>>> R = PolynomialRing(QQ, names=('t',)); (t,) = R._first_ngens(1)
>>> P = ProjectiveSpace(FractionField(R), Integer(2), names=('x', 'y', 'z',));
↪ (x, y, z,) = P._first_ngens(3)
>>> Q = P([t, Integer(3)/t**Integer(2), Integer(1)])
>>> Q.clear_denominators(); Q
(t^3 : 3 : t^2)
```

```
sage: # needs sage.rings.number_field
sage: R.<x> = PolynomialRing(QQ)
sage: K.<w> = NumberField(x^2 - 3)
sage: P.<x,y,z> = ProjectiveSpace(K, 2)
sage: Q = P([1/w, 3, 0])
sage: Q.clear_denominators(); Q
(w : 9 : 0)
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = PolynomialRing(QQ, names=('x',)); (x,) = R._first_ngens(1)
>>> K = NumberField(x**Integer(2) - Integer(3), names=('w',)); (w,) = K._
↪first_ngens(1)
>>> P = ProjectiveSpace(K, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> Q = P([Integer(1)/w, Integer(3), Integer(0)])
>>> Q.clear_denominators(); Q
(w : 9 : 0)
```

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: X = P.subscheme(x^2 - y^2)
sage: Q = X([1/2, 1/2, 1])
sage: Q.clear_denominators(); Q
(1 : 1 : 2)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> X = P.subscheme(x**Integer(2) - y**Integer(2))
>>> Q = X([Integer(1)/Integer(2), Integer(1)/Integer(2), Integer(1)])
>>> Q.clear_denominators(); Q
(1 : 1 : 2)
```

```
sage: PS.<x,y> = ProjectiveSpace(QQ, 1)
sage: Q = PS.point([1, 2/3], False); Q
(1 : 2/3)
sage: Q.clear_denominators(); Q
```

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```
(3 : 2)
```

```
>>> from sage.all import *
>>> PS = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = PS._
↪first_ngens(2)
>>> Q = PS.point([Integer(1), Integer(2)/Integer(3)], False); Q
(1 : 2/3)
>>> Q.clear_denominators(); Q
(3 : 2)
```

intersection_multiplicity(*X*)

Return the intersection multiplicity of the codomain of this point and `X` at this point.

This uses the intersection_multiplicity implementations for projective/affine subschemes. This point must be a point of a projective subscheme.

INPUT:

- `X` – a subscheme in the same ambient space as that of the codomain of this point

OUTPUT: integer

EXAMPLES:

```
sage: P.<x,y,z,w> = ProjectiveSpace(QQ, 3)
sage: X = P.subscheme([x*z - y^2])
sage: Y = P.subscheme([x^3 - y*w^2 + z*w^2, x*y - z*w])
sage: Q1 = X([1/2, 1/4, 1/8, 1])
sage: Q1.intersection_multiplicity(Y)                                    #␣
↪needs sage.libs.singular
1
sage: Q2 = X([0,0,0,1])
sage: Q2.intersection_multiplicity(Y)                                    #␣
↪needs sage.libs.singular
5
sage: Q3 = X([0,0,1,0])
sage: Q3.intersection_multiplicity(Y)                                    #␣
↪needs sage.libs.singular
6
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(3), names=('x', 'y', 'z', 'w',)); (x, y,␣
↪z, w,) = P._first_ngens(4)
>>> X = P.subscheme([x*z - y**Integer(2)])
>>> Y = P.subscheme([x**Integer(3) - y*w**Integer(2) + z*w**Integer(2), x*y -␣
↪z*w])
>>> Q1 = X([Integer(1)/Integer(2), Integer(1)/Integer(4), Integer(1)/
↪Integer(8), Integer(1)])
>>> Q1.intersection_multiplicity(Y)                                      #␣
↪needs sage.libs.singular
1
>>> Q2 = X([Integer(0),Integer(0),Integer(0),Integer(1)])
>>> Q2.intersection_multiplicity(Y)                                      #␣
↪needs sage.libs.singular
```

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```
5
>>> Q3 = X([Integer(0),Integer(0),Integer(1),Integer(0)])
>>> Q3.intersection_multiplicity(Y)                                    #␣
↪needs sage.libs.singular
6
```

```
sage: P.<x,y,z,w> = ProjectiveSpace(QQ, 3)
sage: X = P.subscheme([x^2 - y^2])
sage: Q = P([1,1,1,0])
sage: Q.intersection_multiplicity(X)
Traceback (most recent call last):
...
TypeError: this point must be a point on a projective subscheme
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(3), names=('x', 'y', 'z', 'w',)); (x, y,␣
↪z, w,) = P._first_ngens(4)
>>> X = P.subscheme([x**Integer(2) - y**Integer(2)])
>>> Q = P([Integer(1),Integer(1),Integer(1),Integer(0)])
>>> Q.intersection_multiplicity(X)
Traceback (most recent call last):
...
TypeError: this point must be a point on a projective subscheme
```

multiplicity()

Return the multiplicity of this point on its codomain.

Uses the subscheme multiplicity implementation. This point must be a point on a projective subscheme.

OUTPUT: integer

EXAMPLES:

```
sage: P.<x,y,z,w,t> = ProjectiveSpace(QQ, 4)
sage: X = P.subscheme([y^6 - x^3*w^2*t + t^5*w, x^2 - t^2])
sage: Q1 = X([1,0,2,1,1])
sage: Q1.multiplicity()                                                 #␣
↪needs sage.libs.singular
1
sage: Q2 = X([0,0,-2,1,0])
sage: Q2.multiplicity()                                                 #␣
↪needs sage.libs.singular
8
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(4), names=('x', 'y', 'z', 'w', 't',)); (x,
↪ y, z, w, t,) = P._first_ngens(5)
>>> X = P.subscheme([y**Integer(6) - x**Integer(3)*w**Integer(2)*t +␣
↪t**Integer(5)*w, x**Integer(2) - t**Integer(2)])
>>> Q1 = X([Integer(1),Integer(0),Integer(2),Integer(1),Integer(1)])
>>> Q1.multiplicity()                                                   #␣
↪needs sage.libs.singular
1
```

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```
>>> Q2 = X([Integer(0),Integer(0),-Integer(2),Integer(1),Integer(0)])
>>> Q2.multiplicity()                                                    #␣
↪needs sage.libs.singular
8
```

normalize_coordinates()

Normalize the point so that the last nonzero coordinate is 1.

OUTPUT: none

EXAMPLES:

```
sage: P.<x,y,z> = ProjectiveSpace(GF(5), 2)
sage: Q = P.point([GF(5)(1), GF(5)(3), GF(5)(0)], False); Q
(1 : 3 : 0)
sage: Q.normalize_coordinates(); Q
(2 : 1 : 0)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(GF(Integer(5)), Integer(2), names=('x', 'y', 'z',));␣
↪(x, y, z,) = P._first_ngens(3)
>>> Q = P.point([GF(Integer(5))(Integer(1)), GF(Integer(5))(Integer(3)),␣
↪GF(Integer(5))(Integer(0))], False); Q
(1 : 3 : 0)
>>> Q.normalize_coordinates(); Q
(2 : 1 : 0)
```

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: X = P.subscheme(x^2 - y^2);
sage: Q = X.point([23, 23, 46], False); Q
(23 : 23 : 46)
sage: Q.normalize_coordinates(); Q
(1/2 : 1/2 : 1)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> X = P.subscheme(x**Integer(2) - y**Integer(2));
>>> Q = X.point([Integer(23), Integer(23), Integer(46)], False); Q
(23 : 23 : 46)
>>> Q.normalize_coordinates(); Q
(1/2 : 1/2 : 1)
```

class sage.schemes.projective.projective_point.**SchemeMorphism_point_projective_finite_field**(*X*, *v*, *check=True*

Bases: *SchemeMorphism_point_projective_field*

class sage.schemes.projective.projective_point.**SchemeMorphism_point_projective_ring**(*X*, *v*, *check=True*)

Bases: *SchemeMorphism_point*

A rational point of projective space over a ring.

INPUT:

- `X` – a homset of a subscheme of an ambient projective space over a ring K
- `v` – list or tuple of coordinates in K
- `check` – boolean (default: `True`); whether to check the input for consistency

EXAMPLES:

```
sage: P = ProjectiveSpace(2, ZZ)
sage: P(2,3,4)
(2 : 3 : 4)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(Integer(2), ZZ)
>>> P(Integer(2),Integer(3),Integer(4))
(2 : 3 : 4)
```

dehomogenize(*n*)

Dehomogenizes at the n-th coordinate.

INPUT:

- `n` – nonnegative integer

OUTPUT: `SchemeMorphism_point_affine`

EXAMPLES:

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: X = P.subscheme(x^2 - y^2)
sage: Q = X(23, 23, 46)
sage: Q.dehomogenize(2)                                                    #␣
↪needs sage.libs.singular
(1/2, 1/2)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> X = P.subscheme(x**Integer(2) - y**Integer(2))
>>> Q = X(Integer(23), Integer(23), Integer(46))
>>> Q.dehomogenize(Integer(2))                                              ␣
↪     # needs sage.libs.singular
(1/2, 1/2)
```

```
sage: # needs sage.libs.pari
sage: R.<t> = PolynomialRing(QQ)
sage: S = R.quo(R.ideal(t^3))
sage: P.<x,y,z> = ProjectiveSpace(S, 2)
sage: Q = P(t, 1, 1)
sage: Q.dehomogenize(1)
(tbar, 1)
```

```
>>> from sage.all import *
>>> # needs sage.libs.pari
>>> R = PolynomialRing(QQ, names=('t',)); (t,) = R._first_ngens(1)
>>> S = R.quo(R.ideal(t**Integer(3)))
>>> P = ProjectiveSpace(S, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> Q = P(t, Integer(1), Integer(1))
>>> Q.dehomogenize(Integer(1))
(tbar, 1)
```

```
sage: P.<x,y,z> = ProjectiveSpace(GF(5), 2)
sage: Q = P(1, 3, 1)
sage: Q.dehomogenize(0)
(3, 1)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(GF(Integer(5)), Integer(2), names=('x', 'y', 'z',));␣
↪(x, y, z,) = P._first_ngens(3)
>>> Q = P(Integer(1), Integer(3), Integer(1))
>>> Q.dehomogenize(Integer(0))
(3, 1)
```

```
sage: P.<x,y,z> = ProjectiveSpace(GF(5), 2)
sage: Q = P(1, 3, 0)
sage: Q.dehomogenize(2)
Traceback (most recent call last):
...
ValueError: can...t dehomogenize at 0 coordinate
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(GF(Integer(5)), Integer(2), names=('x', 'y', 'z',));␣
↪(x, y, z,) = P._first_ngens(3)
>>> Q = P(Integer(1), Integer(3), Integer(0))
>>> Q.dehomogenize(Integer(2))
Traceback (most recent call last):
...
ValueError: can...t dehomogenize at 0 coordinate
```

global_height(*prec=None*)

Return the absolute logarithmic height of the point.

INPUT:

- `prec` – desired floating point precision (default: default RealField precision)

OUTPUT: a real number

EXAMPLES:

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: Q = P.point([4, 4, 1/30])
sage: Q.global_height()                                                    #␣
↪needs sage.symbolic
4.78749174278205
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> Q = P.point([Integer(4), Integer(4), Integer(1)/Integer(30)])
>>> Q.global_height()                                                    #␣
↪needs sage.symbolic
4.78749174278205
```

```
sage: P.<x,y,z> = ProjectiveSpace(ZZ, 2)
sage: Q = P([4, 1, 30])
sage: Q.global_height()                                                 #␣
↪needs sage.symbolic
3.40119738166216
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(ZZ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> Q = P([Integer(4), Integer(1), Integer(30)])
>>> Q.global_height()                                                    #␣
↪needs sage.symbolic
3.40119738166216
```

```
sage: R.<x> = PolynomialRing(QQ)
sage: k.<w> = NumberField(x^2 + 5)                                      #␣
↪needs sage.rings.number_field
sage: A = ProjectiveSpace(k, 2, 'z')                                    #␣
↪needs sage.rings.number_field
sage: A([3, 5*w + 1, 1]).global_height(prec=100)                        #␣
↪needs sage.rings.number_field
2.4181409534757389986565376694
```

```
>>> from sage.all import *
>>> R = PolynomialRing(QQ, names=('x',)); (x,) = R._first_ngens(1)
>>> k = NumberField(x**Integer(2) + Integer(5), names=('w',)); (w,) = k._
↪first_ngens(1)# needs sage.rings.number_field
>>> A = ProjectiveSpace(k, Integer(2), 'z')                                 ␣
↪     # needs sage.rings.number_field
>>> A([Integer(3), Integer(5)*w + Integer(1), Integer(1)]).global_
↪height(prec=Integer(100))                              # needs sage.rings.
↪number_field
2.4181409534757389986565376694
```

```
sage: P.<x,y,z> = ProjectiveSpace(QQbar, 2)                             #␣
↪needs sage.rings.number_field
sage: Q = P([QQbar(sqrt(3)), QQbar(sqrt(-2)), 1])                       #␣
↪needs sage.rings.number_field sage.symbolic
sage: Q.global_height()                                                 #␣
↪needs sage.rings.number_field sage.symbolic
0.549306144334055
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQbar, Integer(2), names=('x', 'y', 'z',)); (x, y, z,
↪) = P._first_ngens(3)# needs sage.rings.number_field
>>> Q = P([QQbar(sqrt(Integer(3))), QQbar(sqrt(-Integer(2))), Integer(1)])
↪                        # needs sage.rings.number_field sage.symbolic
>>> Q.global_height()                                                    #␣
↪needs sage.rings.number_field sage.symbolic
0.549306144334055
```

```
sage: # needs sage.rings.number_field
sage: K = UniversalCyclotomicField()
sage: P.<x,y,z> = ProjectiveSpace(K, 2)
sage: Q = P.point([K(4/3), K.gen(7), K.gen(5)])
sage: Q.global_height()
1.38629436111989
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> K = UniversalCyclotomicField()
>>> P = ProjectiveSpace(K, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> Q = P.point([K(Integer(4)/Integer(3)), K.gen(Integer(7)), K.
↪gen(Integer(5))])
>>> Q.global_height()
1.38629436111989
```

is_preperiodic(*f*, *err=0.1*, *return_period=False*)

Determine if the point is preperiodic with respect to the map `f`.

This is implemented for both projective space and subschemes. There are two optional keyword arguments: `error_bound` sets the error_bound used in the canonical height computation and `return_period` a boolean which controls if the period is returned if the point is preperiodic. If `return_period` is `True` and this point is not preperiodic, then $(0, 0)$ is returned for the period.

ALGORITHM:

We know that a point is preperiodic if and only if it has canonical height zero. However, we can only compute the canonical height up to numerical precision. This function first computes the canonical height of the point to the given error bound. If it is larger than that error bound, then it must not be preperiodic. If it is less than the error bound, then we expect preperiodic. In this case we begin computing the orbit stopping if either we determine the orbit is finite, or the height of the point is large enough that it must be wandering. We can determine the height cutoff by computing the height difference constant, i.e., the bound between the height and the canonical height of a point (which depends only on the map and not the point itself). If the height of the point is larger than the difference bound, then the canonical height cannot be zero so the point cannot be preperiodic.

INPUT:

- `f` – an endomorphism of this point's codomain

kwds:

- `err` – a positive real number (default: 0.1)
- `return_period` – boolean (default: `False`)

OUTPUT:

- boolean; `True` if preperiodic.
- if `return_period` is `True`, then `(0,0)` if wandering, and `(m,n)` if preperiod `m` and period `n`.

EXAMPLES:

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: f = DynamicalSystem_projective([x^3 - 3*x*y^2, y^3], domain=P)        #␣
↪needs sage.schemes
sage: Q = P(-1, 1)
sage: Q.is_preperiodic(f)                                                   #␣
↪needs sage.libs.singular sage.schemes
True
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> f = DynamicalSystem_projective([x**Integer(3) -␣
↪Integer(3)*x*y**Integer(2), y**Integer(3)], domain=P)        # needs sage.
↪schemes
>>> Q = P(-Integer(1), Integer(1))
>>> Q.is_preperiodic(f)                                                     #␣
↪needs sage.libs.singular sage.schemes
True
```

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: X = P.subscheme(z)
sage: f = DynamicalSystem([x^2 - y^2, y^2, z^2], domain=X)                  #␣
↪needs sage.schemes
sage: p = X((-1, 1, 0))
sage: p.is_preperiodic(f, return_period=True)                               #␣
↪needs sage.libs.singular sage.schemes
(0, 2)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> X = P.subscheme(z)
>>> f = DynamicalSystem([x**Integer(2) - y**Integer(2), y**Integer(2),␣
↪z**Integer(2)], domain=X)                  # needs sage.schemes
>>> p = X((-Integer(1), Integer(1), Integer(0)))
>>> p.is_preperiodic(f, return_period=True)                                 #␣
↪needs sage.libs.singular sage.schemes
(0, 2)
```

```
sage: P.<x,y> = ProjectiveSpace(QQ,1)
sage: f = DynamicalSystem_projective([x^2 - 29/16*y^2, y^2], domain=P)      #␣
↪needs sage.schemes
sage: Q = P(1, 4)
sage: Q.is_preperiodic(f, return_period=True)                               #␣
↪needs sage.libs.singular sage.schemes
(1, 3)
sage: Q = P(1, 1)
```

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```
sage: Q.is_preperiodic(f, return_period=True)                                   #␣
↪needs sage.libs.singular sage.schemes
(0, 0)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ,Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> f = DynamicalSystem_projective([x**Integer(2) - Integer(29)/
↪Integer(16)*y**Integer(2), y**Integer(2)], domain=P)       # needs sage.
↪schemes
>>> Q = P(Integer(1), Integer(4))
>>> Q.is_preperiodic(f, return_period=True)                                     #␣
↪needs sage.libs.singular sage.schemes
(1, 3)
>>> Q = P(Integer(1), Integer(1))
>>> Q.is_preperiodic(f, return_period=True)                                     #␣
↪needs sage.libs.singular sage.schemes
(0, 0)
```

```
sage: # needs sage.rings.number_field
sage: R.<x> = PolynomialRing(QQ)
sage: K.<a> = NumberField(x^2 + 1)
sage: P.<x,y> = ProjectiveSpace(K, 1)
sage: f = DynamicalSystem_projective([x^5 + 5/4*x*y^4, y^5], domain=P)       #␣
↪needs sage.schemes
sage: Q = P([-1/2*a + 1/2, 1])
sage: Q.is_preperiodic(f)                                                       #␣
↪needs sage.schemes
True
sage: Q = P([a, 1])
sage: Q.is_preperiodic(f)                                                       #␣
↪needs sage.schemes
False
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = PolynomialRing(QQ, names=('x',)); (x,) = R._first_ngens(1)
>>> K = NumberField(x**Integer(2) + Integer(1), names=('a',)); (a,) = K._
↪first_ngens(1)
>>> P = ProjectiveSpace(K, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> f = DynamicalSystem_projective([x**Integer(5) + Integer(5)/
↪Integer(4)*x*y**Integer(4), y**Integer(5)], domain=P)       # needs sage.
↪schemes
>>> Q = P([-Integer(1)/Integer(2)*a + Integer(1)/Integer(2), Integer(1)])
>>> Q.is_preperiodic(f)                                                         #␣
↪needs sage.schemes
True
>>> Q = P([a, Integer(1)])
>>> Q.is_preperiodic(f)                                                         #␣
↪needs sage.schemes
```

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```
False
```

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: f = DynamicalSystem_projective([                                          #␣
↪needs sage.schemes
....:         -38/45*x^2 + (2*y - 7/45*z)*x + (-1/2*y^2 - 1/2*y*z + z^2),
....:         -67/90*x^2 + (2*y + z*157/90)*x - y*z,
....:         z^2
....:     ], domain=P)
sage: Q = P([1, 3, 1])
sage: Q.is_preperiodic(f, return_period=True)                                   #␣
↪needs sage.libs.singular sage.schemes
(0, 9)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> f = DynamicalSystem_projective([                                            #␣
↪needs sage.schemes
...         -Integer(38)/Integer(45)*x**Integer(2) + (Integer(2)*y -␣
↪Integer(7)/Integer(45)*z)*x + (-Integer(1)/Integer(2)*y**Integer(2) -␣
↪Integer(1)/Integer(2)*y*z + z**Integer(2)),
...         -Integer(67)/Integer(90)*x**Integer(2) + (Integer(2)*y +␣
↪z*Integer(157)/Integer(90))*x - y*z,
...         z**Integer(2)
...     ], domain=P)
>>> Q = P([Integer(1), Integer(3), Integer(1)])
>>> Q.is_preperiodic(f, return_period=True)                                     #␣
↪needs sage.libs.singular sage.schemes
(0, 9)
```

```
sage: P.<x,y,z,w> = ProjectiveSpace(QQ, 3)
sage: f = DynamicalSystem_projective([                                          #␣
↪needs sage.schemes
....:         (-y - w)*x + (-13/30*y^2 + 13/30*w*y + w^2),
....:         -1/2*x^2 + (-y + 3/2*w)*x + (-1/3*y^2 + 4/3*w*y),
....:         -3/2*z^2 + 5/2*z*w + w^2,
....:         w^2
....:     ], domain=P)
sage: Q = P([3,0,4/3,1])
sage: Q.is_preperiodic(f, return_period=True)                                   #␣
↪needs sage.libs.singular sage.schemes
(2, 24)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(3), names=('x', 'y', 'z', 'w',)); (x, y,␣
↪z, w,) = P._first_ngens(4)
>>> f = DynamicalSystem_projective([                                            #␣
↪needs sage.schemes
...         (-y - w)*x + (-Integer(13)/Integer(30)*y**Integer(2) +␣
↪Integer(13)/Integer(30)*w*y + w**Integer(2)),
```

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```
...          -Integer(1)/Integer(2)*x**Integer(2) + (-y + Integer(3)/
↪Integer(2)*w)*x + (-Integer(1)/Integer(3)*y**Integer(2) + Integer(4)/
↪Integer(3)*w*y),
...          -Integer(3)/Integer(2)*z**Integer(2) + Integer(5)/Integer(2)*z*w␣
↪+ w**Integer(2),
...          w**Integer(2)
...      ], domain=P)
>>> Q = P([Integer(3),Integer(0),Integer(4)/Integer(3),Integer(1)])
>>> Q.is_preperiodic(f, return_period=True)                                #␣
↪needs sage.libs.singular sage.schemes
(2, 24)
```

```
sage: # needs sage.rings.number_field sage.schemes sage.symbolic
sage: from sage.misc.verbose import set_verbose
sage: set_verbose(-1)
sage: P.<x,y,z> = ProjectiveSpace(QQbar, 2)
sage: f = DynamicalSystem_projective([x^2, QQbar(sqrt(-1))*y^2, z^2],
....:                                domain=P)
sage: Q = P([1, 1, 1])
sage: Q.is_preperiodic(f)
True
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field sage.schemes sage.symbolic
>>> from sage.misc.verbose import set_verbose
>>> set_verbose(-Integer(1))
>>> P = ProjectiveSpace(QQbar, Integer(2), names=('x', 'y', 'z',)); (x, y, z,
↪) = P._first_ngens(3)
>>> f = DynamicalSystem_projective([x**Integer(2), QQbar(sqrt(-
↪Integer(1)))*y**Integer(2), z**Integer(2)],
...                                domain=P)
>>> Q = P([Integer(1), Integer(1), Integer(1)])
>>> Q.is_preperiodic(f)
True
```

```
sage: # needs sage.rings.number_field sage.schemes sage.symbolic
sage: set_verbose(-1)
sage: P.<x,y,z> = ProjectiveSpace(QQbar, 2)
sage: f = DynamicalSystem_projective([x^2, y^2, z^2], domain=P)
sage: Q = P([QQbar(sqrt(-1)), 1, 1])
sage: Q.is_preperiodic(f)
True
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field sage.schemes sage.symbolic
>>> set_verbose(-Integer(1))
>>> P = ProjectiveSpace(QQbar, Integer(2), names=('x', 'y', 'z',)); (x, y, z,
↪) = P._first_ngens(3)
>>> f = DynamicalSystem_projective([x**Integer(2), y**Integer(2),␣
↪z**Integer(2)], domain=P)
>>> Q = P([QQbar(sqrt(-Integer(1))), Integer(1), Integer(1)])
```

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```
>>> Q.is_preperiodic(f)
True
```

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: f = DynamicalSystem_projective([16*x^2 - 29*y^2, 16*y^2], domain=P)    #␣
↪needs sage.schemes
sage: Q = P(-1,4)
sage: Q.is_preperiodic(f)                                                    #␣
↪needs sage.libs.singular sage.schemes
True
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> f = DynamicalSystem_projective([Integer(16)*x**Integer(2) -␣
↪Integer(29)*y**Integer(2), Integer(16)*y**Integer(2)], domain=P)    # needs␣
↪sage.schemes
>>> Q = P(-Integer(1),Integer(4))
>>> Q.is_preperiodic(f)                                                      #␣
↪needs sage.libs.singular sage.schemes
True
```

```
sage: P.<x,y,z> = ProjectiveSpace(GF(3), 2)
sage: F = DynamicalSystem([x^2 - 2*y^2, y^2, z^2])                           #␣
↪needs sage.schemes
sage: Q = P(1, 1, 1)
sage: Q.is_preperiodic(F, return_period=True)                                #␣
↪needs sage.schemes
(1, 1)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(GF(Integer(3)), Integer(2), names=('x', 'y', 'z',));␣
↪(x, y, z,) = P._first_ngens(3)
>>> F = DynamicalSystem([x**Integer(2) - Integer(2)*y**Integer(2),␣
↪y**Integer(2), z**Integer(2)])                          # needs sage.schemes
>>> Q = P(Integer(1), Integer(1), Integer(1))
>>> Q.is_preperiodic(F, return_period=True)                                  #␣
↪needs sage.schemes
(1, 1)
```

local_height(*v*, *prec=None*)

Return the maximum of the local height of the coordinates of this point.

INPUT:

- `v` – a prime or prime ideal of the base ring
- `prec` – desired floating point precision (default: default RealField precision)

OUTPUT: a real number

EXAMPLES:

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: Q = P.point([4, 4, 1/150], False)
sage: Q.local_height(5)                                                     #␣
↪needs sage.rings.real_mpfr
3.21887582486820
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> Q = P.point([Integer(4), Integer(4), Integer(1)/Integer(150)], False)
>>> Q.local_height(Integer(5))                                              ␣
↪     # needs sage.rings.real_mpfr
3.21887582486820
```

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: Q = P([4, 1, 30])
sage: Q.local_height(2)                                                     #␣
↪needs sage.rings.real_mpfr
0.693147180559945
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> Q = P([Integer(4), Integer(1), Integer(30)])
>>> Q.local_height(Integer(2))                                              ␣
↪     # needs sage.rings.real_mpfr
0.693147180559945
```

local_height_arch(*i*, *prec=None*)

Return the maximum of the local heights at the `i`-th infinite place of this point.

INPUT:

- `i` – integer
- `prec` – desired floating point precision (default: default RealField precision)

OUTPUT: a real number

EXAMPLES:

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: Q = P.point([4, 4, 1/150], False)
sage: Q.local_height_arch(0)                                                #␣
↪needs sage.rings.real_mpfr
1.38629436111989
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> Q = P.point([Integer(4), Integer(4), Integer(1)/Integer(150)], False)
>>> Q.local_height_arch(Integer(0))                                         ␣
↪     # needs sage.rings.real_mpfr
1.38629436111989
```

```
sage: # needs sage.rings.number_field
sage: P.<x,y,z> = ProjectiveSpace(QuadraticField(5, 'w'), 2)
sage: Q = P.point([4, 1, 30], False)
sage: Q.local_height_arch(1)
3.4011973816621553754132366916 07
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> P = ProjectiveSpace(QuadraticField(Integer(5), 'w'), Integer(2), names=('x
↪', 'y', 'z',)); (x, y, z,) = P._first_ngens(3)
>>> Q = P.point([Integer(4), Integer(1), Integer(30)], False)
>>> Q.local_height_arch(Integer(1))
3.4011973816621553754132366916 07
```

multiplier(*f*, *n*, *check=True*)

Return the multiplier of this point of period `n` by the function `f`.

`f` must be an endomorphism of projective space.

INPUT:

- `f` – a endomorphism of this point's codomain
- `n` – positive integer; the period of this point
- `check` – boolean (default: `True`); check if `P` is periodic of period `n`

OUTPUT:

- a square matrix of size `self.codomain().dimension_relative()` in the `base_ring` of this point.

EXAMPLES:

```
sage: P.<x,y,z,w> = ProjectiveSpace(QQ, 3)
sage: f = DynamicalSystem_projective([x^2, y^2, 4*w^2, 4*z^2], domain=P)     #␣
↪needs sage.schemes
sage: Q = P.point([4, 4, 1, 1], False)
sage: Q.multiplier(f, 1)                                                     #␣
↪needs sage.schemes
[ 2  0 -8]
[ 0  2 -8]
[ 0  0 -2]
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(3), names=('x', 'y', 'z', 'w',)); (x, y,␣
↪z, w,) = P._first_ngens(4)
>>> f = DynamicalSystem_projective([x**Integer(2), y**Integer(2),␣
↪Integer(4)*w**Integer(2), Integer(4)*z**Integer(2)], domain=P)     # needs␣
↪sage.schemes
>>> Q = P.point([Integer(4), Integer(4), Integer(1), Integer(1)], False)
>>> Q.multiplier(f, Integer(1))                                              ␣
↪     # needs sage.schemes
[ 2  0 -8]
[ 0  2 -8]
[ 0  0 -2]
```

normalize_coordinates()

Removes the gcd from the coordinates of this point (including -1) and rescales everything so that the last nonzero entry is as "simple" as possible. The notion of "simple" here depends on the base ring; concretely, the last nonzero coordinate will be 1 in a field and positive over an ordered ring.

Warning

The gcd will depend on the base ring.

OUTPUT: none

EXAMPLES:

```
sage: P = ProjectiveSpace(ZZ, 2, 'x')
sage: p = P([-5, -15, -20])
sage: p.normalize_coordinates(); p
(1 : 3 : 4)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(ZZ, Integer(2), 'x')
>>> p = P([-Integer(5), -Integer(15), -Integer(20)])
>>> p.normalize_coordinates(); p
(1 : 3 : 4)
```

```
sage: # needs sage.rings.padics
sage: P = ProjectiveSpace(Zp(7), 2, 'x')
sage: p = P([-5, -15, -2])
sage: p.normalize_coordinates(); p
(6 + 3*7 + 3*7^2 + 3*7^3 + 3*7^4 + 3*7^5 + 3*7^6 + 3*7^7 + 3*7^8 + 3*7^9 +␣
↪3*7^10 + 3*7^11 + 3*7^12 + 3*7^13 + 3*7^14 + 3*7^15 + 3*7^16 + 3*7^17 + 3*7^
↪18 + 3*7^19 + O(7^20) : 4 + 4*7 + 3*7^2 + 3*7^3 + 3*7^4 + 3*7^5 + 3*7^6 +␣
↪3*7^7 + 3*7^8 + 3*7^9 + 3*7^10 + 3*7^11 + 3*7^12 + 3*7^13 + 3*7^14 + 3*7^15␣
↪+ 3*7^16 + 3*7^17 + 3*7^18 + 3*7^19 + O(7^20) : 1 + O(7^20))
```

```
>>> from sage.all import *
>>> # needs sage.rings.padics
>>> P = ProjectiveSpace(Zp(Integer(7)), Integer(2), 'x')
>>> p = P([-Integer(5), -Integer(15), -Integer(2)])
>>> p.normalize_coordinates(); p
(6 + 3*7 + 3*7^2 + 3*7^3 + 3*7^4 + 3*7^5 + 3*7^6 + 3*7^7 + 3*7^8 + 3*7^9 +␣
↪3*7^10 + 3*7^11 + 3*7^12 + 3*7^13 + 3*7^14 + 3*7^15 + 3*7^16 + 3*7^17 + 3*7^
↪18 + 3*7^19 + O(7^20) : 4 + 4*7 + 3*7^2 + 3*7^3 + 3*7^4 + 3*7^5 + 3*7^6 +␣
↪3*7^7 + 3*7^8 + 3*7^9 + 3*7^10 + 3*7^11 + 3*7^12 + 3*7^13 + 3*7^14 + 3*7^15␣
↪+ 3*7^16 + 3*7^17 + 3*7^18 + 3*7^19 + O(7^20) : 1 + O(7^20))
```

```
sage: R.<t> = PolynomialRing(QQ)
sage: P = ProjectiveSpace(R, 2, 'x')
sage: p = P([3/5*t^3, 6*t, t])
sage: p.normalize_coordinates(); p
(3/5*t^2 : 6 : 1)
```

```
>>> from sage.all import *
>>> R = PolynomialRing(QQ, names=('t',)); (t,) = R._first_ngens(1)
>>> P = ProjectiveSpace(R, Integer(2), 'x')
>>> p = P([Integer(3)/Integer(5)*t**Integer(3), Integer(6)*t, t])
>>> p.normalize_coordinates(); p
(3/5*t^2 : 6 : 1)
```

```
sage: P.<x,y> = ProjectiveSpace(Zmod(20), 1)
sage: Q = P(3, 6)
sage: Q.normalize_coordinates()
sage: Q
(1 : 2)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(Zmod(Integer(20)), Integer(1), names=('x', 'y',)); (x,
↪ y,) = P._first_ngens(2)
>>> Q = P(Integer(3), Integer(6))
>>> Q.normalize_coordinates()
>>> Q
(1 : 2)
```

Since the base ring is a polynomial ring over a field, only the gcd c is removed.

```
sage: R.<c> = PolynomialRing(QQ)
sage: P = ProjectiveSpace(R, 1)
sage: Q = P(2*c, 4*c)
sage: Q.normalize_coordinates(); Q
(1/2 : 1)
```

```
>>> from sage.all import *
>>> R = PolynomialRing(QQ, names=('c',)); (c,) = R._first_ngens(1)
>>> P = ProjectiveSpace(R, Integer(1))
>>> Q = P(Integer(2)*c, Integer(4)*c)
>>> Q.normalize_coordinates(); Q
(1/2 : 1)
```

A polynomial ring over a ring gives the more intuitive result.

```
sage: R.<c> = PolynomialRing(ZZ)
sage: P = ProjectiveSpace(R, 1)
sage: Q = P(2*c, 4*c)
sage: Q.normalize_coordinates();Q
(1 : 2)
```

```
>>> from sage.all import *
>>> R = PolynomialRing(ZZ, names=('c',)); (c,) = R._first_ngens(1)
>>> P = ProjectiveSpace(R, Integer(1))
>>> Q = P(Integer(2)*c, Integer(4)*c)
>>> Q.normalize_coordinates();Q
(1 : 2)
```

```
sage: # needs sage.libs.singular
sage: R.<t> = QQ[]
sage: S = R.quotient_ring(R.ideal(t^3))
sage: P.<x,y> = ProjectiveSpace(S, 1)
sage: Q = P(t + 1, t^2 + t)
sage: Q.normalize_coordinates()
sage: Q
(1 : tbar)
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> R = QQ['t']; (t,) = R._first_ngens(1)
>>> S = R.quotient_ring(R.ideal(t**Integer(3)))
>>> P = ProjectiveSpace(S, Integer(1), names=('x', 'y',)); (x, y,) = P._first_
↪ngens(2)
>>> Q = P(t + Integer(1), t**Integer(2) + t)
>>> Q.normalize_coordinates()
>>> Q
(1 : tbar)
```

scale_by(*t*)

Scale the coordinates of the point by `t`.

A `TypeError` occurs if the point is not in the base_ring of the codomain after scaling.

INPUT:

- `t` – a ring element

OUTPUT: none

EXAMPLES:

```
sage: R.<t> = PolynomialRing(QQ)
sage: P = ProjectiveSpace(R, 2, 'x')
sage: p = P([3/5*t^3, 6*t, t])
sage: p.scale_by(1/t); p
(3/5*t^2 : 6 : 1)
```

```
>>> from sage.all import *
>>> R = PolynomialRing(QQ, names=('t',)); (t,) = R._first_ngens(1)
>>> P = ProjectiveSpace(R, Integer(2), 'x')
>>> p = P([Integer(3)/Integer(5)*t**Integer(3), Integer(6)*t, t])
>>> p.scale_by(Integer(1)/t); p
(3/5*t^2 : 6 : 1)
```

```
sage: # needs sage.libs.pari
sage: R.<t> = PolynomialRing(QQ)
sage: S = R.quo(R.ideal(t^3))
sage: P.<x,y,z> = ProjectiveSpace(S, 2)
sage: Q = P(t, 1, 1)
sage: Q.scale_by(t);Q
(tbar^2 : tbar : tbar)
```

```
>>> from sage.all import *
>>> # needs sage.libs.pari
>>> R = PolynomialRing(QQ, names=('t',)); (t,) = R._first_ngens(1)
>>> S = R.quo(R.ideal(t**Integer(3)))
>>> P = ProjectiveSpace(S, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> Q = P(t, Integer(1), Integer(1))
>>> Q.scale_by(t);Q
(tbar^2 : tbar : tbar)
```

```
sage: P.<x,y,z> = ProjectiveSpace(ZZ,2)
sage: Q = P(2, 2, 2)
sage: Q.scale_by(1/2);Q
(1 : 1 : 1)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(ZZ,Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> Q = P(Integer(2), Integer(2), Integer(2))
>>> Q.scale_by(Integer(1)/Integer(2));Q
(1 : 1 : 1)
```

14.4 Subschemes of projective space

AUTHORS:

- David Kohel (2005): initial version.
- William Stein (2005): initial version.
- Volker Braun (2010-12-24): documentation of schemes and refactoring. Added coordinate neighborhoods and is_smooth()
- Ben Hutz (2013) refactoring

class sage.schemes.projective.projective_subscheme.**AlgebraicScheme_subscheme_projective**(*A*, *polynomials*, *category=None*)

Bases: *AlgebraicScheme_subscheme*

Construct an algebraic subscheme of projective space.

Warning

You should not create objects of this class directly. The preferred method to construct such subschemes is to use `subscheme()` method of *projective space*.

INPUT:

- A – ambient *projective space*
- polynomials – single polynomial, ideal or iterable of defining homogeneous polynomials

EXAMPLES:

```
sage: P.<x, y, z> = ProjectiveSpace(2, QQ)
sage: P.subscheme([x^2 - y*z])
Closed subscheme of Projective Space of dimension 2 over Rational Field defined␣
↪by:
  x^2 - y*z
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(Integer(2), QQ, names=('x', 'y', 'z',)); (x, y, z,) = P._
↪first_ngens(3)
>>> P.subscheme([x**Integer(2) - y*z])
Closed subscheme of Projective Space of dimension 2 over Rational Field defined␣
↪by:
  x^2 - y*z
```

affine_patch(*i*, *AA=None*)

Return the i-th affine patch of this projective scheme.

This is the intersection with this i-th affine patch of its ambient space.

INPUT:

- i – integer between 0 and dimension of self, inclusive
- AA – (default: None) ambient affine space, this is constructed if it is not given

OUTPUT:

An affine algebraic scheme with fixed embedding_morphism() equal to the default projective_embedding() map`.

EXAMPLES:

```
sage: # needs sage.libs.singular
sage: PP = ProjectiveSpace(2, QQ, names='X,Y,Z')
sage: X,Y,Z = PP.gens()
sage: C = PP.subscheme(X^3*Y + Y^3*Z + Z^3*X)
sage: U = C.affine_patch(0); U
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  Y^3*Z + Z^3 + Y
sage: U.embedding_morphism()
Scheme morphism:
  From: Closed subscheme of Affine Space of dimension 2 over Rational Field
        defined by: Y^3*Z + Z^3 + Y
  To:   Closed subscheme of Projective Space of dimension 2 over Rational␣
↪Field
        defined by: X^3*Y + Y^3*Z + X*Z^3
  Defn: Defined on coordinates by sending (Y, Z) to (1 : Y : Z)
sage: U.projective_embedding() is U.embedding_morphism()
True
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> PP = ProjectiveSpace(Integer(2), QQ, names='X,Y,Z')
>>> X,Y,Z = PP.gens()
>>> C = PP.subscheme(X**Integer(3)*Y + Y**Integer(3)*Z + Z**Integer(3)*X)
>>> U = C.affine_patch(Integer(0)); U
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  Y^3*Z + Z^3 + Y
>>> U.embedding_morphism()
Scheme morphism:
  From: Closed subscheme of Affine Space of dimension 2 over Rational Field
        defined by: Y^3*Z + Z^3 + Y
  To:   Closed subscheme of Projective Space of dimension 2 over Rational␣
↪Field
        defined by: X^3*Y + Y^3*Z + X*Z^3
  Defn: Defined on coordinates by sending (Y, Z) to (1 : Y : Z)
>>> U.projective_embedding() is U.embedding_morphism()
True
```

```
sage: A.<x,y,z> = AffineSpace(QQ, 3)
sage: X = A.subscheme([x - y*z])
sage: Y = X.projective_embedding(1).codomain()                                #␣
↪needs sage.libs.singular
sage: Y.affine_patch(1, A).ambient_space() == A                               #␣
↪needs sage.libs.singular
True
```

```
>>> from sage.all import *
>>> A = AffineSpace(QQ, Integer(3), names=('x', 'y', 'z',)); (x, y, z,) = A._
↪first_ngens(3)
>>> X = A.subscheme([x - y*z])
>>> Y = X.projective_embedding(Integer(1)).codomain()                          ␣
↪     # needs sage.libs.singular
>>> Y.affine_patch(Integer(1), A).ambient_space() == A                         ␣
↪     # needs sage.libs.singular
True
```

```
sage: P.<u,v,w> = ProjectiveSpace(2, ZZ)
sage: S = P.subscheme([u^2 - v*w])
sage: A.<x, y> = AffineSpace(2, ZZ)
sage: S.affine_patch(1, A)                                                    #␣
↪needs sage.libs.singular
Closed subscheme of Affine Space of dimension 2 over Integer Ring defined by:
  x^2 - y
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(Integer(2), ZZ, names=('u', 'v', 'w',)); (u, v, w,) =␣
↪P._first_ngens(3)
>>> S = P.subscheme([u**Integer(2) - v*w])
>>> A = AffineSpace(Integer(2), ZZ, names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
```

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```
>>> S.affine_patch(Integer(1), A)
↪     # needs sage.libs.singular
Closed subscheme of Affine Space of dimension 2 over Integer Ring defined by:
  x^2 - y
```

degree()

Return the degree of this projective subscheme.

If $P(t) = a_m t^m + \ldots + a_0$ is the Hilbert polynomial of this subscheme, then the degree is $a_m m!$.

OUTPUT: integer

EXAMPLES:

```
sage: P.<x,y,z,w,t,u> = ProjectiveSpace(QQ, 5)
sage: X = P.subscheme([x^7 + x*y*z*t^4 - u^7])
sage: X.degree()                                                              #
↪needs sage.libs.singular
7

sage: P.<x,y,z,w> = ProjectiveSpace(GF(13), 3)
sage: X = P.subscheme([y^3 - w^3, x + 7*z])
sage: X.degree()                                                              #
↪needs sage.libs.singular
3

sage: # needs sage.libs.singular sage.schemes
sage: P.<x,y,z,w,u> = ProjectiveSpace(QQ, 4)
sage: C = P.curve([x^7 - y*z^3*w^2*u, w*x^2 - y*u^2, z^3 + y^3])
sage: C.degree()
63
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(5), names=('x', 'y', 'z', 'w', 't', 'u',
↪)); (x, y, z, w, t, u,) = P._first_ngens(6)
>>> X = P.subscheme([x**Integer(7) + x*y*z*t**Integer(4) - u**Integer(7)])
>>> X.degree()                                                                #
↪needs sage.libs.singular
7

>>> P = ProjectiveSpace(GF(Integer(13)), Integer(3), names=('x', 'y', 'z', 'w
↪',)); (x, y, z, w,) = P._first_ngens(4)
>>> X = P.subscheme([y**Integer(3) - w**Integer(3), x + Integer(7)*z])
>>> X.degree()                                                                #
↪needs sage.libs.singular
3

>>> # needs sage.libs.singular sage.schemes
>>> P = ProjectiveSpace(QQ, Integer(4), names=('x', 'y', 'z', 'w', 'u',)); (x,
↪ y, z, w, u,) = P._first_ngens(5)
>>> C = P.curve([x**Integer(7) - y*z**Integer(3)*w**Integer(2)*u,
↪w*x**Integer(2) - y*u**Integer(2), z**Integer(3) + y**Integer(3)])
>>> C.degree()
```

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```
63
```

dimension()

Return the dimension of the projective algebraic subscheme.

OUTPUT: integer

EXAMPLES:

```
sage: # needs sage.libs.singular
sage: P2.<x,y,z> = ProjectiveSpace(2, QQ)
sage: P2.subscheme([]).dimension()
2
sage: P2.subscheme([x]).dimension()
1
sage: P2.subscheme([x^5]).dimension()
1
sage: P2.subscheme([x^2 + y^2 - z^2]).dimension()
1
sage: P2.subscheme([x*(x-z), y*(y-z)]).dimension()
0
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> P2 = ProjectiveSpace(Integer(2), QQ, names=('x', 'y', 'z',)); (x, y, z,)␣
↪= P2._first_ngens(3)
>>> P2.subscheme([]).dimension()
2
>>> P2.subscheme([x]).dimension()
1
>>> P2.subscheme([x**Integer(5)]).dimension()
1
>>> P2.subscheme([x**Integer(2) + y**Integer(2) - z**Integer(2)]).dimension()
1
>>> P2.subscheme([x*(x-z), y*(y-z)]).dimension()
0
```

Something less obvious:

```
sage: P3.<x,y,z,w,t> = ProjectiveSpace(4, QQ)
sage: X = P3.subscheme([x^2, x^2*y^2 + z^2*t^2,
....:                   z^2 - w^2, 10*x^2 + w^2 - z^2]); X
Closed subscheme of Projective Space of dimension 4 over Rational Field␣
↪defined by:
  x^2,
  x^2*y^2 + z^2*t^2,
  z^2 - w^2,
  10*x^2 - z^2 + w^2
sage: X.dimension()                                                    #␣
↪needs sage.libs.singular
1
```

```
>>> from sage.all import *
>>> P3 = ProjectiveSpace(Integer(4), QQ, names=('x', 'y', 'z', 'w', 't',));␣
↪(x, y, z, w, t,) = P3._first_ngens(5)
>>> X = P3.subscheme([x**Integer(2), x**Integer(2)*y**Integer(2) +␣
↪z**Integer(2)*t**Integer(2),
...                    z**Integer(2) - w**Integer(2),␣
↪Integer(10)*x**Integer(2) + w**Integer(2) - z**Integer(2)]); X
Closed subscheme of Projective Space of dimension 4 over Rational Field␣
↪defined by:
  x^2,
  x^2*y^2 + z^2*t^2,
  z^2 - w^2,
  10*x^2 - z^2 + w^2
>>> X.dimension()                                                    #␣
↪needs sage.libs.singular
1
```

dual()

Return the projective dual of the given subscheme of projective space.

INPUT:

- X – a subscheme of projective space. At present, X is required to be an irreducible and reduced hypersurface defined over **Q** or a finite field.

OUTPUT: the dual of X as a subscheme of the dual projective space

EXAMPLES:

The dual of a smooth conic in the plane is also a smooth conic:

```
sage: R.<x, y, z> = QQ[]
sage: P.<x, y, z> = ProjectiveSpace(2, QQ)
sage: I = R.ideal(x^2 + y^2 + z^2)
sage: X = P.subscheme(I)
sage: X.dual()                                                        #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 2 over Rational Field
 defined by:
  y0^2 + y1^2 + y2^2
```

```
>>> from sage.all import *
>>> R = QQ['x, y, z']; (x, y, z,) = R._first_ngens(3)
>>> P = ProjectiveSpace(Integer(2), QQ, names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> I = R.ideal(x**Integer(2) + y**Integer(2) + z**Integer(2))
>>> X = P.subscheme(I)
>>> X.dual()                                                          #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 2 over Rational Field
 defined by:
  y0^2 + y1^2 + y2^2
```

The dual of the twisted cubic curve in projective 3-space is a singular quartic surface. In the following example, we compute the dual of this surface, which by double duality is equal to the twisted cubic itself. The output is the twisted cubic as an intersection of three quadrics:

```
sage: R.<x, y, z, w> = QQ[]
sage: P.<x, y, z, w> = ProjectiveSpace(3, QQ)
sage: I = R.ideal(y^2*z^2 - 4*x*z^3 - 4*y^3*w + 18*x*y*z*w - 27*x^2*w^2)
sage: X = P.subscheme(I)
sage: X.dual()                                                              #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 3 over
 Rational Field defined by:
  y2^2 - y1*y3,
  y1*y2 - y0*y3,
  y1^2 - y0*y2
```

```
>>> from sage.all import *
>>> R = QQ['x, y, z, w']; (x, y, z, w,) = R._first_ngens(4)
>>> P = ProjectiveSpace(Integer(3), QQ, names=('x', 'y', 'z', 'w',)); (x, y,␣
↪z, w,) = P._first_ngens(4)
>>> I = R.ideal(y**Integer(2)*z**Integer(2) - Integer(4)*x*z**Integer(3) -␣
↪Integer(4)*y**Integer(3)*w + Integer(18)*x*y*z*w -␣
↪Integer(27)*x**Integer(2)*w**Integer(2))
>>> X = P.subscheme(I)
>>> X.dual()                                                                #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 3 over
 Rational Field defined by:
  y2^2 - y1*y3,
  y1*y2 - y0*y3,
  y1^2 - y0*y2
```

The singular locus of the quartic surface in the last example is itself supported on a twisted cubic:

```
sage: X.Jacobian().radical()                                                #␣
↪needs sage.libs.singular
Ideal (z^2 - 3*y*w, y*z - 9*x*w, y^2 - 3*x*z) of Multivariate
Polynomial Ring in x, y, z, w over Rational Field
```

```
>>> from sage.all import *
>>> X.Jacobian().radical()                                                  #␣
↪needs sage.libs.singular
Ideal (z^2 - 3*y*w, y*z - 9*x*w, y^2 - 3*x*z) of Multivariate
Polynomial Ring in x, y, z, w over Rational Field
```

An example over a finite field:

```
sage: R = PolynomialRing(GF(61), 'a,b,c')
sage: P.<a, b, c> = ProjectiveSpace(2, R.base_ring())
sage: X = P.subscheme(R.ideal(a*a + 2*b*b + 3*c*c))
sage: X.dual()                                                              #␣
↪needs sage.libs.singular sage.rings.finite_rings
Closed subscheme of Projective Space of dimension 2 over
 Finite Field of size 61 defined by:
  y0^2 - 30*y1^2 - 20*y2^2
```

```
>>> from sage.all import *
>>> R = PolynomialRing(GF(Integer(61)), 'a,b,c')
>>> P = ProjectiveSpace(Integer(2), R.base_ring(), names=('a', 'b', 'c',));␣
↪(a, b, c,) = P._first_ngens(3)
>>> X = P.subscheme(R.ideal(a*a + Integer(2)*b*b + Integer(3)*c*c))
>>> X.dual()                                                                #␣
↪needs sage.libs.singular sage.rings.finite_rings
Closed subscheme of Projective Space of dimension 2 over
 Finite Field of size 61 defined by:
  y0^2 - 30*y1^2 - 20*y2^2
```

intersection_multiplicity(*X*, *P*)

Return the intersection multiplicity of this subscheme and the subscheme `X` at the point `P`.

This uses the intersection_multiplicity function for affine subschemes on affine patches of this subscheme and `X` that contain `P`.

INPUT:

- `X` – subscheme in the same ambient space as this subscheme
- `P` – a point in the intersection of this subscheme with `X`

OUTPUT: integer

EXAMPLES:

```
sage: # needs sage.schemes
sage: P.<x,y,z> = ProjectiveSpace(GF(5), 2)
sage: C = Curve([x^4 - z^2*y^2], P)
sage: D = Curve([y^4*z - x^5 - x^3*z^2], P)
sage: Q1 = P([0,1,0])
sage: C.intersection_multiplicity(D, Q1)                                 #␣
↪needs sage.libs.singular
4
sage: Q2 = P([0,0,1])
sage: C.intersection_multiplicity(D, Q2)                                 #␣
↪needs sage.libs.singular
6
```

```
>>> from sage.all import *
>>> # needs sage.schemes
>>> P = ProjectiveSpace(GF(Integer(5)), Integer(2), names=('x', 'y', 'z',));␣
↪(x, y, z,) = P._first_ngens(3)
>>> C = Curve([x**Integer(4) - z**Integer(2)*y**Integer(2)], P)
>>> D = Curve([y**Integer(4)*z - x**Integer(5) - x**Integer(3)*z**Integer(2)],
↪ P)
>>> Q1 = P([Integer(0),Integer(1),Integer(0)])
>>> C.intersection_multiplicity(D, Q1)                                   #␣
↪needs sage.libs.singular
4
>>> Q2 = P([Integer(0),Integer(0),Integer(1)])
>>> C.intersection_multiplicity(D, Q2)                                   #␣
↪needs sage.libs.singular
6
```

```
sage: # needs sage.rings.number_field
sage: R.<a> = QQ[]
sage: K.<b> = NumberField(a^4 + 1)
sage: P.<x,y,z,w> = ProjectiveSpace(K, 3)
sage: X = P.subscheme([x^2 + y^2 - z*w])
sage: Y = P.subscheme([y*z - x*w, z - w])
sage: Q1 = P([b^2,1,0,0])
sage: X.intersection_multiplicity(Y, Q1)                                    #␣
↪needs sage.libs.singular
1
sage: Q2 = P([1/2*b^3 - 1/2*b, 1/2*b^3 - 1/2*b, 1, 1])
sage: X.intersection_multiplicity(Y, Q2)                                    #␣
↪needs sage.libs.singular
1
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = QQ['a']; (a,) = R._first_ngens(1)
>>> K = NumberField(a**Integer(4) + Integer(1), names=('b',)); (b,) = K._
↪first_ngens(1)
>>> P = ProjectiveSpace(K, Integer(3), names=('x', 'y', 'z', 'w',)); (x, y, z,
↪ w,) = P._first_ngens(4)
>>> X = P.subscheme([x**Integer(2) + y**Integer(2) - z*w])
>>> Y = P.subscheme([y*z - x*w, z - w])
>>> Q1 = P([b**Integer(2),Integer(1),Integer(0),Integer(0)])
>>> X.intersection_multiplicity(Y, Q1)                                      #␣
↪needs sage.libs.singular
1
>>> Q2 = P([Integer(1)/Integer(2)*b**Integer(3) - Integer(1)/Integer(2)*b,␣
↪Integer(1)/Integer(2)*b**Integer(3) - Integer(1)/Integer(2)*b, Integer(1),␣
↪Integer(1)])
>>> X.intersection_multiplicity(Y, Q2)                                      #␣
↪needs sage.libs.singular
1
```

```
sage: P.<x,y,z,w> = ProjectiveSpace(QQ, 3)
sage: X = P.subscheme([x^2 - z^2, y^3 - w*x^2])
sage: Y = P.subscheme([w^2 - 2*x*y + z^2, y^2 - w^2])
sage: Q = P([1,1,-1,1])
sage: X.intersection_multiplicity(Y, Q)                                     #␣
↪needs sage.libs.singular
Traceback (most recent call last):
...
TypeError: the intersection of this subscheme and (=Closed subscheme of␣
↪Affine Space of dimension 3
over Rational Field defined by: z^2 + w^2 - 2*y, y^2 - w^2)
must be proper and finite
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(3), names=('x', 'y', 'z', 'w',)); (x, y,␣
↪z, w,) = P._first_ngens(4)
>>> X = P.subscheme([x**Integer(2) - z**Integer(2), y**Integer(3) -␣
```

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```
↪w*x**Integer(2)])
>>> Y = P.subscheme([w**Integer(2) - Integer(2)*x*y + z**Integer(2),␣
↪y**Integer(2) - w**Integer(2)])
>>> Q = P([Integer(1),Integer(1),-Integer(1),Integer(1)])
>>> X.intersection_multiplicity(Y, Q)                                    #␣
↪needs sage.libs.singular
Traceback (most recent call last):
...
TypeError: the intersection of this subscheme and (=Closed subscheme of␣
↪Affine Space of dimension 3
over Rational Field defined by: z^2 + w^2 - 2*y, y^2 - w^2)
must be proper and finite
```

is_smooth(*point=None*)

Test whether the algebraic subscheme is smooth.

INPUT:

- `point` – a point or `None` (default); the point to test smoothness at

OUTPUT:

boolean; if no point was specified, returns whether the algebraic subscheme is smooth everywhere. Otherwise, smoothness at the specified point is tested.

EXAMPLES:

```
sage: # needs sage.libs.singular
sage: P2.<x,y,z> = ProjectiveSpace(2, QQ)
sage: cuspidal_curve = P2.subscheme([y^2*z - x^3])
sage: cuspidal_curve
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  -x^3 + y^2*z
sage: cuspidal_curve.is_smooth([1,1,1])
True
sage: cuspidal_curve.is_smooth([0,0,1])
False
sage: cuspidal_curve.is_smooth()
False
sage: P2.subscheme([y^2*z - x^3 + z^3 + 1/10*x*y*z]).is_smooth()
True
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> P2 = ProjectiveSpace(Integer(2), QQ, names=('x', 'y', 'z',)); (x, y, z,)␣
↪= P2._first_ngens(3)
>>> cuspidal_curve = P2.subscheme([y**Integer(2)*z - x**Integer(3)])
>>> cuspidal_curve
Closed subscheme of Projective Space of dimension 2 over Rational Field␣
↪defined by:
  -x^3 + y^2*z
>>> cuspidal_curve.is_smooth([Integer(1),Integer(1),Integer(1)])
True
```

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```
>>> cuspidal_curve.is_smooth([Integer(0),Integer(0),Integer(1)])
False
>>> cuspidal_curve.is_smooth()
False
>>> P2.subscheme([y**Integer(2)*z - x**Integer(3) + z**Integer(3) +␣
↪Integer(1)/Integer(10)*x*y*z]).is_smooth()
True
```

multiplicity(*P*)

Return the multiplicity of `P` on this subscheme.

This is computed as the multiplicity of the corresponding point on an affine patch of this subscheme that contains `P`. This subscheme must be defined over a field. An error is returned if `P` not a point on this subscheme.

INPUT:

- `P` – a point on this subscheme

OUTPUT: integer

EXAMPLES:

```
sage: P.<x,y,z,w,t> = ProjectiveSpace(QQ, 4)
sage: X = P.subscheme([y^2 - x*t, w^7 - t*w*x^5 - z^7])
sage: Q1 = P([0,0,1,1,1])
sage: X.multiplicity(Q1)                                                    #␣
↪needs sage.libs.singular
1
sage: Q2 = P([1,0,0,0,0])
sage: X.multiplicity(Q2)                                                    #␣
↪needs sage.libs.singular
3
sage: Q3 = P([0,0,0,0,1])
sage: X.multiplicity(Q3)                                                    #␣
↪needs sage.libs.singular
7
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(4), names=('x', 'y', 'z', 'w', 't',)); (x,
↪ y, z, w, t,) = P._first_ngens(5)
>>> X = P.subscheme([y**Integer(2) - x*t, w**Integer(7) - t*w*x**Integer(5) -␣
↪z**Integer(7)])
>>> Q1 = P([Integer(0),Integer(0),Integer(1),Integer(1),Integer(1)])
>>> X.multiplicity(Q1)                                                      #␣
↪needs sage.libs.singular
1
>>> Q2 = P([Integer(1),Integer(0),Integer(0),Integer(0),Integer(0)])
>>> X.multiplicity(Q2)                                                      #␣
↪needs sage.libs.singular
3
>>> Q3 = P([Integer(0),Integer(0),Integer(0),Integer(0),Integer(1)])
>>> X.multiplicity(Q3)                                                      #␣
↪needs sage.libs.singular
7
```

```
sage: # needs sage.rings.real_mpfr
sage: P.<x,y,z,w> = ProjectiveSpace(CC, 3)
sage: X = P.subscheme([z^5*x^2*w - y^8])
sage: Q = P([2,0,0,1])
sage: X.multiplicity(Q)                                                    #␣
↪needs sage.libs.singular
5
```

```
>>> from sage.all import *
>>> # needs sage.rings.real_mpfr
>>> P = ProjectiveSpace(CC, Integer(3), names=('x', 'y', 'z', 'w',)); (x, y,␣
↪z, w,) = P._first_ngens(4)
>>> X = P.subscheme([z**Integer(5)*x**Integer(2)*w - y**Integer(8)])
>>> Q = P([Integer(2),Integer(0),Integer(0),Integer(1)])
>>> X.multiplicity(Q)                                                      #␣
↪needs sage.libs.singular
5
```

```
sage: # needs sage.libs.singular sage.schemes
sage: P.<x,y,z,w> = ProjectiveSpace(GF(29), 3)
sage: C = Curve([y^17 - x^5*w^4*z^8, x*y - z^2], P)
sage: Q = P([3,0,0,1])
sage: C.multiplicity(Q)
8
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular sage.schemes
>>> P = ProjectiveSpace(GF(Integer(29)), Integer(3), names=('x', 'y', 'z', 'w
↪',)); (x, y, z, w,) = P._first_ngens(4)
>>> C = Curve([y**Integer(17) - x**Integer(5)*w**Integer(4)*z**Integer(8),␣
↪x*y - z**Integer(2)], P)
>>> Q = P([Integer(3),Integer(0),Integer(0),Integer(1)])
>>> C.multiplicity(Q)
8
```

neighborhood(*point*)

Return an affine algebraic subscheme isomorphic to a neighborhood of the `point`.

INPUT:

- `point` – a point of the projective subscheme

OUTPUT:

An affine algebraic scheme (polynomial equations in affine space) `result` such that

- `embedding_morphism` is an isomorphism to a neighborhood of `point`
- `embedding_center` is mapped to `point`.

EXAMPLES:

```
sage: P.<x,y,z>= ProjectiveSpace(QQ, 2)
sage: S = P.subscheme(x + 2*y + 3*z)
sage: s = S.point([0,-3,2]); s
```

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```
(0 : -3/2 : 1)
sage: patch = S.neighborhood(s); patch
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  x + 3*z
sage: patch.embedding_morphism()
Scheme morphism:
  From: Closed subscheme of Affine Space of dimension 2 over Rational Field
        defined by: x + 3*z
  To:   Closed subscheme of Projective Space of dimension 2 over Rational␣
↪Field
        defined by: x + 2*y + 3*z
  Defn: Defined on coordinates by sending (x, z) to (x : -3/2 : z + 1)
sage: patch.embedding_center()
(0, 0)
sage: patch.embedding_morphism()([0,0])
(0 : -3/2 : 1)
sage: patch.embedding_morphism()(patch.embedding_center())
(0 : -3/2 : 1)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> S = P.subscheme(x + Integer(2)*y + Integer(3)*z)
>>> s = S.point([Integer(0),-Integer(3),Integer(2)]); s
(0 : -3/2 : 1)
>>> patch = S.neighborhood(s); patch
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  x + 3*z
>>> patch.embedding_morphism()
Scheme morphism:
  From: Closed subscheme of Affine Space of dimension 2 over Rational Field
        defined by: x + 3*z
  To:   Closed subscheme of Projective Space of dimension 2 over Rational␣
↪Field
        defined by: x + 2*y + 3*z
  Defn: Defined on coordinates by sending (x, z) to (x : -3/2 : z + 1)
>>> patch.embedding_center()
(0, 0)
>>> patch.embedding_morphism()([Integer(0),Integer(0)])
(0 : -3/2 : 1)
>>> patch.embedding_morphism()(patch.embedding_center())
(0 : -3/2 : 1)
```

nth_iterate(f, n)

The n-th forward image of this scheme by the map `f`.

INPUT:

- `f` – a `DynamicalSystem_projective` with `self` in `f.domain()`
- `n` – positive integer

OUTPUT:

- A subscheme in `f.codomain()`

EXAMPLES:

```
sage: P.<x,y,z,w> = ProjectiveSpace(QQ, 3)
sage: f = DynamicalSystem_projective([y^2, z^2, x^2, w^2])                  #␣
↪needs sage.schemes
sage: f.nth_iterate(P.subscheme([x - w, y - z]), 3)                         #␣
↪needs sage.libs.singular sage.schemes
Closed subscheme of Projective Space of dimension 3 over Rational Field
 defined by:
  y - z,
  x - w
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(3), names=('x', 'y', 'z', 'w',)); (x, y,␣
↪z, w,) = P._first_ngens(4)
>>> f = DynamicalSystem_projective([y**Integer(2), z**Integer(2),␣
↪x**Integer(2), w**Integer(2)])                  # needs sage.schemes
>>> f.nth_iterate(P.subscheme([x - w, y - z]), Integer(3))                  ␣
↪     # needs sage.libs.singular sage.schemes
Closed subscheme of Projective Space of dimension 3 over Rational Field
 defined by:
  y - z,
  x - w
```

```
sage: PS.<x,y,z> = ProjectiveSpace(ZZ, 2)
sage: f = DynamicalSystem_projective([x^2, y^2, z^2])                       #␣
↪needs sage.schemes
sage: X = PS.subscheme([x - y])
sage: X.nth_iterate(f, -2)                                                  #␣
↪needs sage.libs.singular sage.schemes
Traceback (most recent call last):
...
TypeError: must be a forward orbit
```

```
>>> from sage.all import *
>>> PS = ProjectiveSpace(ZZ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,)␣
↪= PS._first_ngens(3)
>>> f = DynamicalSystem_projective([x**Integer(2), y**Integer(2),␣
↪z**Integer(2)])                         # needs sage.schemes
>>> X = PS.subscheme([x - y])
>>> X.nth_iterate(f, -Integer(2))                                           ␣
↪     # needs sage.libs.singular sage.schemes
Traceback (most recent call last):
...
TypeError: must be a forward orbit
```

```
sage: PS.<x,y,z> = ProjectiveSpace(ZZ, 2)
sage: P2.<u,v,w> = ProjectiveSpace(QQ, 2)
sage: H = Hom(PS, P2)
```

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```
sage: f = H([x^2, y^2, z^2])
sage: X = PS.subscheme([x - y])
sage: X.nth_iterate(f, 2)
Traceback (most recent call last):
...
TypeError: map must be a dynamical system for iteration
```

```
>>> from sage.all import *
>>> PS = ProjectiveSpace(ZZ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,)␣
↪= PS._first_ngens(3)
>>> P2 = ProjectiveSpace(QQ, Integer(2), names=('u', 'v', 'w',)); (u, v, w,)␣
↪= P2._first_ngens(3)
>>> H = Hom(PS, P2)
>>> f = H([x**Integer(2), y**Integer(2), z**Integer(2)])
>>> X = PS.subscheme([x - y])
>>> X.nth_iterate(f, Integer(2))
Traceback (most recent call last):
...
TypeError: map must be a dynamical system for iteration
```

```
sage: PS.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: f = DynamicalSystem_projective([x^2, y^2, z^2])                    #␣
↪needs sage.schemes
sage: X = PS.subscheme([x - y])
sage: X.nth_iterate(f, 2.5)                                              #␣
↪needs sage.schemes
Traceback (most recent call last):
...
TypeError: Attempt to coerce non-integral RealNumber to Integer
```

```
>>> from sage.all import *
>>> PS = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,)␣
↪= PS._first_ngens(3)
>>> f = DynamicalSystem_projective([x**Integer(2), y**Integer(2),␣
↪z**Integer(2)])                          # needs sage.schemes
>>> X = PS.subscheme([x - y])
>>> X.nth_iterate(f, RealNumber('2.5'))                                   ␣
↪          # needs sage.schemes
Traceback (most recent call last):
...
TypeError: Attempt to coerce non-integral RealNumber to Integer
```

orbit(f, N)

Return the orbit of this scheme by `f`.

If N is an integer it returns $[self, f(self), \ldots, f^N(self)]$. If N is a list or tuple $N = [m, k]$ it returns $[f^m(self), \ldots, f^k(self)]$.

INPUT:

- `f` – a `DynamicalSystem_projective` with `self` in `f.domain()`
- `N` – nonnegative integer or list or tuple of two nonnegative integers

OUTPUT: list of projective subschemes

EXAMPLES:

```
sage: # needs sage.libs.singular sage.schemes
sage: P.<x,y,z,w> = ProjectiveSpace(QQ, 3)
sage: f = DynamicalSystem_projective([(x-2*y)^2, (x-2*z)^2,
....:                                 (x-2*w)^2, x^2])
sage: f.orbit(P.subscheme([x]), 5)
[Closed subscheme of Projective Space of dimension 3 over Rational Field
  defined by: x,
 Closed subscheme of Projective Space of dimension 3 over Rational Field
  defined by: w,
 Closed subscheme of Projective Space of dimension 3 over Rational Field
  defined by: z - w,
 Closed subscheme of Projective Space of dimension 3 over Rational Field
  defined by: y - z,
 Closed subscheme of Projective Space of dimension 3 over Rational Field
  defined by: x - y,
 Closed subscheme of Projective Space of dimension 3 over Rational Field
  defined by: x - w]
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular sage.schemes
>>> P = ProjectiveSpace(QQ, Integer(3), names=('x', 'y', 'z', 'w',)); (x, y,␣
↪z, w,) = P._first_ngens(4)
>>> f = DynamicalSystem_projective([(x-Integer(2)*y)**Integer(2), (x-
↪Integer(2)*z)**Integer(2),
...                                 (x-Integer(2)*w)**Integer(2),␣
↪x**Integer(2)])
>>> f.orbit(P.subscheme([x]), Integer(5))
[Closed subscheme of Projective Space of dimension 3 over Rational Field
  defined by: x,
 Closed subscheme of Projective Space of dimension 3 over Rational Field
  defined by: w,
 Closed subscheme of Projective Space of dimension 3 over Rational Field
  defined by: z - w,
 Closed subscheme of Projective Space of dimension 3 over Rational Field
  defined by: y - z,
 Closed subscheme of Projective Space of dimension 3 over Rational Field
  defined by: x - y,
 Closed subscheme of Projective Space of dimension 3 over Rational Field
  defined by: x - w]
```

```
sage: PS.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: P1.<u,v> = ProjectiveSpace(QQ, 1)
sage: H = Hom(PS, P1)
sage: f = H([x^2, y^2])
sage: X = PS.subscheme([x - y])
sage: X.orbit(f, 2)
Traceback (most recent call last):
...
TypeError: map must be a dynamical system for iteration
```

```
>>> from sage.all import *
>>> PS = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,)␣
↪= PS._first_ngens(3)
>>> P1 = ProjectiveSpace(QQ, Integer(1), names=('u', 'v',)); (u, v,) = P1._
↪first_ngens(2)
>>> H = Hom(PS, P1)
>>> f = H([x**Integer(2), y**Integer(2)])
>>> X = PS.subscheme([x - y])
>>> X.orbit(f, Integer(2))
Traceback (most recent call last):
...
TypeError: map must be a dynamical system for iteration
```

```
sage: PS.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: f = DynamicalSystem_projective([x^2, y^2, z^2])                    #␣
↪needs sage.schemes
sage: X = PS.subscheme([x - y])
sage: X.orbit(f, [-1,2])                                                 #␣
↪needs sage.schemes
Traceback (most recent call last):
...
TypeError: orbit bounds must be nonnegative
```

```
>>> from sage.all import *
>>> PS = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,)␣
↪= PS._first_ngens(3)
>>> f = DynamicalSystem_projective([x**Integer(2), y**Integer(2),␣
↪z**Integer(2)])                        # needs sage.schemes
>>> X = PS.subscheme([x - y])
>>> X.orbit(f, [-Integer(1),Integer(2)])                                  ␣
↪              # needs sage.schemes
Traceback (most recent call last):
...
TypeError: orbit bounds must be nonnegative
```

point(*v*, *check=True*)

Create a point on this projective subscheme.

INPUT:

- `v` – anything that defines a point
- `check` – boolean (default: `True`); whether to check the defining data for consistency

OUTPUT: a point of the subscheme

EXAMPLES:

```
sage: P2.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: X = P2.subscheme([x - y, y - z])
sage: X.point([1,1,1])
(1 : 1 : 1)
```

```
>>> from sage.all import *
>>> P2 = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,)␣
↪= P2._first_ngens(3)
>>> X = P2.subscheme([x - y, y - z])
>>> X.point([Integer(1),Integer(1),Integer(1)])
(1 : 1 : 1)
```

```
sage: P2.<x,y> = ProjectiveSpace(QQ, 1)
sage: X = P2.subscheme([y])
sage: X.point(infinity)
(1 : 0)
```

```
>>> from sage.all import *
>>> P2 = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P2._
↪first_ngens(2)
>>> X = P2.subscheme([y])
>>> X.point(infinity)
(1 : 0)
```

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: X = P.subscheme(x^2 + 2*y^2)
sage: X.point(infinity)
Traceback (most recent call last):
...
TypeError: Coordinates [1, 0] do not define a point on Closed subscheme
of Projective Space of dimension 1 over Rational Field defined by:
  x^2 + 2*y^2
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> X = P.subscheme(x**Integer(2) + Integer(2)*y**Integer(2))
>>> X.point(infinity)
Traceback (most recent call last):
...
TypeError: Coordinates [1, 0] do not define a point on Closed subscheme
of Projective Space of dimension 1 over Rational Field defined by:
  x^2 + 2*y^2
```

preimage(*f*, *k=1*, *check=True*)

The subscheme that maps to this scheme by the map f^k.

In particular, $f^{-k}(V(h_1, \ldots, h_t)) = V(h_1 \circ f^k, \ldots, h_t \circ f^k)$. Map must be a morphism and also must be an endomorphism for $k > 1$.

INPUT:

- `f` – a map whose codomain contains this scheme
- `k` – positive integer
- `check` – boolean; if `False` no input checking is done

OUTPUT: a subscheme in the domain of `f`

EXAMPLES:

```
sage: PS.<x,y,z> = ProjectiveSpace(ZZ, 2)
sage: H = End(PS)
sage: f = H([y^2, x^2, z^2])
sage: X = PS.subscheme([x - y])
sage: X.preimage(f)                                                    #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 2 over Integer Ring
 defined by:
  -x^2 + y^2
```

```
>>> from sage.all import *
>>> PS = ProjectiveSpace(ZZ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,)␣
↪= PS._first_ngens(3)
>>> H = End(PS)
>>> f = H([y**Integer(2), x**Integer(2), z**Integer(2)])
>>> X = PS.subscheme([x - y])
>>> X.preimage(f)                                                      #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 2 over Integer Ring
 defined by:
  -x^2 + y^2
```

```
sage: P.<x,y,z,w,t> = ProjectiveSpace(QQ, 4)
sage: H = End(P)
sage: f = H([x^2 - y^2, y^2, z^2, w^2, t^2 + w^2])
sage: f.rational_preimages(P.subscheme([x - z, t^2, w - t]))           #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 4 over Rational Field
 defined by:
  x^2 - y^2 - z^2,
  w^4 + 2*w^2*t^2 + t^4,
  -t^2
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(4), names=('x', 'y', 'z', 'w', 't',)); (x,
↪ y, z, w, t,) = P._first_ngens(5)
>>> H = End(P)
>>> f = H([x**Integer(2) - y**Integer(2), y**Integer(2), z**Integer(2),␣
↪w**Integer(2), t**Integer(2) + w**Integer(2)])
>>> f.rational_preimages(P.subscheme([x - z, t**Integer(2), w - t]))      ␣
↪      # needs sage.libs.singular
Closed subscheme of Projective Space of dimension 4 over Rational Field
 defined by:
  x^2 - y^2 - z^2,
  w^4 + 2*w^2*t^2 + t^4,
  -t^2
```

```
sage: P1.<x,y> = ProjectiveSpace(QQ, 1)
sage: P3.<u,v,w,t> = ProjectiveSpace(QQ, 3)
sage: H = Hom(P1, P3)
sage: X = P3.subscheme([u - v, 2*u - w, u + t])
sage: f = H([x^2, y^2, x^2 + y^2, x*y])
```

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```
sage: X.preimage(f)                                                          #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 1 over Rational Field
 defined by:
  x^2 - y^2,
  x^2 - y^2,
  x^2 + x*y
```

```
>>> from sage.all import *
>>> P1 = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P1._
↪first_ngens(2)
>>> P3 = ProjectiveSpace(QQ, Integer(3), names=('u', 'v', 'w', 't',)); (u, v,␣
↪w, t,) = P3._first_ngens(4)
>>> H = Hom(P1, P3)
>>> X = P3.subscheme([u - v, Integer(2)*u - w, u + t])
>>> f = H([x**Integer(2), y**Integer(2), x**Integer(2) + y**Integer(2), x*y])
>>> X.preimage(f)                                                            #␣
↪needs sage.libs.singular
Closed subscheme of Projective Space of dimension 1 over Rational Field
 defined by:
  x^2 - y^2,
  x^2 - y^2,
  x^2 + x*y
```

```
sage: P1.<x,y> = ProjectiveSpace(QQ, 1)
sage: P3.<u,v,w,t> = ProjectiveSpace(QQ, 3)
sage: H = Hom(P3, P1)
sage: X = P1.subscheme([x - y])
sage: f = H([u^2, v^2])
sage: X.preimage(f)                                                          #␣
↪needs sage.libs.singular
Traceback (most recent call last):
...
TypeError: map must be a morphism
```

```
>>> from sage.all import *
>>> P1 = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P1._
↪first_ngens(2)
>>> P3 = ProjectiveSpace(QQ, Integer(3), names=('u', 'v', 'w', 't',)); (u, v,␣
↪w, t,) = P3._first_ngens(4)
>>> H = Hom(P3, P1)
>>> X = P1.subscheme([x - y])
>>> f = H([u**Integer(2), v**Integer(2)])
>>> X.preimage(f)                                                            #␣
↪needs sage.libs.singular
Traceback (most recent call last):
...
TypeError: map must be a morphism
```

```
sage: PS.<x,y,z> = ProjectiveSpace(ZZ, 2)
sage: H = End(PS)
```

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```
sage: f = H([x^2, x^2, x^2])
sage: X = PS.subscheme([x - y])
sage: X.preimage(f)                                                    #␣
↪needs sage.libs.singular
Traceback (most recent call last):
...
TypeError: map must be a morphism
```

```
>>> from sage.all import *
>>> PS = ProjectiveSpace(ZZ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,)␣
↪= PS._first_ngens(3)
>>> H = End(PS)
>>> f = H([x**Integer(2), x**Integer(2), x**Integer(2)])
>>> X = PS.subscheme([x - y])
>>> X.preimage(f)                                                      #␣
↪needs sage.libs.singular
Traceback (most recent call last):
...
TypeError: map must be a morphism
```

```
sage: PS.<x,y,z> = ProjectiveSpace(ZZ, 2)
sage: P1.<u,v> = ProjectiveSpace(ZZ, 1)
sage: Y = P1.subscheme([u^2 - v^2])
sage: H = End(PS)
sage: f = H([x^2, y^2, z^2])
sage: Y.preimage(f)                                                    #␣
↪needs sage.libs.singular
Traceback (most recent call last):
...
TypeError: subscheme must be in ambient space of codomain
```

```
>>> from sage.all import *
>>> PS = ProjectiveSpace(ZZ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,)␣
↪= PS._first_ngens(3)
>>> P1 = ProjectiveSpace(ZZ, Integer(1), names=('u', 'v',)); (u, v,) = P1._
↪first_ngens(2)
>>> Y = P1.subscheme([u**Integer(2) - v**Integer(2)])
>>> H = End(PS)
>>> f = H([x**Integer(2), y**Integer(2), z**Integer(2)])
>>> Y.preimage(f)                                                      #␣
↪needs sage.libs.singular
Traceback (most recent call last):
...
TypeError: subscheme must be in ambient space of codomain
```

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: Y = P.subscheme([x - y])
sage: H = End(P)
sage: f = H([x^2, y^2, z^2])
sage: Y.preimage(f, k=2)                                               #␣
↪needs sage.libs.singular
```

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```
Closed subscheme of Projective Space of dimension 2 over Rational Field
 defined by:
  x^4 - y^4
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> Y = P.subscheme([x - y])
>>> H = End(P)
>>> f = H([x**Integer(2), y**Integer(2), z**Integer(2)])
>>> Y.preimage(f, k=Integer(2))                                                ␣
↪     # needs sage.libs.singular
Closed subscheme of Projective Space of dimension 2 over Rational Field
 defined by:
  x^4 - y^4
```

veronese_embedding(*d*, *CS=None*, *order='lex'*)

Return the degree `d` Veronese embedding of this projective subscheme.

INPUT:

- `d` – positive integer
- `CS` – (default: `None`) a projective ambient space to embed into. If the projective ambient space of this subscheme is of dimension N, the dimension of `CS` must be $\binom{N+d}{d} - 1$. This is constructed if not specified.
- `order` – string (default: `'lex'`); a monomial order to use to arrange the monomials defining the embedding. The monomials will be arranged from greatest to least with respect to this order.

OUTPUT: a scheme morphism from this subscheme to its image by the degree `d` Veronese embedding

EXAMPLES:

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: L = P.subscheme([y - x])
sage: v = L.veronese_embedding(2); v                                           #␣
↪needs sage.libs.singular
Scheme morphism:
  From: Closed subscheme of Projective Space of dimension 2
        over Rational Field defined by: -x + y
  To:   Closed subscheme of Projective Space of dimension 5
        over Rational Field defined by:
          -x4^2 + x3*x5,
          x2 - x4,
          x1 - x3,
          x0 - x3
  Defn: Defined on coordinates by sending (x : y : z) to
        (x^2 : x*y : x*z : y^2 : y*z : z^2)
sage: v.codomain().degree()                                                    #␣
↪needs sage.libs.singular
2
sage: C = P.subscheme([y*z - x^2])
sage: C.veronese_embedding(2).codomain().degree()                              #␣
```

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```
↪needs sage.libs.singular
4
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> L = P.subscheme([y - x])
>>> v = L.veronese_embedding(Integer(2)); v                                    ␣
↪     # needs sage.libs.singular
Scheme morphism:
  From: Closed subscheme of Projective Space of dimension 2
        over Rational Field defined by: -x + y
  To:   Closed subscheme of Projective Space of dimension 5
        over Rational Field defined by:
          -x4^2 + x3*x5,
          x2 - x4,
          x1 - x3,
          x0 - x3
  Defn: Defined on coordinates by sending (x : y : z) to
        (x^2 : x*y : x*z : y^2 : y*z : z^2)
>>> v.codomain().degree()                                                  #␣
↪needs sage.libs.singular
2
>>> C = P.subscheme([y*z - x**Integer(2)])
>>> C.veronese_embedding(Integer(2)).codomain().degree()                       ␣
↪     # needs sage.libs.singular
4
```

twisted cubic:

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: Q.<u,v,s,t> = ProjectiveSpace(QQ, 3)
sage: P.subscheme([]).veronese_embedding(3, Q)                              #␣
↪needs sage.libs.singular
Scheme morphism:
  From: Closed subscheme of Projective Space of dimension 1
        over Rational Field defined by: (no polynomials)
  To:   Closed subscheme of Projective Space of dimension 3
        over Rational Field defined by:
          -s^2 + v*t,
          -v*s + u*t,
          -v^2 + u*s
  Defn: Defined on coordinates by sending (x : y) to
        (x^3 : x^2*y : x*y^2 : y^3)
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> Q = ProjectiveSpace(QQ, Integer(3), names=('u', 'v', 's', 't',)); (u, v,␣
↪s, t,) = Q._first_ngens(4)
>>> P.subscheme([]).veronese_embedding(Integer(3), Q)                          ␣
↪     # needs sage.libs.singular
```

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```
Scheme morphism:
  From: Closed subscheme of Projective Space of dimension 1
        over Rational Field defined by: (no polynomials)
  To:   Closed subscheme of Projective Space of dimension 3
        over Rational Field defined by:
          -s^2 + v*t,
          -v*s + u*t,
          -v^2 + u*s
  Defn: Defined on coordinates by sending (x : y) to
        (x^3 : x^2*y : x*y^2 : y^3)
```

class sage.schemes.projective.projective_subscheme.**AlgebraicScheme_subscheme_projective_field**(*A*, *polynomials*, *category=No*

Bases: *AlgebraicScheme_subscheme_projective*

Algebraic subschemes of projective spaces defined over fields.

Chow_form()

Return the Chow form associated to this subscheme.

For a k-dimensional subvariety of $\mathbb{P}^N$ of degree D. The $(N-k-1)$-dimensional projective linear subspaces of $\mathbb{P}^N$ meeting X form a hypersurface in the Grassmannian $G(N-k-1,N)$. The homogeneous form of degree D defining this hypersurface in Plucker coordinates is called the Chow form of X.

The base ring needs to be a number field, finite field, or $\overline{\mathbf{Q}}$.

ALGORITHM:

For a k-dimension subscheme X consider the $k+1$ linear forms $l_i = u_{i0}x_0 + \cdots + u_{in}x_n$. Let J be the ideal in the polynomial ring $K[x_i, u_{ij}]$ defined by the equations of X and the l_i. Let J' be the saturation of J with respect to the irrelevant ideal of the ambient projective space of X. The elimination ideal $I = J' \cap K[u_{ij}]$ is a principal ideal, let R be its generator. The Chow form is obtained by writing R as a polynomial in Plucker coordinates (i.e. bracket polynomials). [DS1994].

OUTPUT: a homogeneous polynomial

EXAMPLES:

```
sage: P.<x0,x1,x2,x3> = ProjectiveSpace(GF(17), 3)
sage: X = P.subscheme([x3 + x1, x2 - x0, x2 - x3])
sage: X.Chow_form()                                                    #␣
↪needs sage.libs.singular
t0 - t1 + t2 + t3
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(GF(Integer(17)), Integer(3), names=('x0', 'x1', 'x2',
↪'x3',)); (x0, x1, x2, x3,) = P._first_ngens(4)
>>> X = P.subscheme([x3 + x1, x2 - x0, x2 - x3])
>>> X.Chow_form()                                                      #␣
```

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```
↪needs sage.libs.singular
t0 - t1 + t2 + t3
```

```
sage: P.<x0,x1,x2,x3> = ProjectiveSpace(QQ, 3)
sage: X = P.subscheme([x3^2 - 101*x1^2 - 3*x2*x0])
sage: X.Chow_form()                                                    #␣
↪needs sage.libs.singular
t0^2 - 101*t2^2 - 3*t1*t3
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(3), names=('x0', 'x1', 'x2', 'x3',)); (x0,
↪ x1, x2, x3,) = P._first_ngens(4)
>>> X = P.subscheme([x3**Integer(2) - Integer(101)*x1**Integer(2) -␣
↪Integer(3)*x2*x0])
>>> X.Chow_form()                                                      #␣
↪needs sage.libs.singular
t0^2 - 101*t2^2 - 3*t1*t3
```

```
sage: # needs sage.libs.singular
sage: P.<x0,x1,x2,x3> = ProjectiveSpace(QQ, 3)
sage: X = P.subscheme([x0*x2 - x1^2, x0*x3 - x1*x2, x1*x3 - x2^2])
sage: Ch = X.Chow_form(); Ch
t2^3 + 2*t2^2*t3 + t2*t3^2 - 3*t1*t2*t4 - t1*t3*t4 + t0*t4^2 + t1^2*t5
sage: Y = P.subscheme_from_Chow_form(Ch, 1); Y
Closed subscheme of Projective Space of dimension 3 over Rational Field
 defined by:
  x2^2*x3 - x1*x3^2,                    -x2^3 + x0*x3^2,
  -x2^2*x3 + x1*x3^2,                   x1*x2*x3 - x0*x3^2,
  3*x1*x2^2 - 3*x0*x2*x3,               -2*x1^2*x3 + 2*x0*x2*x3,
  -3*x1^2*x2 + 3*x0*x1*x3,              x1^3 - x0^2*x3,
  x2^3 - x1*x2*x3,                      -3*x1*x2^2 + 2*x1^2*x3 + x0*x2*x3,
  2*x0*x2^2 - 2*x0*x1*x3,               3*x1^2*x2 - 2*x0*x2^2 - x0*x1*x3,
  -x0*x1*x2 + x0^2*x3,                  -x0*x1^2 + x0^2*x2,
  -x1^3 + x0*x1*x2,                     x0*x1^2 - x0^2*x2
sage: I = Y.defining_ideal()
sage: I.saturation(I.ring().ideal(list(I.ring().gens())))[0]
Ideal (x2^2 - x1*x3, x1*x2 - x0*x3, x1^2 - x0*x2)
 of Multivariate Polynomial Ring in x0, x1, x2, x3 over Rational Field
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> P = ProjectiveSpace(QQ, Integer(3), names=('x0', 'x1', 'x2', 'x3',)); (x0,
↪ x1, x2, x3,) = P._first_ngens(4)
>>> X = P.subscheme([x0*x2 - x1**Integer(2), x0*x3 - x1*x2, x1*x3 -␣
↪x2**Integer(2)])
>>> Ch = X.Chow_form(); Ch
t2^3 + 2*t2^2*t3 + t2*t3^2 - 3*t1*t2*t4 - t1*t3*t4 + t0*t4^2 + t1^2*t5
>>> Y = P.subscheme_from_Chow_form(Ch, Integer(1)); Y
Closed subscheme of Projective Space of dimension 3 over Rational Field
 defined by:
  x2^2*x3 - x1*x3^2,                    -x2^3 + x0*x3^2,
```

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```
  -x2^2*x3 + x1*x3^2,                    x1*x2*x3 - x0*x3^2,
  3*x1*x2^2 - 3*x0*x2*x3,                -2*x1^2*x3 + 2*x0*x2*x3,
  -3*x1^2*x2 + 3*x0*x1*x3,               x1^3 - x0^2*x3,
  x2^3 - x1*x2*x3,                       -3*x1*x2^2 + 2*x1^2*x3 + x0*x2*x3,
  2*x0*x2^2 - 2*x0*x1*x3,                3*x1^2*x2 - 2*x0*x2^2 - x0*x1*x3,
  -x0*x1*x2 + x0^2*x3,                   -x0*x1^2 + x0^2*x2,
  -x1^3 + x0*x1*x2,                      x0*x1^2 - x0^2*x2
>>> I = Y.defining_ideal()
>>> I.saturation(I.ring().ideal(list(I.ring().gens())))[Integer(0)]
Ideal (x2^2 - x1*x3, x1*x2 - x0*x3, x1^2 - x0*x2)
 of Multivariate Polynomial Ring in x0, x1, x2, x3 over Rational Field
```

global_height(*prec=None*)

Return the (projective) global height of the subscheme.

INPUT:

- `prec` – desired floating point precision (default: default `RealField` precision)

OUTPUT: a real number

EXAMPLES:

```
sage: # needs sage.rings.number_field
sage: R.<x> = QQ[]
sage: NF.<a> = NumberField(x^2 - 5)
sage: P.<x,y,z> = ProjectiveSpace(NF, 2)
sage: X = P.subscheme([x^2 + y*z, 2*y*z, 3*x*y])
sage: X.global_height()                                                     #␣
↪needs sage.libs.singular
0.000000000000000
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> NF = NumberField(x**Integer(2) - Integer(5), names=('a',)); (a,) = NF._
↪first_ngens(1)
>>> P = ProjectiveSpace(NF, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> X = P.subscheme([x**Integer(2) + y*z, Integer(2)*y*z, Integer(3)*x*y])
>>> X.global_height()                                                       #␣
↪needs sage.libs.singular
0.000000000000000
```

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: X = P.subscheme([z^2 - 101*y^2 - 3*x*z])
sage: X.global_height()             # long time                             #␣
↪needs sage.libs.singular
4.61512051684126
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
```

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```
>>> X = P.subscheme([z**Integer(2) - Integer(101)*y**Integer(2) -␣
↪Integer(3)*x*z])
>>> X.global_height()              # long time                              #␣
↪needs sage.libs.singular
4.61512051684126
```

local_height(*v*, *prec=None*)

Return the (projective) local height of the subscheme.

INPUT:

- `v` – a prime or prime ideal of the base ring
- `prec` – desired floating point precision (default: default `RealField` precision)

OUTPUT: a real number

EXAMPLES:

```
sage: # needs sage.rings.number_field
sage: R.<x> = QQ[]
sage: NF.<a> = NumberField(x^2 - 5)
sage: I = NF.ideal(3)
sage: P.<x,y,z> = ProjectiveSpace(NF, 2)
sage: X = P.subscheme([3*x*y - 5*x*z, y^2])
sage: X.local_height(I)                                                    #␣
↪needs sage.libs.singular
0.000000000000000
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> NF = NumberField(x**Integer(2) - Integer(5), names=('a',)); (a,) = NF._
↪first_ngens(1)
>>> I = NF.ideal(Integer(3))
>>> P = ProjectiveSpace(NF, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> X = P.subscheme([Integer(3)*x*y - Integer(5)*x*z, y**Integer(2)])
>>> X.local_height(I)                                                      #␣
↪needs sage.libs.singular
0.000000000000000
```

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: X = P.subscheme([z^2 - 101*y^2 - 3*x*z])
sage: X.local_height(2)                                                    #␣
↪needs sage.libs.singular
0.000000000000000
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> X = P.subscheme([z**Integer(2) - Integer(101)*y**Integer(2) -␣
↪Integer(3)*x*z])
>>> X.local_height(Integer(2))                                               ␣
```

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```
↪     # needs sage.libs.singular
0.000000000000000
```

local_height_arch(*i*, *prec=None*)

Return the local height at the `i`-th infinite place of the subscheme.

INPUT:

- `i` – integer
- `prec` – desired floating point precision (default: default `RealField` precision)

OUTPUT: a real number

EXAMPLES:

```
sage: # needs sage.rings.number_field
sage: R.<x> = QQ[]
sage: NF.<a> = NumberField(x^2 - 5)
sage: P.<x,y,z> = ProjectiveSpace(NF, 2)
sage: X = P.subscheme([x^2 + y*z, 3*x*y])
sage: X.local_height_arch(1)                                                #␣
↪needs sage.libs.singular
0.00000000000000000000000000000000
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> NF = NumberField(x**Integer(2) - Integer(5), names=('a',)); (a,) = NF._
↪first_ngens(1)
>>> P = ProjectiveSpace(NF, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> X = P.subscheme([x**Integer(2) + y*z, Integer(3)*x*y])
>>> X.local_height_arch(Integer(1))                                          ␣
↪     # needs sage.libs.singular
0.00000000000000000000000000000000
```

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: X = P.subscheme([z^2 - 101*y^2 - 3*x*z])
sage: X.local_height_arch(1)                                                #␣
↪needs sage.libs.singular
4.61512051684126
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> X = P.subscheme([z**Integer(2) - Integer(101)*y**Integer(2) -␣
↪Integer(3)*x*z])
>>> X.local_height_arch(Integer(1))                                          ␣
↪     # needs sage.libs.singular
4.61512051684126
```

14.5 Enumeration of rational points on projective schemes

Naive algorithms for enumerating rational points over **Q** or finite fields over for general schemes.

Warning

Incorrect results and infinite loops may occur if using a wrong function. (For instance using an affine function for a projective scheme or a finite field function for a scheme defined over an infinite field.)

EXAMPLES:

Projective, over **Q**:

```
sage: from sage.schemes.projective.projective_rational_point import enum_projective_
↪rational_field
sage: P.<X,Y,Z> = ProjectiveSpace(2, QQ)
sage: C = P.subscheme([X + Y - Z])
sage: enum_projective_rational_field(C, 3)
[(-2 : 3 : 1), (-1 : 1 : 0), (-1 : 2 : 1), (-1/2 : 3/2 : 1),
 (0 : 1 : 1), (1/3 : 2/3 : 1), (1/2 : 1/2 : 1), (2/3 : 1/3 : 1),
 (1 : 0 : 1), (3/2 : -1/2 : 1), (2 : -1 : 1), (3 : -2 : 1)]
```

```
>>> from sage.all import *
>>> from sage.schemes.projective.projective_rational_point import enum_projective_
↪rational_field
>>> P = ProjectiveSpace(Integer(2), QQ, names=('X', 'Y', 'Z',)); (X, Y, Z,) = P._
↪first_ngens(3)
>>> C = P.subscheme([X + Y - Z])
>>> enum_projective_rational_field(C, Integer(3))
[(-2 : 3 : 1), (-1 : 1 : 0), (-1 : 2 : 1), (-1/2 : 3/2 : 1),
 (0 : 1 : 1), (1/3 : 2/3 : 1), (1/2 : 1/2 : 1), (2/3 : 1/3 : 1),
 (1 : 0 : 1), (3/2 : -1/2 : 1), (2 : -1 : 1), (3 : -2 : 1)]
```

Projective over a finite field:

```
sage: from sage.schemes.projective.projective_rational_point import enum_projective_
↪finite_field
sage: E = EllipticCurve('72').change_ring(GF(19))                                #␣
↪needs sage.schemes
sage: enum_projective_finite_field(E)                                            #␣
↪needs sage.schemes
[(0 : 1 : 0), (1 : 0 : 1), (3 : 0 : 1), (4 : 9 : 1), (4 : 10 : 1),
 (6 : 6 : 1), (6 : 13 : 1), (7 : 6 : 1), (7 : 13 : 1), (9 : 4 : 1),
 (9 : 15 : 1), (12 : 8 : 1), (12 : 11 : 1), (13 : 8 : 1), (13 : 11 : 1),
 (14 : 3 : 1), (14 : 16 : 1), (15 : 0 : 1), (16 : 9 : 1), (16 : 10 : 1),
 (17 : 7 : 1), (17 : 12 : 1), (18 : 9 : 1), (18 : 10 : 1)]
```

```
>>> from sage.all import *
>>> from sage.schemes.projective.projective_rational_point import enum_projective_
↪finite_field
>>> E = EllipticCurve('72').change_ring(GF(Integer(19)))                         ␣
↪     # needs sage.schemes
```

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```
>>> enum_projective_finite_field(E)                                    #␣
↪needs sage.schemes
[(0 : 1 : 0), (1 : 0 : 1), (3 : 0 : 1), (4 : 9 : 1), (4 : 10 : 1),
 (6 : 6 : 1), (6 : 13 : 1), (7 : 6 : 1), (7 : 13 : 1), (9 : 4 : 1),
 (9 : 15 : 1), (12 : 8 : 1), (12 : 11 : 1), (13 : 8 : 1), (13 : 11 : 1),
 (14 : 3 : 1), (14 : 16 : 1), (15 : 0 : 1), (16 : 9 : 1), (16 : 10 : 1),
 (17 : 7 : 1), (17 : 12 : 1), (18 : 9 : 1), (18 : 10 : 1)]
```

AUTHORS:

- David R. Kohel <kohel@maths.usyd.edu.au>: original version.
- John Cremona and Charlie Turner <charlotteturner@gmail.com> (06-2010): improvements to clarity and documentation.
- Raghukul Raman <raghukul.raman01@gmail.com> (2018): Added sieve algorithm

`sage.schemes.projective.projective_rational_point.`**`enum_projective_finite_field`**`(X)`

Enumerates projective points on scheme `X` defined over a finite field.

INPUT:

- `X` – a scheme defined over a finite field or a set of abstract rational points of such a scheme

OUTPUT:

A list containing the projective points of `X` over the finite field, sorted.

EXAMPLES:

```
sage: from sage.schemes.projective.projective_rational_point import enum_
↪projective_finite_field
sage: F = GF(53)
sage: P.<X,Y,Z> = ProjectiveSpace(2, F)
sage: len(enum_projective_finite_field(P(F)))
2863
sage: 53^2 + 53 + 1
2863
```

```
>>> from sage.all import *
>>> from sage.schemes.projective.projective_rational_point import enum_projective_
↪finite_field
>>> F = GF(Integer(53))
>>> P = ProjectiveSpace(Integer(2), F, names=('X', 'Y', 'Z',)); (X, Y, Z,) = P._
↪first_ngens(3)
>>> len(enum_projective_finite_field(P(F)))
2863
>>> Integer(53)**Integer(2) + Integer(53) + Integer(1)
2863
```

```
sage: # needs sage.rings.finite_rings
sage: F = GF(9, 'a')
sage: P.<X,Y,Z> = ProjectiveSpace(2,F)
sage: C = Curve(X^3 - Y^3 + Z^2*Y)                                     #␣
↪needs sage.schemes
sage: enum_projective_finite_field(C(F))                               #␣
```

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```
↪needs sage.schemes
[(0 : 0 : 1), (0 : 1 : 1), (0 : 2 : 1), (1 : 1 : 0), (a + 1 : 2*a : 1),
 (a + 1 : 2*a + 1 : 1), (a + 1 : 2*a + 2 : 1), (2*a + 2 : a : 1),
 (2*a + 2 : a + 1 : 1), (2*a + 2 : a + 2 : 1)]
```

```
>>> from sage.all import *
>>> # needs sage.rings.finite_rings
>>> F = GF(Integer(9), 'a')
>>> P = ProjectiveSpace(Integer(2),F, names=('X', 'Y', 'Z',)); (X, Y, Z,) = P._
↪first_ngens(3)
>>> C = Curve(X**Integer(3) - Y**Integer(3) + Z**Integer(2)*Y)                  ␣
↪                          # needs sage.schemes
>>> enum_projective_finite_field(C(F))                                          #␣
↪needs sage.schemes
[(0 : 0 : 1), (0 : 1 : 1), (0 : 2 : 1), (1 : 1 : 0), (a + 1 : 2*a : 1),
 (a + 1 : 2*a + 1 : 1), (a + 1 : 2*a + 2 : 1), (2*a + 2 : a : 1),
 (2*a + 2 : a + 1 : 1), (2*a + 2 : a + 2 : 1)]
```

```
sage: F = GF(5)
sage: P2F.<X,Y,Z> = ProjectiveSpace(2, F)
sage: enum_projective_finite_field(P2F)
[(0 : 0 : 1), (0 : 1 : 0), (0 : 1 : 1), (0 : 2 : 1), (0 : 3 : 1), (0 : 4 : 1),
 (1 : 0 : 0), (1 : 0 : 1), (1 : 1 : 0), (1 : 1 : 1), (1 : 2 : 1), (1 : 3 : 1),
 (1 : 4 : 1), (2 : 0 : 1), (2 : 1 : 0), (2 : 1 : 1), (2 : 2 : 1), (2 : 3 : 1),
 (2 : 4 : 1), (3 : 0 : 1), (3 : 1 : 0), (3 : 1 : 1), (3 : 2 : 1), (3 : 3 : 1),
 (3 : 4 : 1), (4 : 0 : 1), (4 : 1 : 0), (4 : 1 : 1), (4 : 2 : 1), (4 : 3 : 1),
 (4 : 4 : 1)]
```

```
>>> from sage.all import *
>>> F = GF(Integer(5))
>>> P2F = ProjectiveSpace(Integer(2), F, names=('X', 'Y', 'Z',)); (X, Y, Z,) =␣
↪P2F._first_ngens(3)
>>> enum_projective_finite_field(P2F)
[(0 : 0 : 1), (0 : 1 : 0), (0 : 1 : 1), (0 : 2 : 1), (0 : 3 : 1), (0 : 4 : 1),
 (1 : 0 : 0), (1 : 0 : 1), (1 : 1 : 0), (1 : 1 : 1), (1 : 2 : 1), (1 : 3 : 1),
 (1 : 4 : 1), (2 : 0 : 1), (2 : 1 : 0), (2 : 1 : 1), (2 : 2 : 1), (2 : 3 : 1),
 (2 : 4 : 1), (3 : 0 : 1), (3 : 1 : 0), (3 : 1 : 1), (3 : 2 : 1), (3 : 3 : 1),
 (3 : 4 : 1), (4 : 0 : 1), (4 : 1 : 0), (4 : 1 : 1), (4 : 2 : 1), (4 : 3 : 1),
 (4 : 4 : 1)]
```

ALGORITHM:

Checks all points in projective space to see if they lie on X.

Warning

If X is defined over an infinite field, this code will not finish!

AUTHORS:

- John Cremona and Charlie Turner (06-2010).

sage.schemes.projective.projective_rational_point.**enum_projective_number_field**(*X*, ****kwds*)

Enumerates projective points on scheme X defined over a number field.

Simply checks all of the points of absolute height of at most B and adds those that are on the scheme to the list.

This algorithm computes 2 lists: L containing elements x in K such that H_k(x) <= B, and a list L' containing elements x in K that, due to floating point issues, may be slightly larger then the bound. This can be controlled by lowering the tolerance.

ALGORITHM:

This is an implementation of the revised algorithm (Algorithm 4) in [DK2013]. Algorithm 5 is used for imaginary quadratic fields.

INPUT: keyword arguments:

- bound – a real number
- tolerance – a rational number in (0,1] used in Doyle-Krumm algorithm-4
- precision – the precision to use for computing the elements of bounded height of number fields

OUTPUT: a sorted list containing the projective points of X of absolute height up to B

EXAMPLES:

```
sage: # needs sage.rings.number_field
sage: from sage.schemes.projective.projective_rational_point import enum_
↪projective_number_field
sage: u = QQ['u'].0
sage: K = NumberField(u^3 - 5, 'v')
sage: P.<x,y,z> = ProjectiveSpace(K, 2)
sage: X = P.subscheme([x - y])
sage: enum_projective_number_field(X(K), bound=RR(5^(1/3)), prec=2^10)          #␣
↪needs sage.symbolic
[(0 : 0 : 1), (1 : 1 : 0), (-1 : -1 : 1), (1 : 1 : 1)]
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> from sage.schemes.projective.projective_rational_point import enum_projective_
↪number_field
>>> u = QQ['u'].gen(0)
>>> K = NumberField(u**Integer(3) - Integer(5), 'v')
>>> P = ProjectiveSpace(K, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) = P._
↪first_ngens(3)
>>> X = P.subscheme([x - y])
>>> enum_projective_number_field(X(K), bound=RR(Integer(5)**(Integer(1)/
↪Integer(3))), prec=Integer(2)**Integer(10))          # needs sage.symbolic
[(0 : 0 : 1), (1 : 1 : 0), (-1 : -1 : 1), (1 : 1 : 1)]
```

```
sage: # needs sage.rings.number_field
sage: u = QQ['u'].0
sage: K = NumberField(u^2 + 3, 'v')
sage: A.<x,y> = ProjectiveSpace(K, 1)
sage: X = A.subscheme(x - y)
sage: enum_projective_number_field(X, bound=2)
[(1 : 1)]
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> u = QQ['u'].gen(0)
>>> K = NumberField(u**Integer(2) + Integer(3), 'v')
>>> A = ProjectiveSpace(K, Integer(1), names=('x', 'y',)); (x, y,) = A._first_
↪ngens(2)
>>> X = A.subscheme(x - y)
>>> enum_projective_number_field(X, bound=Integer(2))
[(1 : 1)]
```

sage.schemes.projective.projective_rational_point.**enum_projective_rational_field**(*X*, *B*)

Enumerates projective, rational points on scheme X of height up to bound B.

INPUT:

- X – a scheme or set of abstract rational points of a scheme
- B – a positive integer bound

OUTPUT:

A list containing the projective points of X of height up to B, sorted.

EXAMPLES:

```
sage: P.<X,Y,Z> = ProjectiveSpace(2, QQ)
sage: C = P.subscheme([X + Y - Z])
sage: from sage.schemes.projective.projective_rational_point import enum_
↪projective_rational_field
sage: enum_projective_rational_field(C(QQ), 6)
[(-5 : 6 : 1), (-4 : 5 : 1), (-3 : 4 : 1), (-2 : 3 : 1),
 (-3/2 : 5/2 : 1), (-1 : 1 : 0), (-1 : 2 : 1), (-2/3 : 5/3 : 1),
 (-1/2 : 3/2 : 1), (-1/3 : 4/3 : 1), (-1/4 : 5/4 : 1),
 (-1/5 : 6/5 : 1), (0 : 1 : 1), (1/6 : 5/6 : 1), (1/5 : 4/5 : 1),
 (1/4 : 3/4 : 1), (1/3 : 2/3 : 1), (2/5 : 3/5 : 1), (1/2 : 1/2 : 1),
 (3/5 : 2/5 : 1), (2/3 : 1/3 : 1), (3/4 : 1/4 : 1), (4/5 : 1/5 : 1),
 (5/6 : 1/6 : 1), (1 : 0 : 1), (6/5 : -1/5 : 1), (5/4 : -1/4 : 1),
 (4/3 : -1/3 : 1), (3/2 : -1/2 : 1), (5/3 : -2/3 : 1), (2 : -1 : 1),
 (5/2 : -3/2 : 1), (3 : -2 : 1), (4 : -3 : 1), (5 : -4 : 1),
 (6 : -5 : 1)]
sage: enum_projective_rational_field(C,6) == enum_projective_rational_field(C(QQ),
↪6)
True
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(Integer(2), QQ, names=('X', 'Y', 'Z',)); (X, Y, Z,) = P._
↪first_ngens(3)
>>> C = P.subscheme([X + Y - Z])
>>> from sage.schemes.projective.projective_rational_point import enum_projective_
↪rational_field
>>> enum_projective_rational_field(C(QQ), Integer(6))
[(-5 : 6 : 1), (-4 : 5 : 1), (-3 : 4 : 1), (-2 : 3 : 1),
 (-3/2 : 5/2 : 1), (-1 : 1 : 0), (-1 : 2 : 1), (-2/3 : 5/3 : 1),
 (-1/2 : 3/2 : 1), (-1/3 : 4/3 : 1), (-1/4 : 5/4 : 1),
 (-1/5 : 6/5 : 1), (0 : 1 : 1), (1/6 : 5/6 : 1), (1/5 : 4/5 : 1),
```

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```
 (1/4 : 3/4 : 1), (1/3 : 2/3 : 1), (2/5 : 3/5 : 1), (1/2 : 1/2 : 1),
 (3/5 : 2/5 : 1), (2/3 : 1/3 : 1), (3/4 : 1/4 : 1), (4/5 : 1/5 : 1),
 (5/6 : 1/6 : 1), (1 : 0 : 1), (6/5 : -1/5 : 1), (5/4 : -1/4 : 1),
 (4/3 : -1/3 : 1), (3/2 : -1/2 : 1), (5/3 : -2/3 : 1), (2 : -1 : 1),
 (5/2 : -3/2 : 1), (3 : -2 : 1), (4 : -3 : 1), (5 : -4 : 1),
 (6 : -5 : 1)]
>>> enum_projective_rational_field(C,Integer(6)) == enum_projective_rational_
↪field(C(QQ),Integer(6))
True
```

```
sage: P3.<W,X,Y,Z> = ProjectiveSpace(3, QQ)
sage: enum_projective_rational_field(P3, 1)
[(-1 : -1 : -1 : 1), (-1 : -1 : 0 : 1), (-1 : -1 : 1 : 0), (-1 : -1 : 1 : 1),
 (-1 : 0 : -1 : 1), (-1 : 0 : 0 : 1), (-1 : 0 : 1 : 0), (-1 : 0 : 1 : 1),
 (-1 : 1 : -1 : 1), (-1 : 1 : 0 : 0), (-1 : 1 : 0 : 1), (-1 : 1 : 1 : 0),
 (-1 : 1 : 1 : 1), (0 : -1 : -1 : 1), (0 : -1 : 0 : 1), (0 : -1 : 1 : 0),
 (0 : -1 : 1 : 1), (0 : 0 : -1 : 1), (0 : 0 : 0 : 1), (0 : 0 : 1 : 0),
 (0 : 0 : 1 : 1), (0 : 1 : -1 : 1), (0 : 1 : 0 : 0), (0 : 1 : 0 : 1),
 (0 : 1 : 1 : 0), (0 : 1 : 1 : 1), (1 : -1 : -1 : 1), (1 : -1 : 0 : 1),
 (1 : -1 : 1 : 0), (1 : -1 : 1 : 1), (1 : 0 : -1 : 1), (1 : 0 : 0 : 0),
 (1 : 0 : 0 : 1), (1 : 0 : 1 : 0), (1 : 0 : 1 : 1), (1 : 1 : -1 : 1),
 (1 : 1 : 0 : 0), (1 : 1 : 0 : 1), (1 : 1 : 1 : 0), (1 : 1 : 1 : 1)]
```

```
>>> from sage.all import *
>>> P3 = ProjectiveSpace(Integer(3), QQ, names=('W', 'X', 'Y', 'Z',)); (W, X, Y,␣
↪Z,) = P3._first_ngens(4)
>>> enum_projective_rational_field(P3, Integer(1))
[(-1 : -1 : -1 : 1), (-1 : -1 : 0 : 1), (-1 : -1 : 1 : 0), (-1 : -1 : 1 : 1),
 (-1 : 0 : -1 : 1), (-1 : 0 : 0 : 1), (-1 : 0 : 1 : 0), (-1 : 0 : 1 : 1),
 (-1 : 1 : -1 : 1), (-1 : 1 : 0 : 0), (-1 : 1 : 0 : 1), (-1 : 1 : 1 : 0),
 (-1 : 1 : 1 : 1), (0 : -1 : -1 : 1), (0 : -1 : 0 : 1), (0 : -1 : 1 : 0),
 (0 : -1 : 1 : 1), (0 : 0 : -1 : 1), (0 : 0 : 0 : 1), (0 : 0 : 1 : 0),
 (0 : 0 : 1 : 1), (0 : 1 : -1 : 1), (0 : 1 : 0 : 0), (0 : 1 : 0 : 1),
 (0 : 1 : 1 : 0), (0 : 1 : 1 : 1), (1 : -1 : -1 : 1), (1 : -1 : 0 : 1),
 (1 : -1 : 1 : 0), (1 : -1 : 1 : 1), (1 : 0 : -1 : 1), (1 : 0 : 0 : 0),
 (1 : 0 : 0 : 1), (1 : 0 : 1 : 0), (1 : 0 : 1 : 1), (1 : 1 : -1 : 1),
 (1 : 1 : 0 : 0), (1 : 1 : 0 : 1), (1 : 1 : 1 : 0), (1 : 1 : 1 : 1)]
```

ALGORITHM:

We just check all possible projective points in correct dimension of projective space to see if they lie on `X`.

AUTHORS:

- John Cremona and Charlie Turner (06-2010)

`sage.schemes.projective.projective_rational_point.`**`sieve`**(*X*, *bound*)

Return the list of all projective, rational points on scheme `X` of height up to `bound`.

Height of a projective point $X = (x_1, x_2, \ldots, x_n)$ is given by $H_X = \max(y_1, y_2, \ldots, y_n)$, where the values y_i are the normalized coordinates such that all y_i are integers and $\gcd(y_1, y_2, \ldots, y_n) = 1$.

ALGORITHM:

Main idea behind the algorithm is to find points modulo primes and then reconstruct them using chinese remainder theorem. We find modulo primes parallelly and then lift them and apply LLL in parallel.

For the algorithm to work correctly, sufficient primes need to be present, these are calculated using the bound given in this([Hutz2015]) paper.

INPUT:

- `X` – a scheme with ambient space defined over projective space
- `bound` – positive integer bound

OUTPUT:

A list containing the projective rational points of `X` of height up to `bound`, sorted

EXAMPLES:

```
sage: from sage.schemes.projective.projective_rational_point import sieve
sage: P.<x,y,z,q> = ProjectiveSpace(QQ, 3)
sage: Y = P.subscheme([x^2 - 3^2*y^2 + z*q, x + z + 4*q])
sage: sorted(sieve(Y, 12))              # long time                          #␣
↪needs sage.libs.singular
[(-4 : -4/3 : 0 : 1), (-4 : 4/3 : 0 : 1),
 (-1 : -1/3 : 1 : 0), (-1 : 1/3 : 1 : 0)]
```

```
>>> from sage.all import *
>>> from sage.schemes.projective.projective_rational_point import sieve
>>> P = ProjectiveSpace(QQ, Integer(3), names=('x', 'y', 'z', 'q',)); (x, y, z, q,
↪) = P._first_ngens(4)
>>> Y = P.subscheme([x**Integer(2) - Integer(3)**Integer(2)*y**Integer(2) + z*q,␣
↪x + z + Integer(4)*q])
>>> sorted(sieve(Y, Integer(12)))              # long time                      ␣
↪     # needs sage.libs.singular
[(-4 : -4/3 : 0 : 1), (-4 : 4/3 : 0 : 1),
 (-1 : -1/3 : 1 : 0), (-1 : 1/3 : 1 : 0)]
```

```
sage: from sage.schemes.projective.projective_rational_point import sieve
sage: E = EllipticCurve('37a')                                             #␣
↪needs sage.schemes
sage: sorted(sieve(E, 14))              # long time                          #␣
↪needs sage.libs.singular sage.schemes
[(0 : 1 : 0),
 (-1 : -1 : 1),
 (-1 : 0 : 1),
 (0 : -1 : 1),
 (0 : 0 : 1),
 (1/4 : -5/8 : 1),
 (1/4 : -3/8 : 1),
 (1 : -1 : 1),
 (1 : 0 : 1),
 (2 : -3 : 1),
 (2 : 2 : 1),
 (6 : 14 : 1)]
```

```
>>> from sage.all import *
>>> from sage.schemes.projective.projective_rational_point import sieve
>>> E = EllipticCurve('37a')                                               #␣
↪needs sage.schemes
```

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```
>>> sorted(sieve(E, Integer(14)))              # long time
↪     # needs sage.libs.singular sage.schemes
[(0 : 1 : 0),
 (-1 : -1 : 1),
 (-1 : 0 : 1),
 (0 : -1 : 1),
 (0 : 0 : 1),
 (1/4 : -5/8 : 1),
 (1/4 : -3/8 : 1),
 (1 : -1 : 1),
 (1 : 0 : 1),
 (2 : -3 : 1),
 (2 : 2 : 1),
 (6 : 14 : 1)]
```

14.6 Set of homomorphisms between two projective schemes

For schemes X and Y, this module implements the set of morphisms $Hom(X, Y)$. This is done by *SchemeHomset_generic*.

As a special case, the Hom-sets can also represent the points of a scheme. Recall that the K-rational points of a scheme X over k can be identified with the set of morphisms $Spec(K) \to X$. In Sage the rational points are implemented by such scheme morphisms. This is done by *SchemeHomset_points* and its subclasses.

Note

You should not create the Hom-sets manually. Instead, use the `Hom()` method that is inherited by all schemes.

AUTHORS:

- William Stein (2006): initial version.
- Volker Braun (2011-08-11): significant improvement and refactoring.
- Ben Hutz (June 2012): added support for projective ring
- Ben Hutz (2018): add numerical point support

class sage.schemes.projective.projective_homset.**SchemeHomset_points_abelian_variety_field**(*X*, *Y*, *category=None*, *check=True*, *base=Integer Ring*)

Bases: *SchemeHomset_points_projective_field*

Set of rational points of an Abelian variety.

INPUT:

See *SchemeHomset_generic*.

base_extend(*R*)

Extend the base ring.

This is currently not implemented except for the trivial case `R==ZZ`.

INPUT:

- `R` – a ring

EXAMPLES:

```
sage: # needs sage.schemes
sage: E = EllipticCurve('37a')
sage: Hom = E.point_homset();  Hom
Abelian group of points on Elliptic Curve defined
 by y^2 + y = x^3 - x over Rational Field
sage: Hom.base_ring()
Rational Field
sage: Hom.base_extend(QQ)
Traceback (most recent call last):
...
NotImplementedError: Abelian variety point sets are not
implemented as modules over rings other than ZZ
```

```
>>> from sage.all import *
>>> # needs sage.schemes
>>> E = EllipticCurve('37a')
>>> Hom = E.point_homset();  Hom
Abelian group of points on Elliptic Curve defined
 by y^2 + y = x^3 - x over Rational Field
>>> Hom.base_ring()
Rational Field
>>> Hom.base_extend(QQ)
Traceback (most recent call last):
...
NotImplementedError: Abelian variety point sets are not
implemented as modules over rings other than ZZ
```

zero()

Return the neutral element in this group of points.

EXAMPLES:

```
sage: S = EllipticCurve(GF(5), [1,1]).point_homset()
sage: S.zero()
(0 : 1 : 0)
sage: S = EllipticCurve(Zmod(15), [1,1]).point_homset()
sage: S.zero()
(0 : 1 : 0)
```

```
>>> from sage.all import *
>>> S = EllipticCurve(GF(Integer(5)), [Integer(1),Integer(1)]).point_homset()
>>> S.zero()
(0 : 1 : 0)
>>> S = EllipticCurve(Zmod(Integer(15)), [Integer(1),Integer(1)]).point_
```

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```
↪homset()
>>> S.zero()
(0 : 1 : 0)
```

class sage.schemes.projective.projective_homset.**SchemeHomset_points_projective_field**(*X*, *Y*, *category=None*, *check=True*, *base=Integer Ring*)

Bases: *SchemeHomset_points*

Set of rational points of a projective variety over a field.

INPUT:

See *SchemeHomset_generic*.

EXAMPLES:

```
sage: from sage.schemes.projective.projective_homset import SchemeHomset_points_
↪projective_field
sage: SchemeHomset_points_projective_field(Spec(QQ), ProjectiveSpace(QQ,2))
Set of rational points of Projective Space of dimension 2 over Rational Field
```

```
>>> from sage.all import *
>>> from sage.schemes.projective.projective_homset import SchemeHomset_points_
↪projective_field
>>> SchemeHomset_points_projective_field(Spec(QQ), ProjectiveSpace(QQ,Integer(2)))
Set of rational points of Projective Space of dimension 2 over Rational Field
```

numerical_points(*F=None*, ***kwds*)

Return some or all numerical approximations of rational points of a projective scheme.

This is for dimension 0 subschemes only and the points are determined through a groebner calculation over the base ring and then numerically approximating the roots of the resulting polynomials. If the base ring is a number field, the embedding into `F` must be known.

INPUT:

- `F` – numerical ring

kwds:

- `point_tolerance` – positive real number (default: 10^{-10}). For numerically inexact fields, two points are considered the same if their coordinates are within tolerance.
- `zero_tolerance` – positive real number (default: 10^{-10}). For numerically inexact fields, points are on the subscheme if they satisfy the equations to within tolerance.

OUTPUT: list of points in the ambient space

Warning

For numerically inexact fields the list of points returned may contain repeated or be missing points due to tolerance.

EXAMPLES:

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: E = P.subscheme([y^3 - x^3 - x*z^2, x*y*z])
sage: L = E(QQ).numerical_points(F=RR); L                                    #␣
↪needs sage.libs.singular
[(0.000000000000000 : 0.000000000000000 : 1.00000000000000),
 (1.00000000000000 : 1.00000000000000 : 0.000000000000000)]
sage: L[0].codomain()                                                        #␣
↪needs sage.libs.singular
Projective Space of dimension 2 over Real Field with 53 bits of precision
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> E = P.subscheme([y**Integer(3) - x**Integer(3) - x*z**Integer(2), x*y*z])
>>> L = E(QQ).numerical_points(F=RR); L                                      #␣
↪needs sage.libs.singular
[(0.000000000000000 : 0.000000000000000 : 1.00000000000000),
 (1.00000000000000 : 1.00000000000000 : 0.000000000000000)]
>>> L[Integer(0)].codomain()                                                 ␣
↪     # needs sage.libs.singular
Projective Space of dimension 2 over Real Field with 53 bits of precision
```

```
sage: S.<a> = QQ[]
sage: K.<v> = NumberField(a^5 - 7, embedding=CC(7)**(1/5))                   #␣
↪needs sage.rings.number_field
sage: P.<x,y,z> = ProjectiveSpace(K, 2)                                      #␣
↪needs sage.rings.number_field
sage: X = P.subscheme([x^2 - v^2*z^2, y - v*z])                              #␣
↪needs sage.rings.number_field
sage: len(X(K).numerical_points(F=CDF))                                      #␣
↪needs sage.libs.singular sage.rings.number_field
2
```

```
>>> from sage.all import *
>>> S = QQ['a']; (a,) = S._first_ngens(1)
>>> K = NumberField(a**Integer(5) - Integer(7),␣
↪embedding=CC(Integer(7))**(Integer(1)/Integer(5)), names=('v',)); (v,) = K._
↪first_ngens(1)# needs sage.rings.number_field
>>> P = ProjectiveSpace(K, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)# needs sage.rings.number_field
>>> X = P.subscheme([x**Integer(2) - v**Integer(2)*z**Integer(2), y - v*z])  ␣
↪                            # needs sage.rings.number_field
>>> len(X(K).numerical_points(F=CDF))                                        #␣
↪needs sage.libs.singular sage.rings.number_field
2
```

```
sage: P.<x1, x2, x3> = ProjectiveSpace(QQ, 2)
sage: E = P.subscheme([3000*x1^50 + 9875643*x2^2*x3^48 + 12334545*x2^50, x1 +␣
↪x2])
sage: len(E(P.base_ring()).numerical_points(F=CDF, zero_tolerance=1e-6))    #␣
↪needs sage.libs.singular
49
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x1', 'x2', 'x3',)); (x1, x2,␣
↪x3,) = P._first_ngens(3)
>>> E = P.subscheme([Integer(3000)*x1**Integer(50) +␣
↪Integer(9875643)*x2**Integer(2)*x3**Integer(48) +␣
↪Integer(12334545)*x2**Integer(50), x1 + x2])
>>> len(E(P.base_ring()).numerical_points(F=CDF, zero_tolerance=RealNumber(
↪'1e-6')))    # needs sage.libs.singular
49
```

points(***kwds*)

Return some or all rational points of a projective scheme.

For dimension 0 subschemes points are determined through a groebner basis calculation. For schemes or subschemes with dimension greater than 1 points are determined through enumeration up to the specified bound.

INPUT: keyword arguments:

- `bound` – real number (default: 0); the bound for the coordinates for subschemes with dimension at least 1
- `precision` – integer (default: 53); the precision to use to compute the elements of bounded height for number fields
- `point_tolerance` – positive real number (default: 10^{-10}); for numerically inexact fields, two points are considered the same if their coordinates are within tolerance
- `zero_tolerance` – positive real number (default: 10^{-10}); for numerically inexact fields, points are on the subscheme if they satisfy the equations to within tolerance
- `tolerance` – a rational number in (0,1] used in Doyle-Krumm algorithm-4 for enumeration over number fields

OUTPUT: list of rational points of a projective scheme

Warning

For numerically inexact fields such as ComplexField or RealField the list of points returned is very likely to be incomplete. It may also contain repeated points due to tolerances.

EXAMPLES:

```
sage: P.<x,y> = ProjectiveSpace(QQ, 1)
sage: P(QQ).points(bound=4)
[(-4 : 1), (-3 : 1), (-2 : 1), (-3/2 : 1), (-4/3 : 1), (-1 : 1),
 (-3/4 : 1), (-2/3 : 1), (-1/2 : 1), (-1/3 : 1), (-1/4 : 1), (0 : 1),
 (1/4 : 1), (1/3 : 1), (1/2 : 1), (2/3 : 1), (3/4 : 1), (1 : 0), (1 : 1),
 (4/3 : 1), (3/2 : 1), (2 : 1), (3 : 1), (4 : 1)]
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(1), names=('x', 'y',)); (x, y,) = P._
↪first_ngens(2)
>>> P(QQ).points(bound=Integer(4))
[(-4 : 1), (-3 : 1), (-2 : 1), (-3/2 : 1), (-4/3 : 1), (-1 : 1),
 (-3/4 : 1), (-2/3 : 1), (-1/2 : 1), (-1/3 : 1), (-1/4 : 1), (0 : 1),
 (1/4 : 1), (1/3 : 1), (1/2 : 1), (2/3 : 1), (3/4 : 1), (1 : 0), (1 : 1),
 (4/3 : 1), (3/2 : 1), (2 : 1), (3 : 1), (4 : 1)]
```

```
sage: u = QQ['u'].0
sage: K.<v> = NumberField(u^2 + 3)                                          #␣
↪needs sage.rings.number_field
sage: P.<x,y,z> = ProjectiveSpace(K, 2)                                     #␣
↪needs sage.rings.number_field
sage: len(P(K).points(bound=1.8))                                           #␣
↪needs sage.rings.number_field
309
```

```
>>> from sage.all import *
>>> u = QQ['u'].gen(0)
>>> K = NumberField(u**Integer(2) + Integer(3), names=('v',)); (v,) = K._
↪first_ngens(1)# needs sage.rings.number_field
>>> P = ProjectiveSpace(K, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)# needs sage.rings.number_field
>>> len(P(K).points(bound=RealNumber('1.8')))                                ␣
↪          # needs sage.rings.number_field
309
```

```
sage: P1 = ProjectiveSpace(GF(2), 1)
sage: F.<a> = GF(4, 'a')                                                    #␣
↪needs sage.rings.finite_rings
sage: P1(F).points()                                                        #␣
↪needs sage.libs.singular sage.rings.finite_rings
[(0 : 1), (1 : 0), (1 : 1), (a : 1), (a + 1 : 1)]
```

```
>>> from sage.all import *
>>> P1 = ProjectiveSpace(GF(Integer(2)), Integer(1))
>>> F = GF(Integer(4), 'a', names=('a',)); (a,) = F._first_ngens(1)# needs␣
↪sage.rings.finite_rings
>>> P1(F).points()                                                          #␣
↪needs sage.libs.singular sage.rings.finite_rings
[(0 : 1), (1 : 0), (1 : 1), (a : 1), (a + 1 : 1)]
```

```
sage: P.<x,y,z> = ProjectiveSpace(QQ, 2)
sage: E = P.subscheme([(y^3-y*z^2) - (x^3-x*z^2), (y^3-y*z^2) + (x^3-x*z^2)])
sage: E(P.base_ring()).points()                                             #␣
↪needs sage.libs.singular
[(-1 : -1 : 1), (-1 : 0 : 1), (-1 : 1 : 1), (0 : -1 : 1), (0 : 0 : 1),
 (0 : 1 : 1), (1 : -1 : 1), (1 : 0 : 1), (1 : 1 : 1)]
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(QQ, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> E = P.subscheme([(y**Integer(3)-y*z**Integer(2)) - (x**Integer(3)-
↪x*z**Integer(2)), (y**Integer(3)-y*z**Integer(2)) + (x**Integer(3)-
↪x*z**Integer(2))])
>>> E(P.base_ring()).points()                                                #␣
↪needs sage.libs.singular
[(-1 : -1 : 1), (-1 : 0 : 1), (-1 : 1 : 1), (0 : -1 : 1), (0 : 0 : 1),
 (0 : 1 : 1), (1 : -1 : 1), (1 : 0 : 1), (1 : 1 : 1)]
```

```
sage: # needs sage.rings.real_mpfr
sage: P.<x,y,z> = ProjectiveSpace(CC, 2)
sage: E = P.subscheme([y^3 - x^3 - x*z^2, x*y*z])
sage: L = E(P.base_ring()).points(); sorted(L, key=str)                   #␣
↪needs sage.libs.singular
verbose 0 (...: projective_homset.py, points) Warning: computations in
the numerical fields are inexact;points may be computed partially or␣
↪incorrectly.
[(-0.500000000000000 + 0.866025403784439*I : 1.00000000000000 : 0.
↪000000000000000),
 (-0.500000000000000 - 0.866025403784439*I : 1.00000000000000 : 0.
↪000000000000000),
 (-1.00000000000000*I : 0.000000000000000 : 1.00000000000000),
 (0.000000000000000 : 0.000000000000000 : 1.00000000000000),
 (1.00000000000000 : 1.00000000000000 : 0.000000000000000),
 (1.00000000000000*I : 0.000000000000000 : 1.00000000000000)]
sage: L[0].codomain()                                                     #␣
↪needs sage.libs.singular
Projective Space of dimension 2 over Complex Field with 53 bits of precision
```

```
>>> from sage.all import *
>>> # needs sage.rings.real_mpfr
>>> P = ProjectiveSpace(CC, Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> E = P.subscheme([y**Integer(3) - x**Integer(3) - x*z**Integer(2), x*y*z])
>>> L = E(P.base_ring()).points(); sorted(L, key=str)                     #␣
↪needs sage.libs.singular
verbose 0 (...: projective_homset.py, points) Warning: computations in
the numerical fields are inexact;points may be computed partially or␣
↪incorrectly.
[(-0.500000000000000 + 0.866025403784439*I : 1.00000000000000 : 0.
↪000000000000000),
 (-0.500000000000000 - 0.866025403784439*I : 1.00000000000000 : 0.
↪000000000000000),
 (-1.00000000000000*I : 0.000000000000000 : 1.00000000000000),
 (0.000000000000000 : 0.000000000000000 : 1.00000000000000),
 (1.00000000000000 : 1.00000000000000 : 0.000000000000000),
 (1.00000000000000*I : 0.000000000000000 : 1.00000000000000)]
>>> L[Integer(0)].codomain()                                                ␣
↪     # needs sage.libs.singular
Projective Space of dimension 2 over Complex Field with 53 bits of precision
```

```
sage: # needs sage.rings.complex_double
sage: P.<x,y,z> = ProjectiveSpace(CDF, 2)
sage: E = P.subscheme([y^2 + x^2 + z^2, x*y*z])
sage: len(E(P.base_ring()).points())                                    #␣
↪needs sage.libs.singular
verbose 0 (...: projective_homset.py, points) Warning: computations in
the numerical fields are inexact;points may be computed partially or␣
↪incorrectly.
6
```

```
>>> from sage.all import *
>>> # needs sage.rings.complex_double
>>> P = ProjectiveSpace(CDF, Integer(2), names=('x', 'y', 'z',)); (x, y, z,)␣
↪= P._first_ngens(3)
>>> E = P.subscheme([y**Integer(2) + x**Integer(2) + z**Integer(2), x*y*z])
>>> len(E(P.base_ring()).points())                                      #␣
↪needs sage.libs.singular
verbose 0 (...: projective_homset.py, points) Warning: computations in
the numerical fields are inexact;points may be computed partially or␣
↪incorrectly.
6
```

class sage.schemes.projective.projective_homset.**SchemeHomset_points_projective_ring**(*X*, *Y*, *category=None*, *check=True*, *base=Integer Ring*)

Bases: *SchemeHomset_points*

Set of rational points of a projective variety over a commutative ring.

INPUT:

See *SchemeHomset_generic*.

EXAMPLES:

```
sage: from sage.schemes.projective.projective_homset import SchemeHomset_points_
↪projective_ring
sage: SchemeHomset_points_projective_ring(Spec(ZZ), ProjectiveSpace(ZZ,2))
Set of rational points of Projective Space of dimension 2 over Integer Ring
```

```
>>> from sage.all import *
>>> from sage.schemes.projective.projective_homset import SchemeHomset_points_
↪projective_ring
>>> SchemeHomset_points_projective_ring(Spec(ZZ), ProjectiveSpace(ZZ,Integer(2)))
Set of rational points of Projective Space of dimension 2 over Integer Ring
```

points(*B=0*)

Return some or all rational points of a projective scheme.

INPUT:

- B – integer (default: 0); the bound for the coordinates

EXAMPLES:

```
sage: from sage.schemes.projective.projective_homset import SchemeHomset_
↪points_projective_ring
sage: H = SchemeHomset_points_projective_ring(Spec(ZZ), ProjectiveSpace(ZZ,␣
↪2))
sage: H.points(3)
[(0 : 0 : 1), (0 : 1 : -3), (0 : 1 : -2), (0 : 1 : -1), (0 : 1 : 0), (0 : 1 :␣
↪1),
 (0 : 1 : 2), (0 : 1 : 3), (0 : 2 : -3), (0 : 2 : -1), (0 : 2 : 1), (0 : 2 :␣
↪3),
 (0 : 3 : -2), (0 : 3 : -1), (0 : 3 : 1), (0 : 3 : 2), (1 : -3 : -3),
 (1 : -3 : -2), (1 : -3 : -1), (1 : -3 : 0), (1 : -3 : 1), (1 : -3 : 2),
 (1 : -3 : 3), (1 : -2 : -3), (1 : -2 : -2), (1 : -2 : -1), (1 : -2 : 0),
 (1 : -2 : 1), (1 : -2 : 2), (1 : -2 : 3), (1 : -1 : -3), (1 : -1 : -2),
 (1 : -1 : -1), (1 : -1 : 0), (1 : -1 : 1), (1 : -1 : 2), (1 : -1 : 3),
 (1 : 0 : -3), (1 : 0 : -2), (1 : 0 : -1), (1 : 0 : 0), (1 : 0 : 1), (1 : 0 :␣
↪2),
 (1 : 0 : 3), (1 : 1 : -3), (1 : 1 : -2), (1 : 1 : -1), (1 : 1 : 0), (1 : 1 :␣
↪1),
 (1 : 1 : 2), (1 : 1 : 3), (1 : 2 : -3), (1 : 2 : -2), (1 : 2 : -1), (1 : 2 :␣
↪0),
 (1 : 2 : 1), (1 : 2 : 2), (1 : 2 : 3), (1 : 3 : -3), (1 : 3 : -2), (1 : 3 : -
↪1),
 (1 : 3 : 0), (1 : 3 : 1), (1 : 3 : 2), (1 : 3 : 3), (2 : -3 : -3),
 (2 : -3 : -2), (2 : -3 : -1), (2 : -3 : 0), (2 : -3 : 1), (2 : -3 : 2),
 (2 : -3 : 3), (2 : -2 : -3), (2 : -2 : -1), (2 : -2 : 1), (2 : -2 : 3),
 (2 : -1 : -3), (2 : -1 : -2), (2 : -1 : -1), (2 : -1 : 0), (2 : -1 : 1),
 (2 : -1 : 2), (2 : -1 : 3), (2 : 0 : -3), (2 : 0 : -1), (2 : 0 : 1),
 (2 : 0 : 3), (2 : 1 : -3), (2 : 1 : -2), (2 : 1 : -1), (2 : 1 : 0), (2 : 1 :␣
↪1),
 (2 : 1 : 2), (2 : 1 : 3), (2 : 2 : -3), (2 : 2 : -1), (2 : 2 : 1), (2 : 2 :␣
↪3),
 (2 : 3 : -3), (2 : 3 : -2), (2 : 3 : -1), (2 : 3 : 0), (2 : 3 : 1), (2 : 3 :␣
↪2),
 (2 : 3 : 3), (3 : -3 : -2), (3 : -3 : -1), (3 : -3 : 1), (3 : -3 : 2),
 (3 : -2 : -3), (3 : -2 : -2), (3 : -2 : -1), (3 : -2 : 0), (3 : -2 : 1),
 (3 : -2 : 2), (3 : -2 : 3), (3 : -1 : -3), (3 : -1 : -2), (3 : -1 : -1),
 (3 : -1 : 0), (3 : -1 : 1), (3 : -1 : 2), (3 : -1 : 3), (3 : 0 : -2),
 (3 : 0 : -1), (3 : 0 : 1), (3 : 0 : 2), (3 : 1 : -3), (3 : 1 : -2),
 (3 : 1 : -1), (3 : 1 : 0), (3 : 1 : 1), (3 : 1 : 2), (3 : 1 : 3), (3 : 2 : -
↪3),
 (3 : 2 : -2), (3 : 2 : -1), (3 : 2 : 0), (3 : 2 : 1), (3 : 2 : 2), (3 : 2 :␣
↪3),
 (3 : 3 : -2), (3 : 3 : -1), (3 : 3 : 1), (3 : 3 : 2)]
```

```
>>> from sage.all import *
>>> from sage.schemes.projective.projective_homset import SchemeHomset_points_
↪projective_ring
>>> H = SchemeHomset_points_projective_ring(Spec(ZZ), ProjectiveSpace(ZZ,␣
```

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```
↪Integer(2)))
>>> H.points(Integer(3))
[(0 : 0 : 1), (0 : 1 : -3), (0 : 1 : -2), (0 : 1 : -1), (0 : 1 : 0), (0 : 1 :␣
↪1),
 (0 : 1 : 2), (0 : 1 : 3), (0 : 2 : -3), (0 : 2 : -1), (0 : 2 : 1), (0 : 2 :␣
↪3),
 (0 : 3 : -2), (0 : 3 : -1), (0 : 3 : 1), (0 : 3 : 2), (1 : -3 : -3),
 (1 : -3 : -2), (1 : -3 : -1), (1 : -3 : 0), (1 : -3 : 1), (1 : -3 : 2),
 (1 : -3 : 3), (1 : -2 : -3), (1 : -2 : -2), (1 : -2 : -1), (1 : -2 : 0),
 (1 : -2 : 1), (1 : -2 : 2), (1 : -2 : 3), (1 : -1 : -3), (1 : -1 : -2),
 (1 : -1 : -1), (1 : -1 : 0), (1 : -1 : 1), (1 : -1 : 2), (1 : -1 : 3),
 (1 : 0 : -3), (1 : 0 : -2), (1 : 0 : -1), (1 : 0 : 0), (1 : 0 : 1), (1 : 0 :␣
↪2),
 (1 : 0 : 3), (1 : 1 : -3), (1 : 1 : -2), (1 : 1 : -1), (1 : 1 : 0), (1 : 1 :␣
↪1),
 (1 : 1 : 2), (1 : 1 : 3), (1 : 2 : -3), (1 : 2 : -2), (1 : 2 : -1), (1 : 2 :␣
↪0),
 (1 : 2 : 1), (1 : 2 : 2), (1 : 2 : 3), (1 : 3 : -3), (1 : 3 : -2), (1 : 3 : -
↪1),
 (1 : 3 : 0), (1 : 3 : 1), (1 : 3 : 2), (1 : 3 : 3), (2 : -3 : -3),
 (2 : -3 : -2), (2 : -3 : -1), (2 : -3 : 0), (2 : -3 : 1), (2 : -3 : 2),
 (2 : -3 : 3), (2 : -2 : -3), (2 : -2 : -1), (2 : -2 : 1), (2 : -2 : 3),
 (2 : -1 : -3), (2 : -1 : -2), (2 : -1 : -1), (2 : -1 : 0), (2 : -1 : 1),
 (2 : -1 : 2), (2 : -1 : 3), (2 : 0 : -3), (2 : 0 : -1), (2 : 0 : 1),
 (2 : 0 : 3), (2 : 1 : -3), (2 : 1 : -2), (2 : 1 : -1), (2 : 1 : 0), (2 : 1 :␣
↪1),
 (2 : 1 : 2), (2 : 1 : 3), (2 : 2 : -3), (2 : 2 : -1), (2 : 2 : 1), (2 : 2 :␣
↪3),
 (2 : 3 : -3), (2 : 3 : -2), (2 : 3 : -1), (2 : 3 : 0), (2 : 3 : 1), (2 : 3 :␣
↪2),
 (2 : 3 : 3), (3 : -3 : -2), (3 : -3 : -1), (3 : -3 : 1), (3 : -3 : 2),
 (3 : -2 : -3), (3 : -2 : -2), (3 : -2 : -1), (3 : -2 : 0), (3 : -2 : 1),
 (3 : -2 : 2), (3 : -2 : 3), (3 : -1 : -3), (3 : -1 : -2), (3 : -1 : -1),
 (3 : -1 : 0), (3 : -1 : 1), (3 : -1 : 2), (3 : -1 : 3), (3 : 0 : -2),
 (3 : 0 : -1), (3 : 0 : 1), (3 : 0 : 2), (3 : 1 : -3), (3 : 1 : -2),
 (3 : 1 : -1), (3 : 1 : 0), (3 : 1 : 1), (3 : 1 : 2), (3 : 1 : 3), (3 : 2 : -
↪3),
 (3 : 2 : -2), (3 : 2 : -1), (3 : 2 : 0), (3 : 2 : 1), (3 : 2 : 2), (3 : 2 :␣
↪3),
 (3 : 3 : -2), (3 : 3 : -1), (3 : 3 : 1), (3 : 3 : 2)]
```

class sage.schemes.projective.projective_homset.**SchemeHomset_polynomial_projective_space**(*X*, *Y*, *category=None*, *check=True*, *base=None*)

Bases: *SchemeHomset_generic*

Set of morphisms of a projective space.

EXAMPLES:

```
sage: P.<x,y,z> = ProjectiveSpace(2, QQ)
sage: Hom(P, P)
Set of morphisms
  From: Projective Space of dimension 2 over Rational Field
  To:   Projective Space of dimension 2 over Rational Field
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(Integer(2), QQ, names=('x', 'y', 'z',)); (x, y, z,) = P._
↪first_ngens(3)
>>> Hom(P, P)
Set of morphisms
  From: Projective Space of dimension 2 over Rational Field
  To:   Projective Space of dimension 2 over Rational Field
```

identity()

Return the identity morphism of this hom-set.

EXAMPLES:

```
sage: P.<x,y,z> = ProjectiveSpace(2, QQ)
sage: Hom(P, P)
Set of morphisms
  From: Projective Space of dimension 2 over Rational Field
  To:   Projective Space of dimension 2 over Rational Field
sage: _.identity()
Scheme endomorphism of Projective Space of dimension 2 over Rational Field
  Defn: Identity map
```

```
>>> from sage.all import *
>>> P = ProjectiveSpace(Integer(2), QQ, names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P._first_ngens(3)
>>> Hom(P, P)
Set of morphisms
  From: Projective Space of dimension 2 over Rational Field
  To:   Projective Space of dimension 2 over Rational Field
>>> _.identity()
Scheme endomorphism of Projective Space of dimension 2 over Rational Field
  Defn: Identity map
```

CHAPTER

FIFTEEN

PRODUCTS OF PROJECTIVE SPACES

15.1 Products of projective spaces

This class builds on the projective space class and its point and morphism classes.

Products of projective spaces of varying dimension are convenient ambient spaces for complete intersections.

Group actions on them, and the interplay with representation theory, provide many interesting examples of algebraic varieties.

EXAMPLES:

We construct products projective spaces of various dimensions over the same ring:

```
sage: P1 = ProjectiveSpace(ZZ, 1, 'x')
sage: P2 = ProjectiveSpace(ZZ, 2, 'y')
sage: ProductProjectiveSpaces([P1, P2])
Product of projective spaces P^1 x P^2 over Integer Ring
```

```
>>> from sage.all import *
>>> P1 = ProjectiveSpace(ZZ, Integer(1), 'x')
>>> P2 = ProjectiveSpace(ZZ, Integer(2), 'y')
>>> ProductProjectiveSpaces([P1, P2])
Product of projective spaces P^1 x P^2 over Integer Ring
```

We can also construct the product by specifying the dimensions and the base ring:

```
sage: ProductProjectiveSpaces([1, 2, 3], QQ, 'z')
Product of projective spaces P^1 x P^2 x P^3 over Rational Field

sage: P2xP2 = ProductProjectiveSpaces([2, 2], QQ, names=['x', 'y'])
sage: P2xP2.coordinate_ring().inject_variables()
Defining x0, x1, x2, y0, y1, y2
```

```
>>> from sage.all import *
>>> ProductProjectiveSpaces([Integer(1), Integer(2), Integer(3)], QQ, 'z')
Product of projective spaces P^1 x P^2 x P^3 over Rational Field

>>> P2xP2 = ProductProjectiveSpaces([Integer(2), Integer(2)], QQ, names=['x', 'y'])
>>> P2xP2.coordinate_ring().inject_variables()
Defining x0, x1, x2, y0, y1, y2
```

sage.schemes.product_projective.space.**ProductProjectiveSpaces**(*n*, *R=None*, *names='x'*)

Return the Cartesian product of projective spaces.

The input `n` is either a list of projective space over the same base ring or the list of dimensions, `R` the base ring, and `names` the variable names.

INPUT:

- `n` – list of integers or a list of projective spaces
- `R` – a ring
- `names` – string or list of strings

EXAMPLES:

```
sage: P1 = ProjectiveSpace(QQ, 2, 'x')
sage: P2 = ProjectiveSpace(QQ, 3, 'y')
sage: ProductProjectiveSpaces([P1, P2])
Product of projective spaces P^2 x P^3 over Rational Field
```

```
>>> from sage.all import *
>>> P1 = ProjectiveSpace(QQ, Integer(2), 'x')
>>> P2 = ProjectiveSpace(QQ, Integer(3), 'y')
>>> ProductProjectiveSpaces([P1, P2])
Product of projective spaces P^2 x P^3 over Rational Field
```

```
sage: ProductProjectiveSpaces([2, 2], GF(7), 'y')
Product of projective spaces P^2 x P^2 over Finite Field of size 7
```

```
>>> from sage.all import *
>>> ProductProjectiveSpaces([Integer(2), Integer(2)], GF(Integer(7)), 'y')
Product of projective spaces P^2 x P^2 over Finite Field of size 7
```

```
sage: P1 = ProjectiveSpace(ZZ, 2, 'x')
sage: P2 = ProjectiveSpace(QQ, 3, 'y')
sage: ProductProjectiveSpaces([P1, P2])
Traceback (most recent call last):
...
AttributeError: components must be over the same base ring
```

```
>>> from sage.all import *
>>> P1 = ProjectiveSpace(ZZ, Integer(2), 'x')
>>> P2 = ProjectiveSpace(QQ, Integer(3), 'y')
>>> ProductProjectiveSpaces([P1, P2])
Traceback (most recent call last):
...
AttributeError: components must be over the same base ring
```

class sage.schemes.product_projective.space.**ProductProjectiveSpaces_field**(*N*, *R=Rational Field*, *names=None*)

Bases: *ProductProjectiveSpaces_ring*

points_of_bounded_height(***kwds*)

Return an iterator of the points in this product of projective spaces with the absolute heights of the components of at most the given bound.

Bound check is strict for the rational field. Requires the base field of this space to be a number field. Uses the Doyle-Krumm algorithm 4 (algorithm 5 for imaginary quadratic) for computing algebraic numbers up to a given height [DK2013].

The algorithm requires floating point arithmetic, so the user is allowed to specify the precision for such calculations. Additionally, due to floating point issues, points slightly larger than the bound may be returned. This can be controlled by lowering the tolerance.

INPUT:

- `bound` – a real number
- `tolerance` – a rational number in (0,1] used in Doyle-Krumm algorithm-4
- `precision` – the precision to use for computing the elements of bounded height of number fields

OUTPUT: an iterator of points in this space

EXAMPLES:

```
sage: PP = ProductProjectiveSpaces(QQ, [1, 2])
sage: sorted(list(PP.points_of_bounded_height(bound=1)))
[(-1 : 1 , -1 : -1 : 1), (-1 : 1 , -1 : 0 : 1), (-1 : 1 , -1 : 1 : 0),
 (-1 : 1 , -1 : 1 : 1), (-1 : 1 , 0 : -1 : 1), (-1 : 1 , 0 : 0 : 1),
 (-1 : 1 , 0 : 1 : 0), (-1 : 1 , 0 : 1 : 1), (-1 : 1 , 1 : -1 : 1),
 (-1 : 1 , 1 : 0 : 0), (-1 : 1 , 1 : 0 : 1), (-1 : 1 , 1 : 1 : 0),
 (-1 : 1 , 1 : 1 : 1), (0 : 1 , -1 : -1 : 1), (0 : 1 , -1 : 0 : 1),
 (0 : 1 , -1 : 1 : 0), (0 : 1 , -1 : 1 : 1), (0 : 1 , 0 : -1 : 1),
 (0 : 1 , 0 : 0 : 1), (0 : 1 , 0 : 1 : 0), (0 : 1 , 0 : 1 : 1),
 (0 : 1 , 1 : -1 : 1), (0 : 1 , 1 : 0 : 0), (0 : 1 , 1 : 0 : 1),
 (0 : 1 , 1 : 1 : 0), (0 : 1 , 1 : 1 : 1), (1 : 0 , -1 : -1 : 1),
 (1 : 0 , -1 : 0 : 1), (1 : 0 , -1 : 1 : 0), (1 : 0 , -1 : 1 : 1),
 (1 : 0 , 0 : -1 : 1), (1 : 0 , 0 : 0 : 1), (1 : 0 , 0 : 1 : 0),
 (1 : 0 , 0 : 1 : 1), (1 : 0 , 1 : -1 : 1), (1 : 0 , 1 : 0 : 0),
 (1 : 0 , 1 : 0 : 1), (1 : 0 , 1 : 1 : 0), (1 : 0 , 1 : 1 : 1),
 (1 : 1 , -1 : -1 : 1), (1 : 1 , -1 : 0 : 1), (1 : 1 , -1 : 1 : 0),
 (1 : 1 , -1 : 1 : 1), (1 : 1 , 0 : -1 : 1), (1 : 1 , 0 : 0 : 1),
 (1 : 1 , 0 : 1 : 0), (1 : 1 , 0 : 1 : 1), (1 : 1 , 1 : -1 : 1),
 (1 : 1 , 1 : 0 : 0), (1 : 1 , 1 : 0 : 1), (1 : 1 , 1 : 1 : 0),
 (1 : 1 , 1 : 1 : 1)]
```

```
>>> from sage.all import *
>>> PP = ProductProjectiveSpaces(QQ, [Integer(1), Integer(2)])
>>> sorted(list(PP.points_of_bounded_height(bound=Integer(1))))
[(-1 : 1 , -1 : -1 : 1), (-1 : 1 , -1 : 0 : 1), (-1 : 1 , -1 : 1 : 0),
 (-1 : 1 , -1 : 1 : 1), (-1 : 1 , 0 : -1 : 1), (-1 : 1 , 0 : 0 : 1),
 (-1 : 1 , 0 : 1 : 0), (-1 : 1 , 0 : 1 : 1), (-1 : 1 , 1 : -1 : 1),
 (-1 : 1 , 1 : 0 : 0), (-1 : 1 , 1 : 0 : 1), (-1 : 1 , 1 : 1 : 0),
 (-1 : 1 , 1 : 1 : 1), (0 : 1 , -1 : -1 : 1), (0 : 1 , -1 : 0 : 1),
 (0 : 1 , -1 : 1 : 0), (0 : 1 , -1 : 1 : 1), (0 : 1 , 0 : -1 : 1),
 (0 : 1 , 0 : 0 : 1), (0 : 1 , 0 : 1 : 0), (0 : 1 , 0 : 1 : 1),
 (0 : 1 , 1 : -1 : 1), (0 : 1 , 1 : 0 : 0), (0 : 1 , 1 : 0 : 1),
 (0 : 1 , 1 : 1 : 0), (0 : 1 , 1 : 1 : 1), (1 : 0 , -1 : -1 : 1),
```

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```
 (1 : 0 , -1 : 0 : 1), (1 : 0 , -1 : 1 : 0), (1 : 0 , -1 : 1 : 1),
 (1 : 0 , 0 : -1 : 1), (1 : 0 , 0 : 0 : 1), (1 : 0 , 0 : 1 : 0),
 (1 : 0 , 0 : 1 : 1), (1 : 0 , 1 : -1 : 1), (1 : 0 , 1 : 0 : 0),
 (1 : 0 , 1 : 0 : 1), (1 : 0 , 1 : 1 : 0), (1 : 0 , 1 : 1 : 1),
 (1 : 1 , -1 : -1 : 1), (1 : 1 , -1 : 0 : 1), (1 : 1 , -1 : 1 : 0),
 (1 : 1 , -1 : 1 : 1), (1 : 1 , 0 : -1 : 1), (1 : 1 , 0 : 0 : 1),
 (1 : 1 , 0 : 1 : 0), (1 : 1 , 0 : 1 : 1), (1 : 1 , 1 : -1 : 1),
 (1 : 1 , 1 : 0 : 0), (1 : 1 , 1 : 0 : 1), (1 : 1 , 1 : 1 : 0),
 (1 : 1 , 1 : 1 : 1)]
```

```
sage: u = QQ['u'].0
sage: P = ProductProjectiveSpaces([1, 1], NumberField(u^2 - 2, 'v'))         #␣
↪needs sage.rings.number_field
sage: sorted(list(P.points_of_bounded_height(bound=1.5)))                    #␣
↪needs sage.rings.number_field
[(-v : 1 , -v : 1), (-v : 1 , -1 : 1), (-v : 1 , -1/2*v : 1), (-v : 1 , 0 :␣
↪1),
 (-v : 1 , 1/2*v : 1), (-v : 1 , 1 : 0), (-v : 1 , 1 : 1), (-v : 1 , v : 1),
 (-1 : 1 , -v : 1), (-1 : 1 , -1 : 1), (-1 : 1 , -1/2*v : 1), (-1 : 1 , 0 :␣
↪1),
 (-1 : 1 , 1/2*v : 1), (-1 : 1 , 1 : 0), (-1 : 1 , 1 : 1), (-1 : 1 , v : 1),
 (-1/2*v : 1 , -v : 1), (-1/2*v : 1 , -1 : 1), (-1/2*v : 1 , -1/2*v : 1),
 (-1/2*v : 1 , 0 : 1), (-1/2*v : 1 , 1/2*v : 1), (-1/2*v : 1 , 1 : 0),
 (-1/2*v : 1 , 1 : 1), (-1/2*v : 1 , v : 1), (0 : 1 , -v : 1), (0 : 1 , -1 :␣
↪1),
 (0 : 1 , -1/2*v : 1), (0 : 1 , 0 : 1), (0 : 1 , 1/2*v : 1), (0 : 1 , 1 : 0),
 (0 : 1 , 1 : 1), (0 : 1 , v : 1), (1/2*v : 1 , -v : 1), (1/2*v : 1 , -1 : 1),
 (1/2*v : 1 , -1/2*v : 1), (1/2*v : 1 , 0 : 1), (1/2*v : 1 , 1/2*v : 1),
 (1/2*v : 1 , 1 : 0), (1/2*v : 1 , 1 : 1), (1/2*v : 1 , v : 1), (1 : 0 , -v :␣
↪1),
 (1 : 0 , -1 : 1), (1 : 0 , -1/2*v : 1), (1 : 0 , 0 : 1), (1 : 0 , 1/2*v : 1),
 (1 : 0 , 1 : 0), (1 : 0 , 1 : 1), (1 : 0 , v : 1), (1 : 1 , -v : 1),
 (1 : 1 , -1 : 1), (1 : 1 , -1/2*v : 1), (1 : 1 , 0 : 1), (1 : 1 , 1/2*v : 1),
 (1 : 1 , 1 : 0), (1 : 1 , 1 : 1), (1 : 1 , v : 1), (v : 1 , -v : 1),
 (v : 1 , -1 : 1), (v : 1 , -1/2*v : 1), (v : 1 , 0 : 1), (v : 1 , 1/2*v : 1),
 (v : 1 , 1 : 0), (v : 1 , 1 : 1), (v : 1 , v : 1)]
```

```
>>> from sage.all import *
>>> u = QQ['u'].gen(0)
>>> P = ProductProjectiveSpaces([Integer(1), Integer(1)],␣
↪NumberField(u**Integer(2) - Integer(2), 'v'))        # needs sage.rings.
↪number_field
>>> sorted(list(P.points_of_bounded_height(bound=RealNumber('1.5'))))        ␣
↪          # needs sage.rings.number_field
[(-v : 1 , -v : 1), (-v : 1 , -1 : 1), (-v : 1 , -1/2*v : 1), (-v : 1 , 0 :␣
↪1),
 (-v : 1 , 1/2*v : 1), (-v : 1 , 1 : 0), (-v : 1 , 1 : 1), (-v : 1 , v : 1),
 (-1 : 1 , -v : 1), (-1 : 1 , -1 : 1), (-1 : 1 , -1/2*v : 1), (-1 : 1 , 0 :␣
↪1),
 (-1 : 1 , 1/2*v : 1), (-1 : 1 , 1 : 0), (-1 : 1 , 1 : 1), (-1 : 1 , v : 1),
 (-1/2*v : 1 , -v : 1), (-1/2*v : 1 , -1 : 1), (-1/2*v : 1 , -1/2*v : 1),
```

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```
 (-1/2*v : 1 , 0 : 1), (-1/2*v : 1 , 1/2*v : 1), (-1/2*v : 1 , 1 : 0),
 (-1/2*v : 1 , 1 : 1), (-1/2*v : 1 , v : 1), (0 : 1 , -v : 1), (0 : 1 , -1 :␣
↪1),
 (0 : 1 , -1/2*v : 1), (0 : 1 , 0 : 1), (0 : 1 , 1/2*v : 1), (0 : 1 , 1 : 0),
 (0 : 1 , 1 : 1), (0 : 1 , v : 1), (1/2*v : 1 , -v : 1), (1/2*v : 1 , -1 : 1),
 (1/2*v : 1 , -1/2*v : 1), (1/2*v : 1 , 0 : 1), (1/2*v : 1 , 1/2*v : 1),
 (1/2*v : 1 , 1 : 0), (1/2*v : 1 , 1 : 1), (1/2*v : 1 , v : 1), (1 : 0 , -v :␣
↪1),
 (1 : 0 , -1 : 1), (1 : 0 , -1/2*v : 1), (1 : 0 , 0 : 1), (1 : 0 , 1/2*v : 1),
 (1 : 0 , 1 : 0), (1 : 0 , 1 : 1), (1 : 0 , v : 1), (1 : 1 , -v : 1),
 (1 : 1 , -1 : 1), (1 : 1 , -1/2*v : 1), (1 : 1 , 0 : 1), (1 : 1 , 1/2*v : 1),
 (1 : 1 , 1 : 0), (1 : 1 , 1 : 1), (1 : 1 , v : 1), (v : 1 , -v : 1),
 (v : 1 , -1 : 1), (v : 1 , -1/2*v : 1), (v : 1 , 0 : 1), (v : 1 , 1/2*v : 1),
 (v : 1 , 1 : 0), (v : 1 , 1 : 1), (v : 1 , v : 1)]
```

class sage.schemes.product_projective.space.**ProductProjectiveSpaces_finite_field**(*N*, *R=Rational Field*, *names=None*)

Bases: *ProductProjectiveSpaces_field*

rational_points(*F=None*)

Return the list of F-rational points on this product of projective spaces, where F is a given finite field, or the base ring of this space.

EXAMPLES:

```
sage: P = ProductProjectiveSpaces([1, 1], GF(5))
sage: P.rational_points()
[(0 : 1 , 0 : 1), (1 : 1 , 0 : 1), (2 : 1 , 0 : 1), (3 : 1 , 0 : 1), (4 : 1 ,␣
↪0 : 1), (1 : 0 , 0 : 1),
 (0 : 1 , 1 : 1), (1 : 1 , 1 : 1), (2 : 1 , 1 : 1), (3 : 1 , 1 : 1), (4 : 1 ,␣
↪1 : 1), (1 : 0 , 1 : 1),
 (0 : 1 , 2 : 1), (1 : 1 , 2 : 1), (2 : 1 , 2 : 1), (3 : 1 , 2 : 1), (4 : 1 ,␣
↪2 : 1), (1 : 0 , 2 : 1),
 (0 : 1 , 3 : 1), (1 : 1 , 3 : 1), (2 : 1 , 3 : 1), (3 : 1 , 3 : 1), (4 : 1 ,␣
↪3 : 1), (1 : 0 , 3 : 1),
 (0 : 1 , 4 : 1), (1 : 1 , 4 : 1), (2 : 1 , 4 : 1), (3 : 1 , 4 : 1), (4 : 1 ,␣
↪4 : 1), (1 : 0 , 4 : 1),
 (0 : 1 , 1 : 0), (1 : 1 , 1 : 0), (2 : 1 , 1 : 0), (3 : 1 , 1 : 0), (4 : 1 ,␣
↪1 : 0), (1 : 0 , 1 : 0)]
```

```
>>> from sage.all import *
>>> P = ProductProjectiveSpaces([Integer(1), Integer(1)], GF(Integer(5)))
>>> P.rational_points()
[(0 : 1 , 0 : 1), (1 : 1 , 0 : 1), (2 : 1 , 0 : 1), (3 : 1 , 0 : 1), (4 : 1 ,␣
↪0 : 1), (1 : 0 , 0 : 1),
 (0 : 1 , 1 : 1), (1 : 1 , 1 : 1), (2 : 1 , 1 : 1), (3 : 1 , 1 : 1), (4 : 1 ,␣
↪1 : 1), (1 : 0 , 1 : 1),
 (0 : 1 , 2 : 1), (1 : 1 , 2 : 1), (2 : 1 , 2 : 1), (3 : 1 , 2 : 1), (4 : 1 ,␣
↪2 : 1), (1 : 0 , 2 : 1),
```

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```
 (0 : 1 , 3 : 1), (1 : 1 , 3 : 1), (2 : 1 , 3 : 1), (3 : 1 , 3 : 1), (4 : 1 ,␣
↪3 : 1), (1 : 0 , 3 : 1),
 (0 : 1 , 4 : 1), (1 : 1 , 4 : 1), (2 : 1 , 4 : 1), (3 : 1 , 4 : 1), (4 : 1 ,␣
↪4 : 1), (1 : 0 , 4 : 1),
 (0 : 1 , 1 : 0), (1 : 1 , 1 : 0), (2 : 1 , 1 : 0), (3 : 1 , 1 : 0), (4 : 1 ,␣
↪1 : 0), (1 : 0 , 1 : 0)]
```

```
sage: P = ProductProjectiveSpaces([1, 1], GF(2))
sage: sorted(P.rational_points(GF(2^2, 'a')), key=str)                    #␣
↪needs sage.rings.finite_rings
[(0 : 1 , 0 : 1), (0 : 1 , 1 : 0), (0 : 1 , 1 : 1), (0 : 1 , a + 1 : 1), (0 :␣
↪1 , a : 1),
 (1 : 0 , 0 : 1), (1 : 0 , 1 : 0), (1 : 0 , 1 : 1), (1 : 0 , a + 1 : 1), (1 :␣
↪0 , a : 1),
 (1 : 1 , 0 : 1), (1 : 1 , 1 : 0), (1 : 1 , 1 : 1), (1 : 1 , a + 1 : 1), (1 :␣
↪1 , a : 1),
 (a + 1 : 1 , 0 : 1), (a + 1 : 1 , 1 : 0), (a + 1 : 1 , 1 : 1), (a + 1 : 1 ,␣
↪a + 1 : 1), (a + 1 : 1 , a : 1),
 (a : 1 , 0 : 1), (a : 1 , 1 : 0), (a : 1 , 1 : 1), (a : 1 , a + 1 : 1), (a :␣
↪1 , a : 1)]
```

```
>>> from sage.all import *
>>> P = ProductProjectiveSpaces([Integer(1), Integer(1)], GF(Integer(2)))
>>> sorted(P.rational_points(GF(Integer(2)**Integer(2), 'a')), key=str)      ␣
↪               # needs sage.rings.finite_rings
[(0 : 1 , 0 : 1), (0 : 1 , 1 : 0), (0 : 1 , 1 : 1), (0 : 1 , a + 1 : 1), (0 :␣
↪1 , a : 1),
 (1 : 0 , 0 : 1), (1 : 0 , 1 : 0), (1 : 0 , 1 : 1), (1 : 0 , a + 1 : 1), (1 :␣
↪0 , a : 1),
 (1 : 1 , 0 : 1), (1 : 1 , 1 : 0), (1 : 1 , 1 : 1), (1 : 1 , a + 1 : 1), (1 :␣
↪1 , a : 1),
 (a + 1 : 1 , 0 : 1), (a + 1 : 1 , 1 : 0), (a + 1 : 1 , 1 : 1), (a + 1 : 1 ,␣
↪a + 1 : 1), (a + 1 : 1 , a : 1),
 (a : 1 , 0 : 1), (a : 1 , 1 : 0), (a : 1 , 1 : 1), (a : 1 , a + 1 : 1), (a :␣
↪1 , a : 1)]
```

class sage.schemes.product_projective.space.**ProductProjectiveSpaces_ring**(*N*, *R=Rational Field*, *names=None*)

Bases: *AmbientSpace*

Cartesian product of projective spaces $\mathbb{P}^{n_1} \times \cdots \times \mathbb{P}^{n_r}$.

EXAMPLES:

```
sage: P.<x0,x1,x2,x3,x4> = ProductProjectiveSpaces([1, 2], QQ); P
Product of projective spaces P^1 x P^2 over Rational Field
sage: P.coordinate_ring()
Multivariate Polynomial Ring in x0, x1, x2, x3, x4 over Rational Field
sage: P[0]
Projective Space of dimension 1 over Rational Field
sage: P[1]
```

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```
Projective Space of dimension 2 over Rational Field
sage: Q = P(6, 3, 2, 2, 2); Q
(2 : 1 , 1 : 1 : 1)
sage: Q[0]
(2 : 1)
sage: H = Hom(P,P)
sage: f = H([x0^2*x3, x2*x1^2, x2^2, 2*x3^2, x4^2])
sage: f(Q)
(4 : 1 , 1 : 2 : 1)
```

```
>>> from sage.all import *
>>> P = ProductProjectiveSpaces([Integer(1), Integer(2)], QQ, names=('x0', 'x1',
↪'x2', 'x3', 'x4',)); (x0, x1, x2, x3, x4,) = P._first_ngens(5); P
Product of projective spaces P^1 x P^2 over Rational Field
>>> P.coordinate_ring()
Multivariate Polynomial Ring in x0, x1, x2, x3, x4 over Rational Field
>>> P[Integer(0)]
Projective Space of dimension 1 over Rational Field
>>> P[Integer(1)]
Projective Space of dimension 2 over Rational Field
>>> Q = P(Integer(6), Integer(3), Integer(2), Integer(2), Integer(2)); Q
(2 : 1 , 1 : 1 : 1)
>>> Q[Integer(0)]
(2 : 1)
>>> H = Hom(P,P)
>>> f = H([x0**Integer(2)*x3, x2*x1**Integer(2), x2**Integer(2),␣
↪Integer(2)*x3**Integer(2), x4**Integer(2)])
>>> f(Q)
(4 : 1 , 1 : 2 : 1)
```

affine_patch(*I*, *return_embedding=False*)

Return the I-th affine patch of this projective space product where `I` is a multi-index.

INPUT:

- `I` – list or tuple of positive integers
- `return_embedding` – boolean; if `True` the projective embedding is also returned

OUTPUT:

- An affine space.
- An embedding into a product of projective spaces (optional).

EXAMPLES:

```
sage: PP = ProductProjectiveSpaces([2, 2, 2], ZZ, 'x')
sage: phi = PP.affine_patch([0, 1, 2], True)
sage: phi.domain()
Affine Space of dimension 6 over Integer Ring
sage: phi
Scheme morphism:
  From: Affine Space of dimension 6 over Integer Ring
  To:   Product of projective spaces P^2 x P^2 x P^2 over Integer Ring
```

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```
  Defn: Defined on coordinates by sending (x0, x1, x2, x3, x4, x5) to
        (1 : x0 : x1 , x2 : 1 : x3 , x4 : x5 : 1)
```

```
>>> from sage.all import *
>>> PP = ProductProjectiveSpaces([Integer(2), Integer(2), Integer(2)], ZZ, 'x
↪')
>>> phi = PP.affine_patch([Integer(0), Integer(1), Integer(2)], True)
>>> phi.domain()
Affine Space of dimension 6 over Integer Ring
>>> phi
Scheme morphism:
  From: Affine Space of dimension 6 over Integer Ring
  To:   Product of projective spaces P^2 x P^2 x P^2 over Integer Ring
  Defn: Defined on coordinates by sending (x0, x1, x2, x3, x4, x5) to
        (1 : x0 : x1 , x2 : 1 : x3 , x4 : x5 : 1)
```

change_ring(*R*)

Return a product of projective spaces over a ring `R` and otherwise the same as this projective space.

INPUT:

- `R` – commutative ring or morphism

OUTPUT: product of projective spaces over `R`

Note

There is no need to have any relation between `R` and the base ring of this space, if you want to have such a relation, use `self.base_extend(R)` instead.

EXAMPLES:

```
sage: T.<x,y,z,u,v,w> = ProductProjectiveSpaces([2, 2], QQ)
sage: T.change_ring(GF(17))
Product of projective spaces P^2 x P^2 over Finite Field of size 17
```

```
>>> from sage.all import *
>>> T = ProductProjectiveSpaces([Integer(2), Integer(2)], QQ, names=('x', 'y',
↪ 'z', 'u', 'v', 'w',)); (x, y, z, u, v, w,) = T._first_ngens(6)
>>> T.change_ring(GF(Integer(17)))
Product of projective spaces P^2 x P^2 over Finite Field of size 17
```

components()

Return the components of this product of projective spaces.

OUTPUT: list of projective spaces

EXAMPLES:

```
sage: P.<x,y,z,u,v> = ProductProjectiveSpaces(QQ, [2, 1])
sage: P.components()
[Projective Space of dimension 2 over Rational Field,
Projective Space of dimension 1 over Rational Field]
```

```
>>> from sage.all import *
>>> P = ProductProjectiveSpaces(QQ, [Integer(2), Integer(1)], names=('x', 'y',
↪ 'z', 'u', 'v',)); (x, y, z, u, v,) = P._first_ngens(5)
>>> P.components()
[Projective Space of dimension 2 over Rational Field,
Projective Space of dimension 1 over Rational Field]
```

dimension()

Return the absolute dimension of the product of projective spaces.

OUTPUT: a positive integer

EXAMPLES:

```
sage: T.<x,y,z,u,v,w> = ProductProjectiveSpaces([2, 2], GF(17))
sage: T.dimension_absolute()
4
sage: T.dimension()
4
```

```
>>> from sage.all import *
>>> T = ProductProjectiveSpaces([Integer(2), Integer(2)], GF(Integer(17)),␣
↪names=('x', 'y', 'z', 'u', 'v', 'w',)); (x, y, z, u, v, w,) = T._first_
↪ngens(6)
>>> T.dimension_absolute()
4
>>> T.dimension()
4
```

dimension_absolute()

Return the absolute dimension of the product of projective spaces.

OUTPUT: a positive integer

EXAMPLES:

```
sage: T.<x,y,z,u,v,w> = ProductProjectiveSpaces([2, 2], GF(17))
sage: T.dimension_absolute()
4
sage: T.dimension()
4
```

```
>>> from sage.all import *
>>> T = ProductProjectiveSpaces([Integer(2), Integer(2)], GF(Integer(17)),␣
↪names=('x', 'y', 'z', 'u', 'v', 'w',)); (x, y, z, u, v, w,) = T._first_
↪ngens(6)
>>> T.dimension_absolute()
4
>>> T.dimension()
4
```

dimension_absolute_components()

Return the absolute dimension of the product of projective spaces.

OUTPUT: list of positive integers

EXAMPLES:

```
sage: T.<x,y,z,u,v,w> = ProductProjectiveSpaces([2, 2], GF(17))
sage: T.dimension_absolute_components()
[2, 2]
sage: T.dimension_components()
[2, 2]
```

```
>>> from sage.all import *
>>> T = ProductProjectiveSpaces([Integer(2), Integer(2)], GF(Integer(17)),␣
↪names=('x', 'y', 'z', 'u', 'v', 'w',)); (x, y, z, u, v, w,) = T._first_
↪ngens(6)
>>> T.dimension_absolute_components()
[2, 2]
>>> T.dimension_components()
[2, 2]
```

dimension_components()

Return the absolute dimension of the product of projective spaces.

OUTPUT: list of positive integers

EXAMPLES:

```
sage: T.<x,y,z,u,v,w> = ProductProjectiveSpaces([2, 2], GF(17))
sage: T.dimension_absolute_components()
[2, 2]
sage: T.dimension_components()
[2, 2]
```

```
>>> from sage.all import *
>>> T = ProductProjectiveSpaces([Integer(2), Integer(2)], GF(Integer(17)),␣
↪names=('x', 'y', 'z', 'u', 'v', 'w',)); (x, y, z, u, v, w,) = T._first_
↪ngens(6)
>>> T.dimension_absolute_components()
[2, 2]
>>> T.dimension_components()
[2, 2]
```

dimension_relative()

Return the relative dimension of the product of projective spaces.

OUTPUT: a positive integer

EXAMPLES:

```
sage: T.<a,x,y,z,u,v,w> = ProductProjectiveSpaces([3, 2], QQ)
sage: T.dimension_relative()
5
```

```
>>> from sage.all import *
>>> T = ProductProjectiveSpaces([Integer(3), Integer(2)], QQ, names=('a', 'x',
↪ 'y', 'z', 'u', 'v', 'w',)); (a, x, y, z, u, v, w,) = T._first_ngens(7)
>>> T.dimension_relative()
5
```

dimension_relative_components()

Return the relative dimension of the product of projective spaces.

OUTPUT: list of positive integers

EXAMPLES:

```
sage: T.<a,x,y,z,u,v,w> = ProductProjectiveSpaces([3, 2], QQ)
sage: T.dimension_relative_components()
[3, 2]
```

```
>>> from sage.all import *
>>> T = ProductProjectiveSpaces([Integer(3), Integer(2)], QQ, names=('a', 'x',
↪ 'y', 'z', 'u', 'v', 'w',)); (a, x, y, z, u, v, w,) = T._first_ngens(7)
>>> T.dimension_relative_components()
[3, 2]
```

ngens()

Return the number of generators of this space.

This is the number of variables in the coordinate ring of the projective space.

OUTPUT: integer

EXAMPLES:

```
sage: T = ProductProjectiveSpaces([1, 1, 1], GF(5), 'x')
sage: T.ngens()
6
```

```
>>> from sage.all import *
>>> T = ProductProjectiveSpaces([Integer(1), Integer(1), Integer(1)],␣
↪GF(Integer(5)), 'x')
>>> T.ngens()
6
```

num_components()

Return the number of components of this space.

OUTPUT: integer

EXAMPLES:

```
sage: T = ProductProjectiveSpaces([1, 1, 1], GF(5), 'x')
sage: T.num_components()
3
```

```
>>> from sage.all import *
>>> T = ProductProjectiveSpaces([Integer(1), Integer(1), Integer(1)],␣
↪GF(Integer(5)), 'x')
>>> T.num_components()
3
```

segre_embedding(*PP=None*, *var='u'*)

Return the Segre embedding of this space into the appropriate projective space.

INPUT:

- **PP – (default: None) ambient image projective space;**
  this is constructed if it is not given
- var – string (default: 'u'); variable name of the image projective space

OUTPUT: Hom; from this space to the appropriate subscheme of projective space

Todo

Cartesian products with more than two components.

EXAMPLES:

```
sage: X.<y0,y1,y2,y3,y4,y5> = ProductProjectiveSpaces(ZZ, [2, 2])
sage: phi = X.segre_embedding(); phi                                    #␣
↪needs sage.libs.singular
Scheme morphism:
  From: Product of projective spaces P^2 x P^2 over Integer Ring
  To:   Closed subscheme of Projective Space of dimension 8 over Integer Ring
        defined by:
          -u5*u7 + u4*u8,       -u5*u6 + u3*u8,       -u4*u6 + u3*u7,
          -u2*u7 + u1*u8,       -u2*u4 + u1*u5,       -u2*u6 + u0*u8,
          -u1*u6 + u0*u7,       -u2*u3 + u0*u5,       -u1*u3 + u0*u4
  Defn: Defined by sending (y0 : y1 : y2 , y3 : y4 : y5) to
        (y0*y3 : y0*y4 : y0*y5 : y1*y3 : y1*y4 : y1*y5 : y2*y3 : y2*y4 :␣
↪y2*y5).

::

sage: T = ProductProjectiveSpaces([1, 2], CC, 'z')                      #␣
↪needs sage.rings.real_mpfr
sage: T.segre_embedding()                                               #␣
↪needs sage.libs.singular sage.rings.real_mpfr
Scheme morphism:
  From: Product of projective spaces P^1 x P^2
        over Complex Field with 53 bits of precision
  To:   Closed subscheme of Projective Space of dimension 5
        over Complex Field with 53 bits of precision defined by:
          -u2*u4 + u1*u5,       -u2*u3 + u0*u5,       -u1*u3 + u0*u4
  Defn: Defined by sending (z0 : z1 , z2 : z3 : z4) to
        (z0*z2 : z0*z3 : z0*z4 : z1*z2 : z1*z3 : z1*z4).

::

sage: T = ProductProjectiveSpaces([1, 2, 1], QQ, 'z')
sage: T.segre_embedding()                                               #␣
↪needs sage.libs.singular
Scheme morphism:
  From: Product of projective spaces P^1 x P^2 x P^1 over Rational Field
  To:   Closed subscheme of Projective Space of dimension 11
        over Rational Field defined by:
          -u9*u10 + u8*u11,     -u7*u10 + u6*u11,     -u7*u8 + u6*u9,
          -u5*u10 + u4*u11,     -u5*u8 + u4*u9,       -u5*u6 + u4*u7,
```

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```
          -u5*u9 + u3*u11,      -u5*u8 + u3*u10,      -u5*u8 + u2*u11,
          -u4*u8 + u2*u10,      -u3*u8 + u2*u9,       -u3*u6 + u2*u7,
          -u3*u4 + u2*u5,       -u5*u7 + u1*u11,      -u5*u6 + u1*u10,
          -u3*u7 + u1*u9,       -u3*u6 + u1*u8,       -u5*u6 + u0*u11,
          -u4*u6 + u0*u10,      -u3*u6 + u0*u9,       -u2*u6 + u0*u8,
          -u1*u6 + u0*u7,       -u1*u4 + u0*u5,       -u1*u2 + u0*u3
  Defn: Defined by sending (z0 : z1 , z2 : z3 : z4 , z5 : z6) to
        (z0*z2*z5 : z0*z2*z6 : z0*z3*z5 : z0*z3*z6 : z0*z4*z5 : z0*z4*z6
         : z1*z2*z5 : z1*z2*z6 : z1*z3*z5 : z1*z3*z6 : z1*z4*z5 : z1*z4*z6).
```

```
>>> from sage.all import *
>>> X = ProductProjectiveSpaces(ZZ, [Integer(2), Integer(2)], names=('y0', 'y1
↪', 'y2', 'y3', 'y4', 'y5',)); (y0, y1, y2, y3, y4, y5,) = X._first_ngens(6)
>>> phi = X.segre_embedding(); phi                                          #␣
↪needs sage.libs.singular
Scheme morphism:
  From: Product of projective spaces P^2 x P^2 over Integer Ring
  To:   Closed subscheme of Projective Space of dimension 8 over Integer Ring
        defined by:
          -u5*u7 + u4*u8,       -u5*u6 + u3*u8,       -u4*u6 + u3*u7,
          -u2*u7 + u1*u8,       -u2*u4 + u1*u5,       -u2*u6 + u0*u8,
          -u1*u6 + u0*u7,       -u2*u3 + u0*u5,       -u1*u3 + u0*u4
  Defn: Defined by sending (y0 : y1 : y2 , y3 : y4 : y5) to
        (y0*y3 : y0*y4 : y0*y5 : y1*y3 : y1*y4 : y1*y5 : y2*y3 : y2*y4 :␣
↪y2*y5).

::

>>> T = ProductProjectiveSpaces([Integer(1), Integer(2)], CC, 'z')          ␣
↪              # needs sage.rings.real_mpfr
>>> T.segre_embedding()                                                     #␣
↪needs sage.libs.singular sage.rings.real_mpfr
Scheme morphism:
  From: Product of projective spaces P^1 x P^2
        over Complex Field with 53 bits of precision
  To:   Closed subscheme of Projective Space of dimension 5
        over Complex Field with 53 bits of precision defined by:
          -u2*u4 + u1*u5,       -u2*u3 + u0*u5,       -u1*u3 + u0*u4
  Defn: Defined by sending (z0 : z1 , z2 : z3 : z4) to
        (z0*z2 : z0*z3 : z0*z4 : z1*z2 : z1*z3 : z1*z4).

::

>>> T = ProductProjectiveSpaces([Integer(1), Integer(2), Integer(1)], QQ, 'z')
>>> T.segre_embedding()                                                     #␣
↪needs sage.libs.singular
Scheme morphism:
  From: Product of projective spaces P^1 x P^2 x P^1 over Rational Field
  To:   Closed subscheme of Projective Space of dimension 11
        over Rational Field defined by:
          -u9*u10 + u8*u11,     -u7*u10 + u6*u11,     -u7*u8 + u6*u9,
          -u5*u10 + u4*u11,     -u5*u8 + u4*u9,       -u5*u6 + u4*u7,
```

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```
          -u5*u9 + u3*u11,      -u5*u8 + u3*u10,      -u5*u8 + u2*u11,
          -u4*u8 + u2*u10,      -u3*u8 + u2*u9,       -u3*u6 + u2*u7,
          -u3*u4 + u2*u5,       -u5*u7 + u1*u11,      -u5*u6 + u1*u10,
          -u3*u7 + u1*u9,       -u3*u6 + u1*u8,       -u5*u6 + u0*u11,
          -u4*u6 + u0*u10,      -u3*u6 + u0*u9,       -u2*u6 + u0*u8,
          -u1*u6 + u0*u7,       -u1*u4 + u0*u5,       -u1*u2 + u0*u3
  Defn: Defined by sending (z0 : z1 , z2 : z3 : z4 , z5 : z6) to
        (z0*z2*z5 : z0*z2*z6 : z0*z3*z5 : z0*z3*z6 : z0*z4*z5 : z0*z4*z6
         : z1*z2*z5 : z1*z2*z6 : z1*z3*z5 : z1*z3*z6 : z1*z4*z5 : z1*z4*z6).
```

subscheme(X)

Return the closed subscheme defined by `X`.

INPUT:

- `X` – list or tuple of equations

OUTPUT: `AlgebraicScheme_subscheme_projective_cartesian_product`

EXAMPLES:

```
sage: P.<x,y,z,w> = ProductProjectiveSpaces([1, 1], GF(5))
sage: X = P.subscheme([x - y, z - w]); X
Closed subscheme of Product of projective spaces P^1 x P^1
 over Finite Field of size 5 defined by:
  x - y,
  z - w
sage: X.defining_polynomials()
[x - y, z - w]
sage: I = X.defining_ideal(); I
Ideal (x - y, z - w) of Multivariate Polynomial Ring in x, y, z, w
 over Finite Field of size 5
sage: X.dimension()                                                          #␣
↪needs sage.libs.singular
0
sage: X.base_ring()
Finite Field of size 5
sage: X.base_scheme()
Spectrum of Finite Field of size 5
sage: X.structure_morphism()
Scheme morphism:
  From: Closed subscheme of Product of projective spaces P^1 x P^1
        over Finite Field of size 5 defined by: x - y, z - w
  To:   Spectrum of Finite Field of size 5
  Defn: Structure map
```

```
>>> from sage.all import *
>>> P = ProductProjectiveSpaces([Integer(1), Integer(1)], GF(Integer(5)),␣
↪names=('x', 'y', 'z', 'w',)); (x, y, z, w,) = P._first_ngens(4)
>>> X = P.subscheme([x - y, z - w]); X
Closed subscheme of Product of projective spaces P^1 x P^1
 over Finite Field of size 5 defined by:
  x - y,
  z - w
```

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```
>>> X.defining_polynomials()
[x - y, z - w]
>>> I = X.defining_ideal(); I
Ideal (x - y, z - w) of Multivariate Polynomial Ring in x, y, z, w
 over Finite Field of size 5
>>> X.dimension()                                                    #␣
↪needs sage.libs.singular
0
>>> X.base_ring()
Finite Field of size 5
>>> X.base_scheme()
Spectrum of Finite Field of size 5
>>> X.structure_morphism()
Scheme morphism:
  From: Closed subscheme of Product of projective spaces P^1 x P^1
        over Finite Field of size 5 defined by: x - y, z - w
  To:   Spectrum of Finite Field of size 5
  Defn: Structure map
```

sage.schemes.product_projective.space.**is_ProductProjectiveSpaces**(x)

Return `True` if `x` is a product of projective spaces.

This is an ambient space defined by $\mathbb{P}^n_R \times \cdots \times \mathbb{P}^m_R$, where R is a ring and $n, \ldots, m \geq 0$ are integers.

OUTPUT: boolean

EXAMPLES:

```
sage: is_ProductProjectiveSpaces(ProjectiveSpace(5, names='x'))
doctest:warning...
DeprecationWarning: The function is_ProductProjectiveSpaces is deprecated; use
↪'isinstance(..., ProductProjectiveSpaces_ring)' instead.
See https://github.com/sagemath/sage/issues/38022 for details.
False
sage: is_ProductProjectiveSpaces(ProductProjectiveSpaces([1, 2, 3], ZZ, 'x'))
True
```

```
>>> from sage.all import *
>>> is_ProductProjectiveSpaces(ProjectiveSpace(Integer(5), names='x'))
doctest:warning...
DeprecationWarning: The function is_ProductProjectiveSpaces is deprecated; use
↪'isinstance(..., ProductProjectiveSpaces_ring)' instead.
See https://github.com/sagemath/sage/issues/38022 for details.
False
>>> is_ProductProjectiveSpaces(ProductProjectiveSpaces([Integer(1), Integer(2),␣
↪Integer(3)], ZZ, 'x'))
True
```

15.2 Set of homomorphisms

AUTHORS:

- Volker Braun and Ben Hutz (2014): initial version

- Raghukul Raman (2018): code cleanup and added support for rational field

class sage.schemes.product_projective.homset.**SchemeHomset_points_product_projective_spaces_field**(*X*, *Y*, *category*, *check*, *base*, *category*, *Integer Ring*)

Bases: *SchemeHomset_points_product_projective_spaces_ring*

points(***kwds*)

Return some or all rational points of a projective scheme.

Over a finite field, all points are returned. Over an infinite field, all points satisfying the bound are returned. For a zero-dimensional subscheme, all points are returned regardless of whether the base ring is a field or not.

For number fields, this uses the Doyle-Krumm algorithm 4 (algorithm 5 for imaginary quadratic) for computing algebraic numbers up to a given height [DK2013] or uses the chinese remainder theorem and points modulo primes for larger bounds.

The algorithm requires floating point arithmetic, so the user is allowed to specify the precision for such calculations. Additionally, due to floating point issues, points slightly larger than the bound may be returned. This can be controlled by lowering the tolerance.

INPUT:

- `bound` – a real number
- `tolerance` – a rational number in (0,1] used in Doyle-Krumm algorithm 4
- `precision` – the precision to use for computing the elements of bounded height of number fields
- `algorithm` – either `'sieve'` or `'enumerate'` algorithms can be used over **Q**. If not specified, `'enumerate'` is used only for small height bounds

OUTPUT: list of rational points of the projective scheme

EXAMPLES:

```
sage: P.<x,y,z,w> = ProductProjectiveSpaces([1, 1], QQ)
sage: X = P.subscheme([x - y, z^2 - 2*w^2])
sage: X(P.base_ring()).points()                                             #␣
↪needs sage.libs.singular
[]
```

```
>>> from sage.all import *
>>> P = ProductProjectiveSpaces([Integer(1), Integer(1)], QQ, names=('x', 'y',
↪ 'z', 'w',)); (x, y, z, w,) = P._first_ngens(4)
>>> X = P.subscheme([x - y, z**Integer(2) - Integer(2)*w**Integer(2)])
>>> X(P.base_ring()).points()                                               #␣
↪needs sage.libs.singular
[]
```

```
sage: u = QQ['u'].0
sage: K = NumberField(u^2 - 2, 'v')                                             #␣
↪needs sage.rings.number_field
sage: P.<x,y,z,w> = ProductProjectiveSpaces([1, 1], K)                          #␣
↪needs sage.rings.number_field
sage: X = P.subscheme([x^2 - y^2, z^2 - 2*w^2])
sage: sorted(X(P.base_ring()).points())                                         #␣
↪needs sage.libs.singular sage.rings.number_field
[(-1 : 1 , -v : 1), (-1 : 1 , v : 1), (1 : 1 , -v : 1), (1 : 1 , v : 1)]
```

```
>>> from sage.all import *
>>> u = QQ['u'].gen(0)
>>> K = NumberField(u**Integer(2) - Integer(2), 'v')                            ␣
↪               # needs sage.rings.number_field
>>> P = ProductProjectiveSpaces([Integer(1), Integer(1)], K, names=('x', 'y',
↪'z', 'w',)); (x, y, z, w,) = P._first_ngens(4)# needs sage.rings.number_
↪field
>>> X = P.subscheme([x**Integer(2) - y**Integer(2), z**Integer(2) -␣
↪Integer(2)*w**Integer(2)])
>>> sorted(X(P.base_ring()).points())                                           #␣
↪needs sage.libs.singular sage.rings.number_field
[(-1 : 1 , -v : 1), (-1 : 1 , v : 1), (1 : 1 , -v : 1), (1 : 1 , v : 1)]
```

```
sage: u = QQ['u'].0
sage: K = NumberField(u^2 + 1, 'v')                                             #␣
↪needs sage.rings.number_field
sage: P.<x,y,z,w> = ProductProjectiveSpaces([1, 1], K)                          #␣
↪needs sage.rings.number_field
sage: P(K).points(bound=1)                                                      #␣
↪needs sage.libs.singular sage.rings.number_field
[(-1 : 1 , -1 : 1), (-1 : 1 , -v : 1), (-1 : 1 , 0 : 1), (-1 : 1 , v : 1),
 (-1 : 1 , 1 : 0), (-1 : 1 , 1 : 1), (-v : 1 , -1 : 1), (-v : 1 , -v : 1),
 (-v : 1 , 0 : 1), (-v : 1 , v : 1), (-v : 1 , 1 : 0), (-v : 1 , 1 : 1),
 (0 : 1 , -1 : 1), (0 : 1 , -v : 1), (0 : 1 , 0 : 1), (0 : 1 , v : 1),
 (0 : 1 , 1 : 0), (0 : 1 , 1 : 1), (v : 1 , -1 : 1), (v : 1 , -v : 1),
 (v : 1 , 0 : 1), (v : 1 , v : 1), (v : 1 , 1 : 0), (v : 1 , 1 : 1),
 (1 : 0 , -1 : 1), (1 : 0 , -v : 1), (1 : 0 , 0 : 1), (1 : 0 , v : 1),
 (1 : 0 , 1 : 0), (1 : 0 , 1 : 1), (1 : 1 , -1 : 1), (1 : 1 , -v : 1),
 (1 : 1 , 0 : 1), (1 : 1 , v : 1), (1 : 1 , 1 : 0), (1 : 1 , 1 : 1)]
```

```
>>> from sage.all import *
>>> u = QQ['u'].gen(0)
>>> K = NumberField(u**Integer(2) + Integer(1), 'v')                            ␣
↪               # needs sage.rings.number_field
>>> P = ProductProjectiveSpaces([Integer(1), Integer(1)], K, names=('x', 'y',
↪'z', 'w',)); (x, y, z, w,) = P._first_ngens(4)# needs sage.rings.number_
↪field
>>> P(K).points(bound=Integer(1))                                               ␣
↪     # needs sage.libs.singular sage.rings.number_field
[(-1 : 1 , -1 : 1), (-1 : 1 , -v : 1), (-1 : 1 , 0 : 1), (-1 : 1 , v : 1),
 (-1 : 1 , 1 : 0), (-1 : 1 , 1 : 1), (-v : 1 , -1 : 1), (-v : 1 , -v : 1),
 (-v : 1 , 0 : 1), (-v : 1 , v : 1), (-v : 1 , 1 : 0), (-v : 1 , 1 : 1),
```

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```
 (0 : 1 , -1 : 1), (0 : 1 , -v : 1), (0 : 1 , 0 : 1), (0 : 1 , v : 1),
 (0 : 1 , 1 : 0), (0 : 1 , 1 : 1), (v : 1 , -1 : 1), (v : 1 , -v : 1),
 (v : 1 , 0 : 1), (v : 1 , v : 1), (v : 1 , 1 : 0), (v : 1 , 1 : 1),
 (1 : 0 , -1 : 1), (1 : 0 , -v : 1), (1 : 0 , 0 : 1), (1 : 0 , v : 1),
 (1 : 0 , 1 : 0), (1 : 0 , 1 : 1), (1 : 1 , -1 : 1), (1 : 1 , -v : 1),
 (1 : 1 , 0 : 1), (1 : 1 , v : 1), (1 : 1 , 1 : 0), (1 : 1 , 1 : 1)]
```

```
sage: P.<x,y,z,u,v> = ProductProjectiveSpaces([2, 1], GF(3))
sage: P(P.base_ring()).points()
[(0 : 0 : 1 , 0 : 1), (0 : 0 : 1 , 1 : 0), (0 : 0 : 1 , 1 : 1), (0 : 0 : 1 ,␣
↪2 : 1),
 (0 : 1 : 0 , 0 : 1), (0 : 1 : 0 , 1 : 0), (0 : 1 : 0 , 1 : 1), (0 : 1 : 0 ,␣
↪2 : 1),
 (0 : 1 : 1 , 0 : 1), (0 : 1 : 1 , 1 : 0), (0 : 1 : 1 , 1 : 1), (0 : 1 : 1 ,␣
↪2 : 1),
 (0 : 2 : 1 , 0 : 1), (0 : 2 : 1 , 1 : 0), (0 : 2 : 1 , 1 : 1), (0 : 2 : 1 ,␣
↪2 : 1),
 (1 : 0 : 0 , 0 : 1), (1 : 0 : 0 , 1 : 0), (1 : 0 : 0 , 1 : 1), (1 : 0 : 0 ,␣
↪2 : 1),
 (1 : 0 : 1 , 0 : 1), (1 : 0 : 1 , 1 : 0), (1 : 0 : 1 , 1 : 1), (1 : 0 : 1 ,␣
↪2 : 1),
 (1 : 1 : 0 , 0 : 1), (1 : 1 : 0 , 1 : 0), (1 : 1 : 0 , 1 : 1), (1 : 1 : 0 ,␣
↪2 : 1),
 (1 : 1 : 1 , 0 : 1), (1 : 1 : 1 , 1 : 0), (1 : 1 : 1 , 1 : 1), (1 : 1 : 1 ,␣
↪2 : 1),
 (1 : 2 : 1 , 0 : 1), (1 : 2 : 1 , 1 : 0), (1 : 2 : 1 , 1 : 1), (1 : 2 : 1 ,␣
↪2 : 1),
 (2 : 0 : 1 , 0 : 1), (2 : 0 : 1 , 1 : 0), (2 : 0 : 1 , 1 : 1), (2 : 0 : 1 ,␣
↪2 : 1),
 (2 : 1 : 0 , 0 : 1), (2 : 1 : 0 , 1 : 0), (2 : 1 : 0 , 1 : 1), (2 : 1 : 0 ,␣
↪2 : 1),
 (2 : 1 : 1 , 0 : 1), (2 : 1 : 1 , 1 : 0), (2 : 1 : 1 , 1 : 1), (2 : 1 : 1 ,␣
↪2 : 1),
 (2 : 2 : 1 , 0 : 1), (2 : 2 : 1 , 1 : 0), (2 : 2 : 1 , 1 : 1), (2 : 2 : 1 ,␣
↪2 : 1)]
```

```
>>> from sage.all import *
>>> P = ProductProjectiveSpaces([Integer(2), Integer(1)], GF(Integer(3)),␣
↪names=('x', 'y', 'z', 'u', 'v',)); (x, y, z, u, v,) = P._first_ngens(5)
>>> P(P.base_ring()).points()
[(0 : 0 : 1 , 0 : 1), (0 : 0 : 1 , 1 : 0), (0 : 0 : 1 , 1 : 1), (0 : 0 : 1 ,␣
↪2 : 1),
 (0 : 1 : 0 , 0 : 1), (0 : 1 : 0 , 1 : 0), (0 : 1 : 0 , 1 : 1), (0 : 1 : 0 ,␣
↪2 : 1),
 (0 : 1 : 1 , 0 : 1), (0 : 1 : 1 , 1 : 0), (0 : 1 : 1 , 1 : 1), (0 : 1 : 1 ,␣
↪2 : 1),
 (0 : 2 : 1 , 0 : 1), (0 : 2 : 1 , 1 : 0), (0 : 2 : 1 , 1 : 1), (0 : 2 : 1 ,␣
↪2 : 1),
 (1 : 0 : 0 , 0 : 1), (1 : 0 : 0 , 1 : 0), (1 : 0 : 0 , 1 : 1), (1 : 0 : 0 ,␣
↪2 : 1),
 (1 : 0 : 1 , 0 : 1), (1 : 0 : 1 , 1 : 0), (1 : 0 : 1 , 1 : 1), (1 : 0 : 1 ,␣
```

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```
↪2 : 1),
 (1 : 1 : 0 , 0 : 1), (1 : 1 : 0 , 1 : 0), (1 : 1 : 0 , 1 : 1), (1 : 1 : 0 ,␣
↪2 : 1),
 (1 : 1 : 1 , 0 : 1), (1 : 1 : 1 , 1 : 0), (1 : 1 : 1 , 1 : 1), (1 : 1 : 1 ,␣
↪2 : 1),
 (1 : 2 : 1 , 0 : 1), (1 : 2 : 1 , 1 : 0), (1 : 2 : 1 , 1 : 1), (1 : 2 : 1 ,␣
↪2 : 1),
 (2 : 0 : 1 , 0 : 1), (2 : 0 : 1 , 1 : 0), (2 : 0 : 1 , 1 : 1), (2 : 0 : 1 ,␣
↪2 : 1),
 (2 : 1 : 0 , 0 : 1), (2 : 1 : 0 , 1 : 0), (2 : 1 : 0 , 1 : 1), (2 : 1 : 0 ,␣
↪2 : 1),
 (2 : 1 : 1 , 0 : 1), (2 : 1 : 1 , 1 : 0), (2 : 1 : 1 , 1 : 1), (2 : 1 : 1 ,␣
↪2 : 1),
 (2 : 2 : 1 , 0 : 1), (2 : 2 : 1 , 1 : 0), (2 : 2 : 1 , 1 : 1), (2 : 2 : 1 ,␣
↪2 : 1)]
```

```
sage: PP.<x,y,z,u,v> = ProductProjectiveSpaces([2, 1], QQ)
sage: X = PP.subscheme([x + y, u*u - v*u])
sage: X.rational_points(bound=2)                                              #␣
↪needs sage.libs.singular
[(-2 : 2 : 1 , 0 : 1),
 (-2 : 2 : 1 , 1 : 1),
 (-1 : 1 : 0 , 0 : 1),
 (-1 : 1 : 0 , 1 : 1),
 (-1 : 1 : 1 , 0 : 1),
 (-1 : 1 : 1 , 1 : 1),
 (-1/2 : 1/2 : 1 , 0 : 1),
 (-1/2 : 1/2 : 1 , 1 : 1),
 (0 : 0 : 1 , 0 : 1),
 (0 : 0 : 1 , 1 : 1),
 (1/2 : -1/2 : 1 , 0 : 1),
 (1/2 : -1/2 : 1 , 1 : 1),
 (1 : -1 : 1 , 0 : 1),
 (1 : -1 : 1 , 1 : 1),
 (2 : -2 : 1 , 0 : 1),
 (2 : -2 : 1 , 1 : 1)]
```

```
>>> from sage.all import *
>>> PP = ProductProjectiveSpaces([Integer(2), Integer(1)], QQ, names=('x', 'y
↪', 'z', 'u', 'v',)); (x, y, z, u, v,) = PP._first_ngens(5)
>>> X = PP.subscheme([x + y, u*u - v*u])
>>> X.rational_points(bound=Integer(2))                                       ␣
↪     # needs sage.libs.singular
[(-2 : 2 : 1 , 0 : 1),
 (-2 : 2 : 1 , 1 : 1),
 (-1 : 1 : 0 , 0 : 1),
 (-1 : 1 : 0 , 1 : 1),
 (-1 : 1 : 1 , 0 : 1),
 (-1 : 1 : 1 , 1 : 1),
 (-1/2 : 1/2 : 1 , 0 : 1),
 (-1/2 : 1/2 : 1 , 1 : 1),
```

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```
 (0 : 0 : 1 , 0 : 1),
 (0 : 0 : 1 , 1 : 1),
 (1/2 : -1/2 : 1 , 0 : 1),
 (1/2 : -1/2 : 1 , 1 : 1),
 (1 : -1 : 1 , 0 : 1),
 (1 : -1 : 1 , 1 : 1),
 (2 : -2 : 1 , 0 : 1),
 (2 : -2 : 1 , 1 : 1)]
```

better to enumerate with low codimension:

```
sage: PP.<x,y,z,u,v,a,b,c> = ProductProjectiveSpaces([2, 1, 2], QQ)
sage: X = PP.subscheme([x*u^2*a, b*z*u*v, z*v^2*c])
sage: len(X.rational_points(bound=1, algorithm='enumerate'))                #␣
↪needs sage.libs.singular
232
```

```
>>> from sage.all import *
>>> PP = ProductProjectiveSpaces([Integer(2), Integer(1), Integer(2)], QQ,␣
↪names=('x', 'y', 'z', 'u', 'v', 'a', 'b', 'c',)); (x, y, z, u, v, a, b, c,)␣
↪= PP._first_ngens(8)
>>> X = PP.subscheme([x*u**Integer(2)*a, b*z*u*v, z*v**Integer(2)*c])
>>> len(X.rational_points(bound=Integer(1), algorithm='enumerate'))          ␣
↪     # needs sage.libs.singular
232
```

class sage.schemes.product_projective.homset.**SchemeHomset_points_product_projective_spaces_ring**(*X*, *Y*, *category=*, *check=*, *base=*, *ring*)

Bases: *SchemeHomset_points*

Set of rational points of a product of projective spaces.

INPUT: See *SchemeHomset_generic*.

EXAMPLES:

```
sage: from sage.schemes.product_projective.homset import SchemeHomset_points_
↪product_projective_spaces_ring
sage: SchemeHomset_points_product_projective_spaces_ring(
....:     Spec(QQ), ProductProjectiveSpaces([1, 1], QQ, 'z'))
Set of rational points of Product of projective spaces P^1 x P^1 over Rational␣
↪Field
```

```
>>> from sage.all import *
>>> from sage.schemes.product_projective.homset import SchemeHomset_points_
```

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```
↪product_projective_spaces_ring
>>> SchemeHomset_points_product_projective_spaces_ring(
...     Spec(QQ), ProductProjectiveSpaces([Integer(1), Integer(1)], QQ, 'z'))
Set of rational points of Product of projective spaces P^1 x P^1 over Rational␣
↪Field
```

15.3 Polynomial morphisms for products of projective spaces

This class builds on the projective space class and its point and morphism classes.

EXAMPLES:

```
sage: P1xP1.<x,y,u,v> = ProductProjectiveSpaces(QQ, [1, 1])
sage: H = End(P1xP1)
sage: H([x^2*u, y^2*v, x*v^2, y*u^2])
Scheme endomorphism of Product of projective spaces P^1 x P^1 over Rational Field
  Defn: Defined by sending (x : y , u : v) to (x^2*u : y^2*v , x*v^2 : y*u^2).
```

```
>>> from sage.all import *
>>> P1xP1 = ProductProjectiveSpaces(QQ, [Integer(1), Integer(1)], names=('x', 'y', 'u
↪', 'v',)); (x, y, u, v,) = P1xP1._first_ngens(4)
>>> H = End(P1xP1)
>>> H([x**Integer(2)*u, y**Integer(2)*v, x*v**Integer(2), y*u**Integer(2)])
Scheme endomorphism of Product of projective spaces P^1 x P^1 over Rational Field
  Defn: Defined by sending (x : y , u : v) to (x^2*u : y^2*v , x*v^2 : y*u^2).
```

class sage.schemes.product_projective.morphism.**ProductProjectiveSpaces_morphism_ring**(*parent*, *polys*, *check=True*)

Bases: *SchemeMorphism_polynomial*

The class of morphisms on products of projective spaces.

The components are projective space morphisms.

EXAMPLES:

```
sage: T.<x,y,z,w,u> = ProductProjectiveSpaces([2, 1], QQ)
sage: H = T.Hom(T)
sage: H([x^2, y^2, z^2, w^2, u^2])
Scheme endomorphism of Product of projective spaces P^2 x P^1 over Rational Field
  Defn: Defined by sending (x : y : z , w : u) to (x^2 : y^2 : z^2 , w^2 : u^2).
```

```
>>> from sage.all import *
>>> T = ProductProjectiveSpaces([Integer(2), Integer(1)], QQ, names=('x', 'y', 'z
↪', 'w', 'u',)); (x, y, z, w, u,) = T._first_ngens(5)
>>> H = T.Hom(T)
>>> H([x**Integer(2), y**Integer(2), z**Integer(2), w**Integer(2), u**Integer(2)])
Scheme endomorphism of Product of projective spaces P^2 x P^1 over Rational Field
  Defn: Defined by sending (x : y : z , w : u) to (x^2 : y^2 : z^2 , w^2 : u^2).
```

as_dynamical_system()

Return this endomorphism as a DynamicalSystem_product_projective.

OUTPUT: DynamicalSystem_product_projective

EXAMPLES:

```
sage: Z.<a,b,x,y,z> = ProductProjectiveSpaces([1, 2], ZZ)
sage: H = End(Z)
sage: f = H([a^3, b^3, x^2, y^2, z^2])
sage: type(f.as_dynamical_system())                                          #␣
↪needs sage.schemes
<class 'sage.dynamics.arithmetic_dynamics.product_projective_ds.
↪DynamicalSystem_product_projective'>
```

```
>>> from sage.all import *
>>> Z = ProductProjectiveSpaces([Integer(1), Integer(2)], ZZ, names=('a', 'b',
↪ 'x', 'y', 'z',)); (a, b, x, y, z,) = Z._first_ngens(5)
>>> H = End(Z)
>>> f = H([a**Integer(3), b**Integer(3), x**Integer(2), y**Integer(2),␣
↪z**Integer(2)])
>>> type(f.as_dynamical_system())                                            #␣
↪needs sage.schemes
<class 'sage.dynamics.arithmetic_dynamics.product_projective_ds.
↪DynamicalSystem_product_projective'>
```

global_height(*prec=None*)

Return the maximum of the absolute logarithmic heights of the coefficients in any of the coordinate functions of this map.

INPUT:

- prec – desired floating point precision (default: default RealField precision)

OUTPUT: a real number

Todo

Add functionality for $\overline{\mathbf{Q}}$, implement function to convert the map defined over $\overline{\mathbf{Q}}$ to map over a number field.

EXAMPLES:

```
sage: P1xP1.<x,y,u,v> = ProductProjectiveSpaces([1, 1], ZZ)
sage: H = End(P1xP1)
sage: f = H([x^2*u, 3*y^2*v, 5*x*v^2, y*u^2])
sage: f.global_height()                                                      #␣
↪needs sage.rings.real_mpfr
1.60943791243410
```

```
>>> from sage.all import *
>>> P1xP1 = ProductProjectiveSpaces([Integer(1), Integer(1)], ZZ, names=('x',
↪'y', 'u', 'v',)); (x, y, u, v,) = P1xP1._first_ngens(4)
>>> H = End(P1xP1)
```

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```
>>> f = H([x**Integer(2)*u, Integer(3)*y**Integer(2)*v,␣
↪Integer(5)*x*v**Integer(2), y*u**Integer(2)])
>>> f.global_height()                                                    #␣
↪needs sage.rings.real_mpfr
1.60943791243410
```

```
sage: # needs sage.rings.number_field
sage: u = QQ['u'].0
sage: R = NumberField(u^2 - 2, 'v')
sage: PP.<x,y,a,b> = ProductProjectiveSpaces([1, 1], R)
sage: H = End(PP)
sage: O = R.maximal_order()
sage: g = H([3*O(u)*x^2, 13*x*y, 7*a*y, 5*b*x + O(u)*a*y])
sage: g.global_height()                                                 #␣
↪needs sage.rings.real_mpfr
2.56494935746154
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> u = QQ['u'].gen(0)
>>> R = NumberField(u**Integer(2) - Integer(2), 'v')
>>> PP = ProductProjectiveSpaces([Integer(1), Integer(1)], R, names=('x', 'y',
↪ 'a', 'b',)); (x, y, a, b,) = PP._first_ngens(4)
>>> H = End(PP)
>>> O = R.maximal_order()
>>> g = H([Integer(3)*O(u)*x**Integer(2), Integer(13)*x*y, Integer(7)*a*y,␣
↪Integer(5)*b*x + O(u)*a*y])
>>> g.global_height()                                                    #␣
↪needs sage.rings.real_mpfr
2.56494935746154
```

is_morphism()

Return `True` if this mapping is a morphism of products of projective spaces.

For each component space of the codomain of this mapping we consider the subscheme of the domain of this map generated by the corresponding coordinates of the map. This map is a morphism if and only if each of these subschemes has no points.

OUTPUT: boolean

EXAMPLES:

```
sage: Z.<a,b,x,y,z> = ProductProjectiveSpaces([1, 2], ZZ)
sage: H = End(Z)
sage: f = H([a^2, b^2, x*z - y*z, x^2 - y^2, z^2])
sage: f.is_morphism()                                                   #␣
↪needs sage.libs.singular
False
```

```
>>> from sage.all import *
>>> Z = ProductProjectiveSpaces([Integer(1), Integer(2)], ZZ, names=('a', 'b',
↪ 'x', 'y', 'z',)); (a, b, x, y, z,) = Z._first_ngens(5)
>>> H = End(Z)
```

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```
>>> f = H([a**Integer(2), b**Integer(2), x*z - y*z, x**Integer(2) -␣
↪y**Integer(2), z**Integer(2)])
>>> f.is_morphism()                                                    #␣
↪needs sage.libs.singular
False
```

```
sage: P.<x,y,z,u,v,w> = ProductProjectiveSpaces([2, 2], QQ)
sage: H = End(P)
sage: f = H([u, v, w, u^2, v^2, w^2])
sage: f.is_morphism()                                                 #␣
↪needs sage.libs.singular
True
```

```
>>> from sage.all import *
>>> P = ProductProjectiveSpaces([Integer(2), Integer(2)], QQ, names=('x', 'y',
↪ 'z', 'u', 'v', 'w',)); (x, y, z, u, v, w,) = P._first_ngens(6)
>>> H = End(P)
>>> f = H([u, v, w, u**Integer(2), v**Integer(2), w**Integer(2)])
>>> f.is_morphism()                                                    #␣
↪needs sage.libs.singular
True
```

```
sage: P.<x,y,z,w,u> = ProductProjectiveSpaces([2, 1], QQ)
sage: Q.<a,b,c,d,e> = ProductProjectiveSpaces([1, 2], QQ)
sage: H = Hom(P, Q)
sage: f = H([x^2, y^2, u^3, w^3, u^3])
sage: f.is_morphism()                                                 #␣
↪needs sage.libs.singular
False
```

```
>>> from sage.all import *
>>> P = ProductProjectiveSpaces([Integer(2), Integer(1)], QQ, names=('x', 'y',
↪ 'z', 'w', 'u',)); (x, y, z, w, u,) = P._first_ngens(5)
>>> Q = ProductProjectiveSpaces([Integer(1), Integer(2)], QQ, names=('a', 'b',
↪ 'c', 'd', 'e',)); (a, b, c, d, e,) = Q._first_ngens(5)
>>> H = Hom(P, Q)
>>> f = H([x**Integer(2), y**Integer(2), u**Integer(3), w**Integer(3),␣
↪u**Integer(3)])
>>> f.is_morphism()                                                    #␣
↪needs sage.libs.singular
False
```

local_height(*v*, *prec=None*)

Return the maximum of the local height of the coefficients in any of the coordinate functions of this map.

INPUT:

- `v` – a prime or prime ideal of the base ring
- `prec` – desired floating point precision (default: default RealField precision)

OUTPUT: a real number

EXAMPLES:

```
sage: T.<x,y,z,w,u> = ProductProjectiveSpaces([2, 1], QQ)
sage: H = T.Hom(T)
sage: f = H([4*x^2 + 3/100*y^2, 8/210*x*y, 1/10000*z^2, 20*w^2, 1/384*u*w])
sage: f.local_height(2)                                                     #␣
↪needs sage.rings.real_mpfr
4.85203026391962
```

```
>>> from sage.all import *
>>> T = ProductProjectiveSpaces([Integer(2), Integer(1)], QQ, names=('x', 'y',
↪ 'z', 'w', 'u',)); (x, y, z, w, u,) = T._first_ngens(5)
>>> H = T.Hom(T)
>>> f = H([Integer(4)*x**Integer(2) + Integer(3)/Integer(100)*y**Integer(2),␣
↪Integer(8)/Integer(210)*x*y, Integer(1)/Integer(10000)*z**Integer(2),␣
↪Integer(20)*w**Integer(2), Integer(1)/Integer(384)*u*w])
>>> f.local_height(Integer(2))                                              ␣
↪     # needs sage.rings.real_mpfr
4.85203026391962
```

```
sage: # needs sage.rings.number_field
sage: R.<z> = PolynomialRing(QQ)
sage: K.<w> = NumberField(z^2 - 5)
sage: P.<x,y,a,b> = ProductProjectiveSpaces([1, 1], K)
sage: H = Hom(P, P)
sage: f = H([2*x^2 + w/3*y^2, 1/w*y^2, a^2, 6*b^2 + 1/9*a*b])
sage: f.local_height(K.ideal(3))                                            #␣
↪needs sage.rings.real_mpfr
2.19722457733622
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = PolynomialRing(QQ, names=('z',)); (z,) = R._first_ngens(1)
>>> K = NumberField(z**Integer(2) - Integer(5), names=('w',)); (w,) = K._
↪first_ngens(1)
>>> P = ProductProjectiveSpaces([Integer(1), Integer(1)], K, names=('x', 'y',
↪'a', 'b',)); (x, y, a, b,) = P._first_ngens(4)
>>> H = Hom(P, P)
>>> f = H([Integer(2)*x**Integer(2) + w/Integer(3)*y**Integer(2), Integer(1)/
↪w*y**Integer(2), a**Integer(2), Integer(6)*b**Integer(2) + Integer(1)/
↪Integer(9)*a*b])
>>> f.local_height(K.ideal(Integer(3)))                                     ␣
↪     # needs sage.rings.real_mpfr
2.19722457733622
```

15.4 Points for products of projective spaces

This class builds on the projective space class and its point and morphism classes.

EXAMPLES:

We construct products projective spaces of various dimensions over the same ring.:

```
sage: P1xP1.<x,y, u,v> = ProductProjectiveSpaces(QQ, [1, 1])
sage: P1xP1([2, 1, 3, 1])
(2 : 1 , 3 : 1)
```

```
>>> from sage.all import *
>>> P1xP1 = ProductProjectiveSpaces(QQ, [Integer(1), Integer(1)], names=('x', 'y', 'u
↪', 'v',)); (x, y, u, v,) = P1xP1._first_ngens(4)
>>> P1xP1([Integer(2), Integer(1), Integer(3), Integer(1)])
(2 : 1 , 3 : 1)
```

class sage.schemes.product_projective.point.**ProductProjectiveSpaces_point_field**(*parent*, *polys*, *check=True*)

Bases: *ProductProjectiveSpaces_point_ring*

intersection_multiplicity(*X*)

Return the intersection multiplicity of the codomain of this point and subscheme `X` at this point.

This uses the subscheme implementation of intersection_multiplicity. This point must be a point on a subscheme of a product of projective spaces.

INPUT:

- `X` – a subscheme in the same ambient space as the codomain of this point

OUTPUT: integer

EXAMPLES:

```
sage: PP.<x,y,z,u,v> = ProductProjectiveSpaces(QQ, [2, 1])
sage: X = PP.subscheme([y^2*z^3*u - x^5*v])
sage: Y = PP.subscheme([u^3 - v^3, x - y])
sage: Q = X([0,0,1,1,1])
sage: Q.intersection_multiplicity(Y)                                    #␣
↪needs sage.libs.singular
2
```

```
>>> from sage.all import *
>>> PP = ProductProjectiveSpaces(QQ, [Integer(2), Integer(1)], names=('x', 'y
↪', 'z', 'u', 'v',)); (x, y, z, u, v,) = PP._first_ngens(5)
>>> X = PP.subscheme([y**Integer(2)*z**Integer(3)*u - x**Integer(5)*v])
>>> Y = PP.subscheme([u**Integer(3) - v**Integer(3), x - y])
>>> Q = X([Integer(0),Integer(0),Integer(1),Integer(1),Integer(1)])
>>> Q.intersection_multiplicity(Y)                                      #␣
↪needs sage.libs.singular
2
```

multiplicity()

Return the multiplicity of this point on its codomain.

This uses the subscheme implementation of multiplicity. This point must be a point on a subscheme of a product of projective spaces.

OUTPUT: integer

EXAMPLES:

```
sage: PP.<x,y,z,w,u,v,t> = ProductProjectiveSpaces(QQ, [3, 2])
sage: X = PP.subscheme([x^8*t - y^8*t + z^5*w^3*v])
sage: Q1 = X([1,1,0,0,-1,-1,1])
sage: Q1.multiplicity()                                                    #␣
↪needs sage.libs.singular
1
sage: Q2 = X([0,0,0,1,0,1,1])
sage: Q2.multiplicity()                                                    #␣
↪needs sage.libs.singular
5
sage: Q3 = X([0,0,0,1,1,0,0])
sage: Q3.multiplicity()                                                    #␣
↪needs sage.libs.singular
6
```

```
>>> from sage.all import *
>>> PP = ProductProjectiveSpaces(QQ, [Integer(3), Integer(2)], names=('x', 'y
↪', 'z', 'w', 'u', 'v', 't',)); (x, y, z, w, u, v, t,) = PP._first_ngens(7)
>>> X = PP.subscheme([x**Integer(8)*t - y**Integer(8)*t +␣
↪z**Integer(5)*w**Integer(3)*v])
>>> Q1 = X([Integer(1),Integer(1),Integer(0),Integer(0),-Integer(1),-
↪Integer(1),Integer(1)])
>>> Q1.multiplicity()                                                      #␣
↪needs sage.libs.singular
1
>>> Q2 = X([Integer(0),Integer(0),Integer(0),Integer(1),Integer(0),Integer(1),
↪Integer(1)])
>>> Q2.multiplicity()                                                      #␣
↪needs sage.libs.singular
5
>>> Q3 = X([Integer(0),Integer(0),Integer(0),Integer(1),Integer(1),Integer(0),
↪Integer(0)])
>>> Q3.multiplicity()                                                      #␣
↪needs sage.libs.singular
6
```

class sage.schemes.product_projective.point.**ProductProjectiveSpaces_point_finite_field**(*parent*, *polys*, *check=True*)

Bases: *ProductProjectiveSpaces_point_field*

class sage.schemes.product_projective.point.**ProductProjectiveSpaces_point_ring**(*parent*, *polys*, *check=True*)

Bases: *SchemeMorphism_point*

The class of points on products of projective spaces.

The components are projective space points.

EXAMPLES:

```
sage: T.<x,y,z,w,u> = ProductProjectiveSpaces([2, 1], QQ)
sage: T.point([1, 2, 3, 4, 5])
(1/3 : 2/3 : 1 , 4/5 : 1)
```

```
>>> from sage.all import *
>>> T = ProductProjectiveSpaces([Integer(2), Integer(1)], QQ, names=('x', 'y', 'z
↪', 'w', 'u',)); (x, y, z, w, u,) = T._first_ngens(5)
>>> T.point([Integer(1), Integer(2), Integer(3), Integer(4), Integer(5)])
(1/3 : 2/3 : 1 , 4/5 : 1)
```

change_ring(*R*, ***kwds*)

Return a new `ProductProjectiveSpaces_point` which is this point coerced to `R`.

If the keyword `check` is `True`, then the initialization checks are performed. The user may specify the embedding into `R` with a keyword.

INPUT:

- `R` – ring

kwds:

- `check` – boolean
- `embedding` – field embedding from the base ring of this point to `R`

OUTPUT: `ProductProjectiveSpaces_point`

EXAMPLES:

```
sage: T.<x,y,z,u,v,w> = ProductProjectiveSpaces([1, 1, 1], ZZ)
sage: P = T.point([5, 3, 15, 4, 2, 6])
sage: P.change_ring(GF(3))
(1 : 0 , 0 : 1 , 1 : 0)
```

```
>>> from sage.all import *
>>> T = ProductProjectiveSpaces([Integer(1), Integer(1), Integer(1)], ZZ,␣
↪names=('x', 'y', 'z', 'u', 'v', 'w',)); (x, y, z, u, v, w,) = T._first_
↪ngens(6)
>>> P = T.point([Integer(5), Integer(3), Integer(15), Integer(4), Integer(2),␣
↪Integer(6)])
>>> P.change_ring(GF(Integer(3)))
(1 : 0 , 0 : 1 , 1 : 0)
```

dehomogenize(*L*)

Dehomogenize k-th point at $L[k]$-th coordinate.

This function computes the appropriate affine patch using `L` and then returns the dehomogenized point on of this affine space.

INPUT:

- `L` – list of nonnegative integers

OUTPUT: `SchemeMorphism_point_affine`

EXAMPLES:

```
sage: PP = ProductProjectiveSpaces([2, 2, 2], QQ, 'x')
sage: A = PP([2, 4, 6, 23, 46, 23, 9, 3, 1])
sage: A.dehomogenize([0, 1, 2])
(2, 3, 1/2, 1/2, 9, 3)
```

```
>>> from sage.all import *
>>> PP = ProductProjectiveSpaces([Integer(2), Integer(2), Integer(2)], QQ, 'x
↪')
>>> A = PP([Integer(2), Integer(4), Integer(6), Integer(23), Integer(46),␣
↪Integer(23), Integer(9), Integer(3), Integer(1)])
>>> A.dehomogenize([Integer(0), Integer(1), Integer(2)])
(2, 3, 1/2, 1/2, 9, 3)
```

```
sage: # needs sage.rings.real_mpfr sage.symbolic
sage: PP.<a,b,x,y,z> = ProductProjectiveSpaces([1, 2], CC)
sage: X = PP.subscheme([a^2 + b^2])
sage: P = X([2, 2*i, -3, 6*i, 3 - 6*i])
sage: P.dehomogenize([1,0])
(-1.00000000000000*I, -2.00000000000000*I, -1.00000000000000 + 2.
↪00000000000000*I)
```

```
>>> from sage.all import *
>>> # needs sage.rings.real_mpfr sage.symbolic
>>> PP = ProductProjectiveSpaces([Integer(1), Integer(2)], CC, names=('a', 'b
↪', 'x', 'y', 'z',)); (a, b, x, y, z,) = PP._first_ngens(5)
>>> X = PP.subscheme([a**Integer(2) + b**Integer(2)])
>>> P = X([Integer(2), Integer(2)*i, -Integer(3), Integer(6)*i, Integer(3) -␣
↪Integer(6)*i])
>>> P.dehomogenize([Integer(1),Integer(0)])
(-1.00000000000000*I, -2.00000000000000*I, -1.00000000000000 + 2.
↪00000000000000*I)
```

```
sage: PP = ProductProjectiveSpaces([1, 1], ZZ)
sage: A = PP([0,1,2,4])
sage: A.dehomogenize([0,0])
Traceback (most recent call last):
...
ValueError: can...t dehomogenize at 0 coordinate
```

```
>>> from sage.all import *
>>> PP = ProductProjectiveSpaces([Integer(1), Integer(1)], ZZ)
>>> A = PP([Integer(0),Integer(1),Integer(2),Integer(4)])
>>> A.dehomogenize([Integer(0),Integer(0)])
Traceback (most recent call last):
...
ValueError: can...t dehomogenize at 0 coordinate
```

global_height(*prec=None*)

Return the absolute logarithmic height of the point.

This function computes the maximum of global height of each component point in the product. Global height of component point is computed using function for projective point.

INPUT:

- `prec` – desired floating point precision (default: default RealField precision)

OUTPUT: a real number

EXAMPLES:

```
sage: PP = ProductProjectiveSpaces(QQ, [2, 2], 'x')
sage: Q = PP([1, 7, 5, 18, 2, 3])
sage: Q.global_height()                                                    #␣
↪needs sage.symbolic
2.89037175789616
```

```
>>> from sage.all import *
>>> PP = ProductProjectiveSpaces(QQ, [Integer(2), Integer(2)], 'x')
>>> Q = PP([Integer(1), Integer(7), Integer(5), Integer(18), Integer(2),␣
↪Integer(3)])
>>> Q.global_height()                                                      #␣
↪needs sage.symbolic
2.89037175789616
```

```
sage: PP = ProductProjectiveSpaces(ZZ, [1, 1], 'x')
sage: A = PP([-30, 2, 1, 6])
sage: A.global_height()                                                    #␣
↪needs sage.symbolic
2.70805020110221
```

```
>>> from sage.all import *
>>> PP = ProductProjectiveSpaces(ZZ, [Integer(1), Integer(1)], 'x')
>>> A = PP([-Integer(30), Integer(2), Integer(1), Integer(6)])
>>> A.global_height()                                                      #␣
↪needs sage.symbolic
2.70805020110221
```

```
sage: # needs sage.rings.number_field
sage: R.<x> = PolynomialRing(QQ)
sage: k.<w> = NumberField(x^2 + 5)
sage: PP = ProductProjectiveSpaces(k, [1, 2], 'y')
sage: Q = PP([3, 5*w + 1, 1, 7*w, 10])
sage: Q.global_height()
2.75062910527236
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = PolynomialRing(QQ, names=('x',)); (x,) = R._first_ngens(1)
>>> k = NumberField(x**Integer(2) + Integer(5), names=('w',)); (w,) = k._
↪first_ngens(1)
>>> PP = ProductProjectiveSpaces(k, [Integer(1), Integer(2)], 'y')
>>> Q = PP([Integer(3), Integer(5)*w + Integer(1), Integer(1), Integer(7)*w,␣
↪Integer(10)])
>>> Q.global_height()
2.75062910527236
```

```
sage: PP = ProductProjectiveSpaces(QQbar, [1, 1], 'x')                    #␣
↪needs sage.rings.number_field
sage: Q = PP([1, QQbar(sqrt(2)), QQbar(5^(1/3)), QQbar(3^(1/3))])        #␣
↪needs sage.rings.number_field sage.symbolic
sage: Q.global_height()                                                   #␣
↪needs sage.rings.number_field sage.symbolic
0.536479304144700
```

```
>>> from sage.all import *
>>> PP = ProductProjectiveSpaces(QQbar, [Integer(1), Integer(1)], 'x')       ␣
↪              # needs sage.rings.number_field
>>> Q = PP([Integer(1), QQbar(sqrt(Integer(2))),␣
↪QQbar(Integer(5)**(Integer(1)/Integer(3))), QQbar(Integer(3)**(Integer(1)/
↪Integer(3)))])           # needs sage.rings.number_field sage.symbolic
>>> Q.global_height()                                                     #␣
↪needs sage.rings.number_field sage.symbolic
0.536479304144700
```

local_height(*v*, *prec=None*)

Return the maximum of the local height of the coordinates of this point.

This function computes the maximum of local height of each component point in the product. Local height of component point is computed using function for projective point.

INPUT:

- `v` – a prime or prime ideal of the base ring
- `prec` – desired floating point precision (default: default RealField precision)

OUTPUT: a real number

EXAMPLES:

```
sage: PP = ProductProjectiveSpaces(QQ, [1, 1], 'x')
sage: A = PP([11, 5, 10, 2])
sage: A.local_height(5)                                                   #␣
↪needs sage.rings.real_mpfr
1.60943791243410
```

```
>>> from sage.all import *
>>> PP = ProductProjectiveSpaces(QQ, [Integer(1), Integer(1)], 'x')
>>> A = PP([Integer(11), Integer(5), Integer(10), Integer(2)])
>>> A.local_height(Integer(5))                                               ␣
↪     # needs sage.rings.real_mpfr
1.60943791243410
```

```
sage: P = ProductProjectiveSpaces(QQ, [1, 2], 'x')
sage: Q = P([1, 4, 1/2, 2, 32])
sage: Q.local_height(2)                                                   #␣
↪needs sage.rings.real_mpfr
4.15888308335967
```

```
>>> from sage.all import *
>>> P = ProductProjectiveSpaces(QQ, [Integer(1), Integer(2)], 'x')
>>> Q = P([Integer(1), Integer(4), Integer(1)/Integer(2), Integer(2),␣
↪Integer(32)])
>>> Q.local_height(Integer(2))                                              ␣
↪     # needs sage.rings.real_mpfr
4.15888308335967
```

normalize_coordinates()

Remove common factors (componentwise) from the coordinates of this point (including -1).

OUTPUT: none

EXAMPLES:

```
sage: T.<x,y,z,u,v,w> = ProductProjectiveSpaces([2, 2], ZZ)
sage: P = T.point([5, 10, 15, 4, 2, 6]);
sage: P.normalize_coordinates()
sage: P
(1 : 2 : 3 , 2 : 1 : 3)
```

```
>>> from sage.all import *
>>> T = ProductProjectiveSpaces([Integer(2), Integer(2)], ZZ, names=('x', 'y',
↪ 'z', 'u', 'v', 'w',)); (x, y, z, u, v, w,) = T._first_ngens(6)
>>> P = T.point([Integer(5), Integer(10), Integer(15), Integer(4), Integer(2),
↪ Integer(6)]);
>>> P.normalize_coordinates()
>>> P
(1 : 2 : 3 , 2 : 1 : 3)
```

scale_by(*t*)

Scale the coordinates of the point by `t`, done componentwise.

A `TypeError` occurs if the point is not in the base ring of the codomain after scaling.

INPUT:

- `t` – a ring element

EXAMPLES:

```
sage: T.<x, y, z, u, v, w> = ProductProjectiveSpaces([1, 1, 1], ZZ)
sage: P = T.point([5, 10, 15, 4, 2, 6]);
sage: P.scale_by([2, 1, 1])
sage: P
(10 : 20 , 15 : 4 , 2 : 6)
```

```
>>> from sage.all import *
>>> T = ProductProjectiveSpaces([Integer(1), Integer(1), Integer(1)], ZZ,␣
↪names=('x', 'y', 'z', 'u', 'v', 'w',)); (x, y, z, u, v, w,) = T._first_
↪ngens(6)
>>> P = T.point([Integer(5), Integer(10), Integer(15), Integer(4), Integer(2),
↪ Integer(6)]);
>>> P.scale_by([Integer(2), Integer(1), Integer(1)])
```

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```
>>> P
(10 : 20 , 15 : 4 , 2 : 6)
```

15.5 Subschemes of products of projective spaces

AUTHORS:

- Ben Hutz (2014): subschemes of Cartesian products of projective space

class sage.schemes.product_projective.subscheme.**AlgebraicScheme_subscheme_product_projective**(*A*, *polynomials*, *category=None*)

Bases: *AlgebraicScheme_subscheme_projective*

Construct an algebraic subscheme of a product of projective spaces.

Warning

You should not create objects of this class directly. The preferred method to construct such subschemes is to use *subscheme()* method of *Product of Projective Spaces*.

INPUT:

- `A` – ambient *Product of Projective Spaces*
- `polynomials` – single polynomial, ideal or iterable of defining multi-homogeneous polynomials

EXAMPLES:

```
sage: P.<x, y, u, v> = ProductProjectiveSpaces([1, 1], QQ)
sage: P.subscheme([u*x^2 - v*y*x])
Closed subscheme of Product of projective spaces P^1 x P^1 over Rational Field
 defined by:
  x^2*u - x*y*v
```

```
>>> from sage.all import *
>>> P = ProductProjectiveSpaces([Integer(1), Integer(1)], QQ, names=('x', 'y', 'u
↪', 'v',)); (x, y, u, v,) = P._first_ngens(4)
>>> P.subscheme([u*x**Integer(2) - v*y*x])
Closed subscheme of Product of projective spaces P^1 x P^1 over Rational Field
 defined by:
  x^2*u - x*y*v
```

affine_patch(*I*, *return_embedding=False*)

Return the I-th affine patch of this projective scheme where I is a multi-index.

INPUT:

- `I` – list or tuple of positive integers

- `return_embedding` – boolean; if `True` the projective embedding is also returned

OUTPUT:

- An affine algebraic scheme
- An embedding into a product of projective space (optional)

EXAMPLES:

```
sage: PP.<x,y,z,w,u,v> = ProductProjectiveSpaces([3, 1],QQ)
sage: W = PP.subscheme([y^2*z - x^3, z^2 - w^2, u^3 - v^3])
sage: W.affine_patch([0, 1], True)
(Closed subscheme of Affine Space of dimension 4 over Rational Field defined␣
↪by:
  x0^2*x1 - 1,
  x1^2 - x2^2,
  x3^3 - 1,
 Scheme morphism:
  From: Closed subscheme of Affine Space of dimension 4
        over Rational Field defined by: x0^2*x1 - 1, x1^2 - x2^2, x3^3 - 1
  To:   Closed subscheme of Product of projective spaces P^3 x P^1
        over Rational Field defined by: -x^3 + y^2*z, z^2 - w^2, u^3 - v^3
  Defn: Defined on coordinates by sending (x0, x1, x2, x3) to
        (1 : x0 : x1 : x2 , x3 : 1))
```

```
>>> from sage.all import *
>>> PP = ProductProjectiveSpaces([Integer(3), Integer(1)],QQ, names=('x', 'y',
↪ 'z', 'w', 'u', 'v',)); (x, y, z, w, u, v,) = PP._first_ngens(6)
>>> W = PP.subscheme([y**Integer(2)*z - x**Integer(3), z**Integer(2) -␣
↪w**Integer(2), u**Integer(3) - v**Integer(3)])
>>> W.affine_patch([Integer(0), Integer(1)], True)
(Closed subscheme of Affine Space of dimension 4 over Rational Field defined␣
↪by:
  x0^2*x1 - 1,
  x1^2 - x2^2,
  x3^3 - 1,
 Scheme morphism:
  From: Closed subscheme of Affine Space of dimension 4
        over Rational Field defined by: x0^2*x1 - 1, x1^2 - x2^2, x3^3 - 1
  To:   Closed subscheme of Product of projective spaces P^3 x P^1
        over Rational Field defined by: -x^3 + y^2*z, z^2 - w^2, u^3 - v^3
  Defn: Defined on coordinates by sending (x0, x1, x2, x3) to
        (1 : x0 : x1 : x2 , x3 : 1))
```

dimension()

Return the dimension of the algebraic subscheme.

OUTPUT: integer

EXAMPLES:

```
sage: X.<x,y,z,w,u,v> = ProductProjectiveSpaces([2, 2], QQ)
sage: L = (-w - v)*x + (-w*y - u*z)
sage: Q = ((-u*w - v^2)*x^2 + ((-w^2 - u*w + (-u*v - u^2))*y + (-w^2 -␣
↪u*v)*z)*x
```

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```
....:       + ((-w^2 - u*w - u^2)*y^2 + (-u*w - v^2)*z*y + (-w^2 + (-v -␣
↪u)*w)*z^2))
sage: W = X.subscheme([L, Q])
sage: W.dimension()                                                    #␣
↪needs sage.libs.singular
2
```

```
>>> from sage.all import *
>>> X = ProductProjectiveSpaces([Integer(2), Integer(2)], QQ, names=('x', 'y',
↪ 'z', 'w', 'u', 'v',)); (x, y, z, w, u, v,) = X._first_ngens(6)
>>> L = (-w - v)*x + (-w*y - u*z)
>>> Q = ((-u*w - v**Integer(2))*x**Integer(2) + ((-w**Integer(2) - u*w + (-
↪u*v - u**Integer(2)))*y + (-w**Integer(2) - u*v)*z)*x
...       + ((-w**Integer(2) - u*w - u**Integer(2))*y**Integer(2) + (-u*w -␣
↪v**Integer(2))*z*y + (-w**Integer(2) + (-v - u)*w)*z**Integer(2)))
>>> W = X.subscheme([L, Q])
>>> W.dimension()                                                      #␣
↪needs sage.libs.singular
2
```

```
sage: PP.<x,y,z,u,v,s,t> = ProductProjectiveSpaces([2, 1, 1], QQ)
sage: X = PP.subscheme([x^3, x^5 + y^5, z^6, x*u - v*y, s^2 - t^2])
sage: X.dimension()                                                    #␣
↪needs sage.libs.singular
-1
```

```
>>> from sage.all import *
>>> PP = ProductProjectiveSpaces([Integer(2), Integer(1), Integer(1)], QQ,␣
↪names=('x', 'y', 'z', 'u', 'v', 's', 't',)); (x, y, z, u, v, s, t,) = PP._
↪first_ngens(7)
>>> X = PP.subscheme([x**Integer(3), x**Integer(5) + y**Integer(5),␣
↪z**Integer(6), x*u - v*y, s**Integer(2) - t**Integer(2)])
>>> X.dimension()                                                      #␣
↪needs sage.libs.singular
-1
```

```
sage: PP = ProductProjectiveSpaces([2, 1, 3], CC, 't')                 #␣
↪needs sage.rings.real_mpfr
sage: PP.subscheme([]).dimension()                                     #␣
↪needs sage.libs.singular sage.rings.real_mpfr
6
```

```
>>> from sage.all import *
>>> PP = ProductProjectiveSpaces([Integer(2), Integer(1), Integer(3)], CC, 't
↪')                       # needs sage.rings.real_mpfr
>>> PP.subscheme([]).dimension()                                       #␣
↪needs sage.libs.singular sage.rings.real_mpfr
6
```

```
sage: PP = ProductProjectiveSpaces([1, 3, 1], ZZ, 't')
```

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```
sage: PP.subscheme([]).dimension()                                          #␣
↪needs sage.libs.singular
5
```

```
>>> from sage.all import *
>>> PP = ProductProjectiveSpaces([Integer(1), Integer(3), Integer(1)], ZZ, 't
↪')
>>> PP.subscheme([]).dimension()                                            #␣
↪needs sage.libs.singular
5
```

```
sage: PP.<x,y,u,v,s,t> = ProductProjectiveSpaces([1,1,1], CC)               #␣
↪needs sage.rings.real_mpfr
sage: X = PP.subscheme([x^2 - y^2, u - v, s^2 - t^2])                       #␣
↪needs sage.libs.singular sage.rings.real_mpfr
sage: X.dimension()                                                         #␣
↪needs sage.libs.singular sage.rings.real_mpfr
0
```

```
>>> from sage.all import *
>>> PP = ProductProjectiveSpaces([Integer(1),Integer(1),Integer(1)], CC,␣
↪names=('x', 'y', 'u', 'v', 's', 't',)); (x, y, u, v, s, t,) = PP._first_
↪ngens(6)# needs sage.rings.real_mpfr
>>> X = PP.subscheme([x**Integer(2) - y**Integer(2), u - v, s**Integer(2) -␣
↪t**Integer(2)])                      # needs sage.libs.singular sage.rings.
↪real_mpfr
>>> X.dimension()                                                           #␣
↪needs sage.libs.singular sage.rings.real_mpfr
0
```

intersection_multiplicity(X, P)

Return the intersection multiplicity of this subscheme and the subscheme `X` at the point `P`.

This uses the intersection_multiplicity function for affine subschemes on affine patches of this subscheme and `X` that contain `P`.

INPUT:

- `X` – subscheme in the same ambient space as this subscheme
- `P` – a point in the intersection of this subscheme with `X`

OUTPUT: integer

EXAMPLES:

Multiplicity of a fixed point of the map $z^2 + \frac{1}{4}$:

```
sage: PP.<x,y,u,v> = ProductProjectiveSpaces(QQ, [1, 1])
sage: G = PP.subscheme([(x^2 + 1/4*y^2)*v - y^2*u])
sage: D = PP.subscheme([x*v - y*u])
sage: sorted(G.intersection(D).rational_points())                           #␣
↪needs sage.libs.singular
[(1/2 : 1 , 1/2 : 1), (1 : 0 , 1 : 0)]
sage: Q = PP([1/2,1,1/2,1])
```

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```
sage: G.intersection_multiplicity(D, Q)                                    #␣
↪needs sage.libs.singular
2
```

```
>>> from sage.all import *
>>> PP = ProductProjectiveSpaces(QQ, [Integer(1), Integer(1)], names=('x', 'y
↪', 'u', 'v',)); (x, y, u, v,) = PP._first_ngens(4)
>>> G = PP.subscheme([(x**Integer(2) + Integer(1)/Integer(4)*y**Integer(2))*v␣
↪- y**Integer(2)*u])
>>> D = PP.subscheme([x*v - y*u])
>>> sorted(G.intersection(D).rational_points())                             #␣
↪needs sage.libs.singular
[(1/2 : 1 , 1/2 : 1), (1 : 0 , 1 : 0)]
>>> Q = PP([Integer(1)/Integer(2),Integer(1),Integer(1)/Integer(2),
↪Integer(1)])
>>> G.intersection_multiplicity(D, Q)                                       #␣
↪needs sage.libs.singular
2
```

```
sage: # needs sage.rings.finite_rings
sage: F.<a> = GF(4)
sage: PP.<x,y,z,u,v,w> = ProductProjectiveSpaces(F, [2, 2])
sage: X = PP.subscheme([z^5 + 3*x*y^4 + 8*y^5, u^2 - v^2])
sage: Y = PP.subscheme([x^6 + z^6, w*z - v*y])
sage: Q = PP([a,a+1,1,a,a,1])
sage: X.intersection_multiplicity(Y, Q)                                    #␣
↪needs sage.libs.singular
16
```

```
>>> from sage.all import *
>>> # needs sage.rings.finite_rings
>>> F = GF(Integer(4), names=('a',)); (a,) = F._first_ngens(1)
>>> PP = ProductProjectiveSpaces(F, [Integer(2), Integer(2)], names=('x', 'y',
↪ 'z', 'u', 'v', 'w',)); (x, y, z, u, v, w,) = PP._first_ngens(6)
>>> X = PP.subscheme([z**Integer(5) + Integer(3)*x*y**Integer(4) +␣
↪Integer(8)*y**Integer(5), u**Integer(2) - v**Integer(2)])
>>> Y = PP.subscheme([x**Integer(6) + z**Integer(6), w*z - v*y])
>>> Q = PP([a,a+Integer(1),Integer(1),a,a,Integer(1)])
>>> X.intersection_multiplicity(Y, Q)                                       #␣
↪needs sage.libs.singular
16
```

```
sage: PP.<x,y,z,u,v,w> = ProductProjectiveSpaces(QQ, [2, 2])
sage: X = PP.subscheme([x^2*u^3 + y*z*u*v^2, x - y])
sage: Y = PP.subscheme([u^3 - w^3, x*v - y*w, z^3*w^2 - y^3*u*v])
sage: Q = PP([0,0,1,0,1,0])
sage: X.intersection_multiplicity(Y, Q)                                    #␣
↪needs sage.libs.singular
Traceback (most recent call last):
...
TypeError: the intersection of this subscheme and (=Closed subscheme of␣
```

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```
↪Affine Space of dimension 4
over Rational Field defined by: x2^3 - x3^3, -x1*x3 + x0, -x1^3*x2 + x3^2)␣
↪must be proper and finite
```

```
>>> from sage.all import *
>>> PP = ProductProjectiveSpaces(QQ, [Integer(2), Integer(2)], names=('x', 'y
↪', 'z', 'u', 'v', 'w',)); (x, y, z, u, v, w,) = PP._first_ngens(6)
>>> X = PP.subscheme([x**Integer(2)*u**Integer(3) + y*z*u*v**Integer(2), x -␣
↪y])
>>> Y = PP.subscheme([u**Integer(3) - w**Integer(3), x*v - y*w,␣
↪z**Integer(3)*w**Integer(2) - y**Integer(3)*u*v])
>>> Q = PP([Integer(0),Integer(0),Integer(1),Integer(0),Integer(1),
↪Integer(0)])
>>> X.intersection_multiplicity(Y, Q)                                    #␣
↪needs sage.libs.singular
Traceback (most recent call last):
...
TypeError: the intersection of this subscheme and (=Closed subscheme of␣
↪Affine Space of dimension 4
over Rational Field defined by: x2^3 - x3^3, -x1*x3 + x0, -x1^3*x2 + x3^2)␣
↪must be proper and finite
```

is_smooth(*point=None*)

Test whether the algebraic subscheme is smooth.

EXAMPLES:

```
sage: X.<x,y,z,w,u,v> = ProductProjectiveSpaces([2, 2],QQ)
sage: L = (-w - v)*x + (-w*y - u*z)
sage: Q = ((-u*w - v^2)*x^2 + ((-w^2 - u*w + (-u*v - u^2))*y + (-w^2 -␣
↪u*v)*z)*x
....:       + ((-w^2 - u*w - u^2)*y^2 + (-u*w - v^2)*z*y + (-w^2 + (-v -␣
↪u)*w)*z^2))
sage: W = X.subscheme([L, Q])
sage: W.is_smooth()
Traceback (most recent call last):
...
NotImplementedError: Not Implemented
```

```
>>> from sage.all import *
>>> X = ProductProjectiveSpaces([Integer(2), Integer(2)],QQ, names=('x', 'y',
↪'z', 'w', 'u', 'v',)); (x, y, z, w, u, v,) = X._first_ngens(6)
>>> L = (-w - v)*x + (-w*y - u*z)
>>> Q = ((-u*w - v**Integer(2))*x**Integer(2) + ((-w**Integer(2) - u*w + (-
↪u*v - u**Integer(2)))*y + (-w**Integer(2) - u*v)*z)*x
...       + ((-w**Integer(2) - u*w - u**Integer(2))*y**Integer(2) + (-u*w -␣
↪v**Integer(2))*z*y + (-w**Integer(2) + (-v - u)*w)*z**Integer(2)))
>>> W = X.subscheme([L, Q])
>>> W.is_smooth()
Traceback (most recent call last):
...
NotImplementedError: Not Implemented
```

multiplicity(*P*)

Return the multiplicity of `P` on this subscheme.

This is computed as the multiplicity of the corresponding point on an affine patch of this subscheme that contains `P`. This subscheme must be defined over a field. An error is returned if `P` not a point on this subscheme.

INPUT:

- `P` – a point on this subscheme

OUTPUT: integer

EXAMPLES:

```
sage: PP.<x,y,z,w> = ProductProjectiveSpaces(QQ, [1, 1])
sage: X = PP.subscheme([x^4*z^3 - y^4*w^3])
sage: Q1 = PP([1,1,1,1])
sage: X.multiplicity(Q1)                                                    #␣
↪needs sage.libs.singular
1
sage: Q2 = PP([0,1,1,0])
sage: X.multiplicity(Q2)                                                    #␣
↪needs sage.libs.singular
3
```

```
>>> from sage.all import *
>>> PP = ProductProjectiveSpaces(QQ, [Integer(1), Integer(1)], names=('x', 'y
↪', 'z', 'w',)); (x, y, z, w,) = PP._first_ngens(4)
>>> X = PP.subscheme([x**Integer(4)*z**Integer(3) -␣
↪y**Integer(4)*w**Integer(3)])
>>> Q1 = PP([Integer(1),Integer(1),Integer(1),Integer(1)])
>>> X.multiplicity(Q1)                                                      #␣
↪needs sage.libs.singular
1
>>> Q2 = PP([Integer(0),Integer(1),Integer(1),Integer(0)])
>>> X.multiplicity(Q2)                                                      #␣
↪needs sage.libs.singular
3
```

```
sage: PP.<x,y,z,w,u> = ProductProjectiveSpaces(GF(11), [1,2])
sage: X = PP.subscheme([x^7*u - y^7*z, u^6*x^2 - w^3*z^3*x*y - w^6*y^2])
sage: Q1 = PP([1,0,10,1,0])
sage: X.multiplicity(Q1)                                                    #␣
↪needs sage.libs.singular sage.rings.finite_rings
1
sage: Q2 = PP([1,0,1,0,0])
sage: X.multiplicity(Q2)                                                    #␣
↪needs sage.libs.singular sage.rings.finite_rings
4
```

```
>>> from sage.all import *
>>> PP = ProductProjectiveSpaces(GF(Integer(11)), [Integer(1),Integer(2)],␣
↪names=('x', 'y', 'z', 'w', 'u',)); (x, y, z, w, u,) = PP._first_ngens(5)
>>> X = PP.subscheme([x**Integer(7)*u - y**Integer(7)*z,␣
↪u**Integer(6)*x**Integer(2) - w**Integer(3)*z**Integer(3)*x*y -␣
```

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```
↪w**Integer(6)*y**Integer(2)])
>>> Q1 = PP([Integer(1),Integer(0),Integer(10),Integer(1),Integer(0)])
>>> X.multiplicity(Q1)                                                    #␣
↪needs sage.libs.singular sage.rings.finite_rings
1
>>> Q2 = PP([Integer(1),Integer(0),Integer(1),Integer(0),Integer(0)])
>>> X.multiplicity(Q2)                                                    #␣
↪needs sage.libs.singular sage.rings.finite_rings
4
```

segre_embedding(*PP=None*)

Return the Segre embedding of this subscheme into the appropriate projective space.

INPUT:

- `PP` – (default: `None`) ambient image projective space; this is constructed if it is not given

OUTPUT: hom from this subscheme to the appropriate subscheme of projective space

EXAMPLES:

```
sage: X.<x,y,z,w,u,v> = ProductProjectiveSpaces([2, 2], QQ)
sage: P = ProjectiveSpace(QQ, 8, 't')
sage: L = (-w - v)*x + (-w*y - u*z)
sage: Q = ((-u*w - v^2)*x^2 + ((-w^2 - u*w + (-u*v - u^2))*y + (-w^2 -␣
↪u*v)*z)*x
....:       + ((-w^2 - u*w - u^2)*y^2 + (-u*w - v^2)*z*y + (-w^2 + (-v -␣
↪u)*w)*z^2))
sage: W = X.subscheme([L,Q])
sage: phi = W.segre_embedding(P)                                          #␣
↪needs sage.libs.singular
sage: phi.codomain().ambient_space() == P                                 #␣
↪needs sage.libs.singular
True
```

```
>>> from sage.all import *
>>> X = ProductProjectiveSpaces([Integer(2), Integer(2)], QQ, names=('x', 'y',
↪ 'z', 'w', 'u', 'v',)); (x, y, z, w, u, v,) = X._first_ngens(6)
>>> P = ProjectiveSpace(QQ, Integer(8), 't')
>>> L = (-w - v)*x + (-w*y - u*z)
>>> Q = ((-u*w - v**Integer(2))*x**Integer(2) + ((-w**Integer(2) - u*w + (-
↪u*v - u**Integer(2)))*y + (-w**Integer(2) - u*v)*z)*x
...       + ((-w**Integer(2) - u*w - u**Integer(2))*y**Integer(2) + (-u*w -␣
↪v**Integer(2))*z*y + (-w**Integer(2) + (-v - u)*w)*z**Integer(2)))
>>> W = X.subscheme([L,Q])
>>> phi = W.segre_embedding(P)                                            #␣
↪needs sage.libs.singular
>>> phi.codomain().ambient_space() == P                                   #␣
↪needs sage.libs.singular
True
```

```
sage: PP.<x,y,u,v,s,t> = ProductProjectiveSpaces([1, 1, 1], CC)           #␣
↪needs sage.rings.real_mpfr
```

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```
sage: PP.subscheme([]).segre_embedding()                                    #␣
↪needs sage.libs.singular sage.rings.real_mpfr
Scheme morphism:
  From: Closed subscheme of Product of projective spaces P^1 x P^1 x P^1
        over Complex Field with 53 bits of precision defined by:
          (no polynomials)
  To:   Closed subscheme of Projective Space of dimension 7
        over Complex Field with 53 bits of precision defined by:
          -u5*u6 + u4*u7,       -u3*u6 + u2*u7,       -u3*u4 + u2*u5,
          -u3*u5 + u1*u7,       -u3*u4 + u1*u6,       -u3*u4 + u0*u7,
          -u2*u4 + u0*u6,       -u1*u4 + u0*u5,       -u1*u2 + u0*u3
  Defn: Defined by sending (x : y , u : v , s : t) to
        (x*u*s : x*u*t : x*v*s : x*v*t : y*u*s : y*u*t : y*v*s : y*v*t).
```

```
>>> from sage.all import *
>>> PP = ProductProjectiveSpaces([Integer(1), Integer(1), Integer(1)], CC,␣
↪names=('x', 'y', 'u', 'v', 's', 't',)); (x, y, u, v, s, t,) = PP._first_
↪ngens(6)# needs sage.rings.real_mpfr
>>> PP.subscheme([]).segre_embedding()                                      #␣
↪needs sage.libs.singular sage.rings.real_mpfr
Scheme morphism:
  From: Closed subscheme of Product of projective spaces P^1 x P^1 x P^1
        over Complex Field with 53 bits of precision defined by:
          (no polynomials)
  To:   Closed subscheme of Projective Space of dimension 7
        over Complex Field with 53 bits of precision defined by:
          -u5*u6 + u4*u7,       -u3*u6 + u2*u7,       -u3*u4 + u2*u5,
          -u3*u5 + u1*u7,       -u3*u4 + u1*u6,       -u3*u4 + u0*u7,
          -u2*u4 + u0*u6,       -u1*u4 + u0*u5,       -u1*u2 + u0*u3
  Defn: Defined by sending (x : y , u : v , s : t) to
        (x*u*s : x*u*t : x*v*s : x*v*t : y*u*s : y*u*t : y*v*s : y*v*t).
```

```
sage: PP.<x,y,z,u,v,s,t> = ProductProjectiveSpaces([2, 1, 1], ZZ)
sage: PP.subscheme([x^3, u - v, s^2 - t^2]).segre_embedding()               #␣
↪needs sage.libs.singular
Scheme morphism:
  From: Closed subscheme of Product of projective spaces P^2 x P^1 x P^1
        over Integer Ring defined by:
          x^3,                  u - v,                s^2 - t^2
  To:   Closed subscheme of Projective Space of dimension 11
        over Integer Ring defined by:
          u10^2 - u11^2,        u9 - u11,             u8 - u10,
          -u7*u10 + u6*u11,     u6*u10 - u7*u11,      u6^2 - u7^2,
          u5 - u7,              u4 - u6,              u3^3,
          -u3*u10 + u2*u11,     u2*u10 - u3*u11,      -u3*u6 + u2*u7,
          u2*u6 - u3*u7,        u2*u3^2,              u2^2 - u3^2,
          u1 - u3,              u0 - u2
  Defn: Defined by sending (x : y : z , u : v , s : t) to
        (x*u*s : x*u*t : x*v*s : x*v*t : y*u*s : y*u*t : y*v*s : y*v*t
         : z*u*s : z*u*t : z*v*s : z*v*t).
```

```
>>> from sage.all import *
>>> PP = ProductProjectiveSpaces([Integer(2), Integer(1), Integer(1)], ZZ,␣
↪names=('x', 'y', 'z', 'u', 'v', 's', 't',)); (x, y, z, u, v, s, t,) = PP._
↪first_ngens(7)
>>> PP.subscheme([x**Integer(3), u - v, s**Integer(2) - t**Integer(2)]).segre_
↪embedding()                # needs sage.libs.singular
Scheme morphism:
  From: Closed subscheme of Product of projective spaces P^2 x P^1 x P^1
        over Integer Ring defined by:
          x^3,                  u - v,                s^2 - t^2
  To:   Closed subscheme of Projective Space of dimension 11
        over Integer Ring defined by:
          u10^2 - u11^2,        u9 - u11,             u8 - u10,
          -u7*u10 + u6*u11,     u6*u10 - u7*u11,      u6^2 - u7^2,
          u5 - u7,              u4 - u6,              u3^3,
          -u3*u10 + u2*u11,     u2*u10 - u3*u11,      -u3*u6 + u2*u7,
          u2*u6 - u3*u7,        u2*u3^2,              u2^2 - u3^2,
          u1 - u3,              u0 - u2
  Defn: Defined by sending (x : y : z , u : v , s : t) to
        (x*u*s : x*u*t : x*v*s : x*v*t : y*u*s : y*u*t : y*v*s : y*v*t
         : z*u*s : z*u*t : z*v*s : z*v*t).
```

15.6 Enumeration of rational points on product projective schemes

Naive algorithms for enumerating rational points over **Q**, number fields or finite fields over general schemes.

Warning

Incorrect results and infinite loops may occur if using a wrong function. (For instance using an affine function for a product projective scheme or a finite field function for a scheme defined over an infinite field.)

EXAMPLES:

Product Projective, over **Q**:

```
sage: PP.<x,y,z> = ProductProjectiveSpaces([1,0], QQ)
sage: from sage.schemes.product_projective.rational_point import \
....:   enum_product_projective_rational_field
sage: enum_product_projective_rational_field(PP, 3)
[(-3 : 1 , 1), (-2 : 1 , 1), (-3/2 : 1 , 1),
 (-1 : 1 , 1), (-2/3 : 1 , 1), (-1/2 : 1 , 1),
 (-1/3 : 1 , 1), (0 : 1 , 1), (1/3 : 1 , 1),
 (1/2 : 1 , 1), (2/3 : 1 , 1), (1 : 0 , 1),
 (1 : 1 , 1), (3/2 : 1 , 1), (2 : 1 , 1),
 (3 : 1 , 1)]
```

```
>>> from sage.all import *
>>> PP = ProductProjectiveSpaces([Integer(1),Integer(0)], QQ, names=('x', 'y', 'z',));
↪ (x, y, z,) = PP._first_ngens(3)
>>> from sage.schemes.product_projective.rational_point import   enum_product_
↪projective_rational_field
```

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```
>>> enum_product_projective_rational_field(PP, Integer(3))
[(-3 : 1 , 1), (-2 : 1 , 1), (-3/2 : 1 , 1),
 (-1 : 1 , 1), (-2/3 : 1 , 1), (-1/2 : 1 , 1),
 (-1/3 : 1 , 1), (0 : 1 , 1), (1/3 : 1 , 1),
 (1/2 : 1 , 1), (2/3 : 1 , 1), (1 : 0 , 1),
 (1 : 1 , 1), (3/2 : 1 , 1), (2 : 1 , 1),
 (3 : 1 , 1)]
```

Product projective over finite field:

```
sage: P1.<x,y,a,b> = ProductProjectiveSpaces([1, 1], GF(7))
sage: X = P1.subscheme([2*x + 3*y])
sage: from sage.schemes.product_projective.rational_point import \
....:   enum_product_projective_finite_field
sage: enum_product_projective_finite_field(X)
[(2 : 1 , 0 : 1), (2 : 1 , 1 : 0), (2 : 1 , 1 : 1),
 (2 : 1 , 2 : 1), (2 : 1 , 3 : 1), (2 : 1 , 4 : 1),
 (2 : 1 , 5 : 1), (2 : 1 , 6 : 1)]
```

```
>>> from sage.all import *
>>> P1 = ProductProjectiveSpaces([Integer(1), Integer(1)], GF(Integer(7)), names=('x',
↪ 'y', 'a', 'b',)); (x, y, a, b,) = P1._first_ngens(4)
>>> X = P1.subscheme([Integer(2)*x + Integer(3)*y])
>>> from sage.schemes.product_projective.rational_point import   enum_product_
↪projective_finite_field
>>> enum_product_projective_finite_field(X)
[(2 : 1 , 0 : 1), (2 : 1 , 1 : 0), (2 : 1 , 1 : 1),
 (2 : 1 , 2 : 1), (2 : 1 , 3 : 1), (2 : 1 , 4 : 1),
 (2 : 1 , 5 : 1), (2 : 1 , 6 : 1)]
```

AUTHORS:

- Volker Braun and Ben Hutz (2014): initial version
- Raghukul Raman (2018): code cleanup and added support for rational fields

sage.schemes.product_projective.rational_point.**enum_product_projective_finite_field**(*X*)

Enumerates projective points on scheme X defined over a finite field.

INPUT:

- X – a scheme defined over a finite field or a set of abstract rational points of such a scheme

OUTPUT:

A list containing the projective points of X over the finite field, sorted.

EXAMPLES:

```
sage: PP.<x,y,z,w> = ProductProjectiveSpaces([1, 1], GF(3))
sage: from sage.schemes.product_projective.rational_point import \
....:   enum_product_projective_finite_field
sage: enum_product_projective_finite_field(PP)
[(0 : 1 , 0 : 1), (0 : 1 , 1 : 0), (0 : 1 , 1 : 1),
 (0 : 1 , 2 : 1), (1 : 0 , 0 : 1), (1 : 0 , 1 : 0),
 (1 : 0 , 1 : 1), (1 : 0 , 2 : 1), (1 : 1 , 0 : 1),
```

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```
 (1 : 1 , 1 : 0), (1 : 1 , 1 : 1), (1 : 1 , 2 : 1),
 (2 : 1 , 0 : 1), (2 : 1 , 1 : 0), (2 : 1 , 1 : 1),
 (2 : 1 , 2 : 1)]
```

```
>>> from sage.all import *
>>> PP = ProductProjectiveSpaces([Integer(1), Integer(1)], GF(Integer(3)), names=(
↪'x', 'y', 'z', 'w',)); (x, y, z, w,) = PP._first_ngens(4)
>>> from sage.schemes.product_projective.rational_point import   enum_product_
↪projective_finite_field
>>> enum_product_projective_finite_field(PP)
[(0 : 1 , 0 : 1), (0 : 1 , 1 : 0), (0 : 1 , 1 : 1),
 (0 : 1 , 2 : 1), (1 : 0 , 0 : 1), (1 : 0 , 1 : 0),
 (1 : 0 , 1 : 1), (1 : 0 , 2 : 1), (1 : 1 , 0 : 1),
 (1 : 1 , 1 : 0), (1 : 1 , 1 : 1), (1 : 1 , 2 : 1),
 (2 : 1 , 0 : 1), (2 : 1 , 1 : 0), (2 : 1 , 1 : 1),
 (2 : 1 , 2 : 1)]
```

```
sage: PP.<x0,x1,x2,x3> = ProductProjectiveSpaces([1, 1], GF(17))
sage: X = PP.subscheme([x0^2 + 2*x1^2])
sage: from sage.schemes.product_projective.rational_point import \
....:   enum_product_projective_finite_field
sage: len(enum_product_projective_finite_field(X))
36
```

```
>>> from sage.all import *
>>> PP = ProductProjectiveSpaces([Integer(1), Integer(1)], GF(Integer(17)),␣
↪names=('x0', 'x1', 'x2', 'x3',)); (x0, x1, x2, x3,) = PP._first_ngens(4)
>>> X = PP.subscheme([x0**Integer(2) + Integer(2)*x1**Integer(2)])
>>> from sage.schemes.product_projective.rational_point import   enum_product_
↪projective_finite_field
>>> len(enum_product_projective_finite_field(X))
36
```

sage.schemes.product_projective.rational_point.**enum_product_projective_number_field**(*X*, ***kwds*)

Enumerates product projective points on scheme X defined over a number field.

Simply checks all of the points of absolute height of at most B and adds those that are on the scheme to the list.

This algorithm computes 2 lists: L containing elements x in K such that H_k(x) <= B, and a list L' containing elements x in K that, due to floating point issues, may be slightly larger then the bound. This can be controlled by lowering the tolerance.

ALGORITHM:

This is an implementation of the revised algorithm (Algorithm 4) in [DK2013]. Algorithm 5 is used for imaginary quadratic fields.

INPUT: keyword arguments:

- bound – a real number
- tolerance – a rational number in (0,1] used in Doyle-Krumm algorithm-4
- precision – the precision to use for computing the elements of bounded height of number fields

OUTPUT:

A list containing the product projective points of X of absolute height up to B, sorted.

EXAMPLES:

```
sage: # needs sage.rings.number_field
sage: u = QQ['u'].0
sage: K = NumberField(u^2 + 2, 'v')
sage: PP.<x,y,z,w> = ProductProjectiveSpaces([1, 1], K)
sage: X = PP.subscheme([x^2 + 2*y^2])
sage: from sage.schemes.product_projective.rational_point import \
....:   enum_product_projective_number_field
sage: enum_product_projective_number_field(X, bound=1.5)
[(-v : 1 , -1 : 1), (-v : 1 , -v : 1), (-v : 1 , -1/2*v : 1),
 (-v : 1 , 0 : 1), (-v : 1 , 1/2*v : 1), (-v : 1 , v : 1),
 (-v : 1 , 1 : 0), (-v : 1 , 1 : 1), (v : 1 , -1 : 1),
 (v : 1 , -v : 1), (v : 1 , -1/2*v : 1), (v : 1 , 0 : 1),
 (v : 1 , 1/2*v : 1), (v : 1 , v : 1), (v : 1 , 1 : 0),
 (v : 1 , 1 : 1)]
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> u = QQ['u'].gen(0)
>>> K = NumberField(u**Integer(2) + Integer(2), 'v')
>>> PP = ProductProjectiveSpaces([Integer(1), Integer(1)], K, names=('x', 'y', 'z
↪', 'w',)); (x, y, z, w,) = PP._first_ngens(4)
>>> X = PP.subscheme([x**Integer(2) + Integer(2)*y**Integer(2)])
>>> from sage.schemes.product_projective.rational_point import   enum_product_
↪projective_number_field
>>> enum_product_projective_number_field(X, bound=RealNumber('1.5'))
[(-v : 1 , -1 : 1), (-v : 1 , -v : 1), (-v : 1 , -1/2*v : 1),
 (-v : 1 , 0 : 1), (-v : 1 , 1/2*v : 1), (-v : 1 , v : 1),
 (-v : 1 , 1 : 0), (-v : 1 , 1 : 1), (v : 1 , -1 : 1),
 (v : 1 , -v : 1), (v : 1 , -1/2*v : 1), (v : 1 , 0 : 1),
 (v : 1 , 1/2*v : 1), (v : 1 , v : 1), (v : 1 , 1 : 0),
 (v : 1 , 1 : 1)]
```

sage.schemes.product_projective.rational_point.**enum_product_projective_rational_field**(*X*, *B*)

Enumerate projective, rational points on scheme X of height up to bound B.

INPUT:

- X – a scheme or set of abstract rational points of a scheme
- B – positive integer bound

OUTPUT:

A list containing the product projective points of X of height up to B, sorted.

EXAMPLES:

```
sage: PP.<x0,x1,x2,x3,x4> = ProductProjectiveSpaces([1, 2], QQ)
sage: from sage.schemes.product_projective.rational_point import \
....:   enum_product_projective_rational_field
```

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```
sage: enum_product_projective_rational_field(PP, 1)
[(-1 : 1 , -1 : -1 : 1), (-1 : 1 , -1 : 0 : 1), (-1 : 1 , -1 : 1 : 0),
 (-1 : 1 , -1 : 1 : 1), (-1 : 1 , 0 : -1 : 1), (-1 : 1 , 0 : 0 : 1),
 (-1 : 1 , 0 : 1 : 0), (-1 : 1 , 0 : 1 : 1), (-1 : 1 , 1 : -1 : 1),
 (-1 : 1 , 1 : 0 : 0), (-1 : 1 , 1 : 0 : 1), (-1 : 1 , 1 : 1 : 0),
 (-1 : 1 , 1 : 1 : 1), (0 : 1 , -1 : -1 : 1), (0 : 1 , -1 : 0 : 1),
 (0 : 1 , -1 : 1 : 0), (0 : 1 , -1 : 1 : 1), (0 : 1 , 0 : -1 : 1),
 (0 : 1 , 0 : 0 : 1), (0 : 1 , 0 : 1 : 0), (0 : 1 , 0 : 1 : 1),
 (0 : 1 , 1 : -1 : 1), (0 : 1 , 1 : 0 : 0), (0 : 1 , 1 : 0 : 1),
 (0 : 1 , 1 : 1 : 0), (0 : 1 , 1 : 1 : 1), (1 : 0 , -1 : -1 : 1),
 (1 : 0 , -1 : 0 : 1), (1 : 0 , -1 : 1 : 0), (1 : 0 , -1 : 1 : 1),
 (1 : 0 , 0 : -1 : 1), (1 : 0 , 0 : 0 : 1), (1 : 0 , 0 : 1 : 0),
 (1 : 0 , 0 : 1 : 1), (1 : 0 , 1 : -1 : 1), (1 : 0 , 1 : 0 : 0),
 (1 : 0 , 1 : 0 : 1), (1 : 0 , 1 : 1 : 0), (1 : 0 , 1 : 1 : 1),
 (1 : 1 , -1 : -1 : 1), (1 : 1 , -1 : 0 : 1), (1 : 1 , -1 : 1 : 0),
 (1 : 1 , -1 : 1 : 1), (1 : 1 , 0 : -1 : 1), (1 : 1 , 0 : 0 : 1),
 (1 : 1 , 0 : 1 : 0), (1 : 1 , 0 : 1 : 1), (1 : 1 , 1 : -1 : 1),
 (1 : 1 , 1 : 0 : 0), (1 : 1 , 1 : 0 : 1), (1 : 1 , 1 : 1 : 0),
 (1 : 1 , 1 : 1 : 1)]
```

```
>>> from sage.all import *
>>> PP = ProductProjectiveSpaces([Integer(1), Integer(2)], QQ, names=('x0', 'x1',
↪'x2', 'x3', 'x4',)); (x0, x1, x2, x3, x4,) = PP._first_ngens(5)
>>> from sage.schemes.product_projective.rational_point import   enum_product_
↪projective_rational_field
>>> enum_product_projective_rational_field(PP, Integer(1))
[(-1 : 1 , -1 : -1 : 1), (-1 : 1 , -1 : 0 : 1), (-1 : 1 , -1 : 1 : 0),
 (-1 : 1 , -1 : 1 : 1), (-1 : 1 , 0 : -1 : 1), (-1 : 1 , 0 : 0 : 1),
 (-1 : 1 , 0 : 1 : 0), (-1 : 1 , 0 : 1 : 1), (-1 : 1 , 1 : -1 : 1),
 (-1 : 1 , 1 : 0 : 0), (-1 : 1 , 1 : 0 : 1), (-1 : 1 , 1 : 1 : 0),
 (-1 : 1 , 1 : 1 : 1), (0 : 1 , -1 : -1 : 1), (0 : 1 , -1 : 0 : 1),
 (0 : 1 , -1 : 1 : 0), (0 : 1 , -1 : 1 : 1), (0 : 1 , 0 : -1 : 1),
 (0 : 1 , 0 : 0 : 1), (0 : 1 , 0 : 1 : 0), (0 : 1 , 0 : 1 : 1),
 (0 : 1 , 1 : -1 : 1), (0 : 1 , 1 : 0 : 0), (0 : 1 , 1 : 0 : 1),
 (0 : 1 , 1 : 1 : 0), (0 : 1 , 1 : 1 : 1), (1 : 0 , -1 : -1 : 1),
 (1 : 0 , -1 : 0 : 1), (1 : 0 , -1 : 1 : 0), (1 : 0 , -1 : 1 : 1),
 (1 : 0 , 0 : -1 : 1), (1 : 0 , 0 : 0 : 1), (1 : 0 , 0 : 1 : 0),
 (1 : 0 , 0 : 1 : 1), (1 : 0 , 1 : -1 : 1), (1 : 0 , 1 : 0 : 0),
 (1 : 0 , 1 : 0 : 1), (1 : 0 , 1 : 1 : 0), (1 : 0 , 1 : 1 : 1),
 (1 : 1 , -1 : -1 : 1), (1 : 1 , -1 : 0 : 1), (1 : 1 , -1 : 1 : 0),
 (1 : 1 , -1 : 1 : 1), (1 : 1 , 0 : -1 : 1), (1 : 1 , 0 : 0 : 1),
 (1 : 1 , 0 : 1 : 0), (1 : 1 , 0 : 1 : 1), (1 : 1 , 1 : -1 : 1),
 (1 : 1 , 1 : 0 : 0), (1 : 1 , 1 : 0 : 1), (1 : 1 , 1 : 1 : 0),
 (1 : 1 , 1 : 1 : 1)]
```

```
sage: PP.<x,y,z,u,v> = ProductProjectiveSpaces([2, 1], QQ)
sage: X = PP.subscheme([x^2 + x*y + y*z, u*u - v*u])
sage: from sage.schemes.product_projective.rational_point import \
....:   enum_product_projective_rational_field
sage: enum_product_projective_rational_field(X, 4)
[(-2 : 4 : 1 , 0 : 1), (-2 : 4 : 1 , 1 : 1), (-1 : 1 : 0 , 0 : 1),
```

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```
 (-1 : 1 : 0 , 1 : 1), (-2/3 : -4/3 : 1 , 0 : 1), (-2/3 : -4/3 : 1 , 1 : 1),
 (-1/2 : -1/2 : 1 , 0 : 1), (-1/2 : -1/2 : 1 , 1 : 1),
 (0 : 0 : 1 , 0 : 1), (0 : 0 : 1 , 1 : 1), (0 : 1 : 0 , 0 : 1),
 (0 : 1 : 0 , 1 : 1), (1 : -1/2 : 1 , 0 : 1), (1 : -1/2 : 1 , 1 : 1)]
```

```
>>> from sage.all import *
>>> PP = ProductProjectiveSpaces([Integer(2), Integer(1)], QQ, names=('x', 'y', 'z
↪', 'u', 'v',)); (x, y, z, u, v,) = PP._first_ngens(5)
>>> X = PP.subscheme([x**Integer(2) + x*y + y*z, u*u - v*u])
>>> from sage.schemes.product_projective.rational_point import   enum_product_
↪projective_rational_field
>>> enum_product_projective_rational_field(X, Integer(4))
[(-2 : 4 : 1 , 0 : 1), (-2 : 4 : 1 , 1 : 1), (-1 : 1 : 0 , 0 : 1),
 (-1 : 1 : 0 , 1 : 1), (-2/3 : -4/3 : 1 , 0 : 1), (-2/3 : -4/3 : 1 , 1 : 1),
 (-1/2 : -1/2 : 1 , 0 : 1), (-1/2 : -1/2 : 1 , 1 : 1),
 (0 : 0 : 1 , 0 : 1), (0 : 0 : 1 , 1 : 1), (0 : 1 : 0 , 0 : 1),
 (0 : 1 : 0 , 1 : 1), (1 : -1/2 : 1 , 0 : 1), (1 : -1/2 : 1 , 1 : 1)]
```

sage.schemes.product_projective.rational_point.**sieve**(*X*, *bound*)

Return the list of all rational points on scheme `X` of height up to `bound`.

ALGORITHM:

Main idea behind the algorithm is to find points modulo primes and then reconstruct them using chinese remainder theorem. We compute the points modulo primes parallelly and then lift them via chinese remainder theorem in parallel. The LLL reduction algorithm is applied to each component of the points, and finally the result is merged and converted to a point on the subscheme.

For the algorithm to work correctly, sufficient primes need to be chosen, these are determined using the bounds dependent on the bound given in [Hutz2015].

INPUT:

- `X` – a scheme with ambient space defined over a product of projective spaces
- `bound` – positive integer bound

OUTPUT:

A list containing the rational points of `X` of height up to `bound`, sorted

EXAMPLES:

```
sage: from sage.schemes.product_projective.rational_point import sieve
sage: PP.<x,y,z,u,v> = ProductProjectiveSpaces([2, 1], QQ)
sage: X = PP.subscheme([x^2 + y^2 - x*z, u*u - v*u])
sage: sieve(X, 2)                                                           #␣
↪needs sage.libs.singular
[(0 : 0 : 1 , 0 : 1), (0 : 0 : 1 , 1 : 1), (1/2 : -1/2 : 1 , 0 : 1),
 (1/2 : -1/2 : 1 , 1 : 1), (1/2 : 1/2 : 1 , 0 : 1), (1/2 : 1/2 : 1 , 1 : 1),
 (1 : 0 : 1 , 0 : 1), (1 : 0 : 1 , 1 : 1)]
```

```
>>> from sage.all import *
>>> from sage.schemes.product_projective.rational_point import sieve
>>> PP = ProductProjectiveSpaces([Integer(2), Integer(1)], QQ, names=('x', 'y', 'z
↪', 'u', 'v',)); (x, y, z, u, v,) = PP._first_ngens(5)
```

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```
>>> X = PP.subscheme([x**Integer(2) + y**Integer(2) - x*z, u*u - v*u])
>>> sieve(X, Integer(2))
↪     # needs sage.libs.singular
[(0 : 0 : 1 , 0 : 1), (0 : 0 : 1 , 1 : 1), (1/2 : -1/2 : 1 , 0 : 1),
 (1/2 : -1/2 : 1 , 1 : 1), (1/2 : 1/2 : 1 , 0 : 1), (1/2 : 1/2 : 1 , 1 : 1),
 (1 : 0 : 1 , 0 : 1), (1 : 0 : 1 , 1 : 1)]
```

CHAPTER

SIXTEEN

TORIC VARIETIES

16.1 Toric varieties

This module provides support for (normal) toric varieties, corresponding to `rational polyhedral fans`. See also *fano_variety* for a more restrictive class of (weak) Fano toric varieties.

An **excellent reference on toric varieties** is the book "Toric Varieties" by David A. Cox, John B. Little, and Hal Schenck [CLS2011].

The interface to this module is provided through functions *AffineToricVariety()* and *ToricVariety()*, although you may also be interested in *normalize_names()*.

Note

We do NOT build "general toric varieties" from affine toric varieties. Instead, we are using the quotient representation of toric varieties with the homogeneous coordinate ring (a.k.a. Cox's ring or the total coordinate ring). This description works best for simplicial fans of the full dimension.

AUTHORS:

- Andrey Novoseltsev (2010-05-17): initial version.
- Volker Braun (2010-07-24): Cohomology and characteristic classes added.

EXAMPLES:

We start with constructing the affine plane as an affine toric variety. First, we need to have a corresponding cone:

```
sage: quadrant = Cone([(1,0), (0,1)])
```

```
>>> from sage.all import *
>>> quadrant = Cone([(Integer(1),Integer(0)), (Integer(0),Integer(1))])
```

If you don't care about variable names and the base field, that's all we need for now:

```
sage: A2 = AffineToricVariety(quadrant)
sage: A2
2-d affine toric variety
sage: origin = A2(0,0)
sage: origin
[0 : 0]
```

```
>>> from sage.all import *
>>> A2 = AffineToricVariety(quadrant)
>>> A2
2-d affine toric variety
>>> origin = A2(Integer(0),Integer(0))
>>> origin
[0 : 0]
```

Only affine toric varieties have points whose (homogeneous) coordinates are all zero.

```
sage: parent(origin)
Set of rational points of 2-d affine toric variety
```

```
>>> from sage.all import *
>>> parent(origin)
Set of rational points of 2-d affine toric variety
```

As you can see, by default toric varieties live over the field of rational numbers:

```
sage: A2.base_ring()
Rational Field
```

```
>>> from sage.all import *
>>> A2.base_ring()
Rational Field
```

While usually toric varieties are considered over the field of complex numbers, for computational purposes it is more convenient to work with fields that have exact representation on computers. You can also always do

```
sage: C2 = AffineToricVariety(quadrant, base_field=CC)
sage: C2.base_ring()
Complex Field with 53 bits of precision
sage: C2(1, 2+i)                                                                #␣
↪needs sage.symbolic
[1.00000000000000 : 2.00000000000000 + 1.00000000000000*I]
```

```
>>> from sage.all import *
>>> C2 = AffineToricVariety(quadrant, base_field=CC)
>>> C2.base_ring()
Complex Field with 53 bits of precision
>>> C2(Integer(1), Integer(2)+i)                                                ␣
↪              # needs sage.symbolic
[1.00000000000000 : 2.00000000000000 + 1.00000000000000*I]
```

or even

```
sage: F = CC["a, b"].fraction_field()
sage: F.inject_variables()
Defining a, b
sage: A2 = AffineToricVariety(quadrant, base_field=F)
sage: A2(a,b)
[a : b]
```

```
>>> from sage.all import *
>>> F = CC["a, b"].fraction_field()
>>> F.inject_variables()
Defining a, b
>>> A2 = AffineToricVariety(quadrant, base_field=F)
>>> A2(a,b)
[a : b]
```

OK, if you need to work only with affine spaces, *AffineSpace()* may be a better way to construct them. Our next example is the product of two projective lines realized as the toric variety associated to the `face fan` of the "diamond":

```
sage: diamond = lattice_polytope.cross_polytope(2)
sage: diamond.vertices()
M( 1,  0),        M( 0,  1),
M(-1,  0),        M( 0, -1)
in 2-d lattice M
sage: fan = FaceFan(diamond)
sage: P1xP1 = ToricVariety(fan)
sage: P1xP1
2-d toric variety covered by 4 affine patches
sage: P1xP1.fan().rays()
M( 1,  0),        M( 0,  1),
M(-1,  0),        M( 0, -1)
in 2-d lattice M
sage: P1xP1.gens()
(z0, z1, z2, z3)
```

```
>>> from sage.all import *
>>> diamond = lattice_polytope.cross_polytope(Integer(2))
>>> diamond.vertices()
M( 1,  0),        M( 0,  1),
M(-1,  0),        M( 0, -1)
in 2-d lattice M
>>> fan = FaceFan(diamond)
>>> P1xP1 = ToricVariety(fan)
>>> P1xP1
2-d toric variety covered by 4 affine patches
>>> P1xP1.fan().rays()
M( 1,  0),        M( 0,  1),
M(-1,  0),        M( 0, -1)
in 2-d lattice M
>>> P1xP1.gens()
(z0, z1, z2, z3)
```

We got four coordinates - two for each of the projective lines, but their names are perhaps not very well chosen. Let's make (x, y) to be coordinates on the first line and (s, t) on the second one:

```
sage: P1xP1 = ToricVariety(fan, coordinate_names="x s y t")
sage: P1xP1.gens()
(x, s, y, t)
```

```
>>> from sage.all import *
>>> P1xP1 = ToricVariety(fan, coordinate_names="x s y t")
```

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```
>>> P1xP1.gens()
(x, s, y, t)
```

Now, if we want to define subschemes of this variety, the defining polynomials must be homogeneous in each of these pairs:

```
sage: P1xP1.inject_variables()
Defining x, s, y, t
sage: P1xP1.subscheme(x)
Closed subscheme of 2-d toric variety covered by 4 affine patches defined by:
  x
sage: P1xP1.subscheme(x^2 + y^2)
Closed subscheme of 2-d toric variety covered by 4 affine patches defined by:
  x^2 + y^2
sage: P1xP1.subscheme(x^2 + s^2)
Traceback (most recent call last):
...
ValueError: x^2 + s^2 is not homogeneous
on 2-d toric variety covered by 4 affine patches
sage: P1xP1.subscheme([x^2*s^2 + x*y*t^2 + y^2*t^2, s^3 + t^3])
Closed subscheme of 2-d toric variety covered by 4 affine patches defined by:
  x^2*s^2 + x*y*t^2 + y^2*t^2,
  s^3 + t^3
```

```
>>> from sage.all import *
>>> P1xP1.inject_variables()
Defining x, s, y, t
>>> P1xP1.subscheme(x)
Closed subscheme of 2-d toric variety covered by 4 affine patches defined by:
  x
>>> P1xP1.subscheme(x**Integer(2) + y**Integer(2))
Closed subscheme of 2-d toric variety covered by 4 affine patches defined by:
  x^2 + y^2
>>> P1xP1.subscheme(x**Integer(2) + s**Integer(2))
Traceback (most recent call last):
...
ValueError: x^2 + s^2 is not homogeneous
on 2-d toric variety covered by 4 affine patches
>>> P1xP1.subscheme([x**Integer(2)*s**Integer(2) + x*y*t**Integer(2) +␣
↪y**Integer(2)*t**Integer(2), s**Integer(3) + t**Integer(3)])
Closed subscheme of 2-d toric variety covered by 4 affine patches defined by:
  x^2*s^2 + x*y*t^2 + y^2*t^2,
  s^3 + t^3
```

While we don't build toric varieties from affine toric varieties, we still can access the "building pieces":

```
sage: patch = P1xP1.affine_patch(2)
sage: patch
2-d affine toric variety
sage: patch.fan().rays()
M(1, 0),
M(0, 1)
```

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```
in 2-d lattice M
sage: patch.embedding_morphism()
Scheme morphism:
  From: 2-d affine toric variety
  To:   2-d toric variety covered by 4 affine patches
  Defn: Defined on coordinates by sending [x : s] to [x : s : 1 : 1]
```

```
>>> from sage.all import *
>>> patch = P1xP1.affine_patch(Integer(2))
>>> patch
2-d affine toric variety
>>> patch.fan().rays()
M(1, 0),
M(0, 1)
in 2-d lattice M
>>> patch.embedding_morphism()
Scheme morphism:
  From: 2-d affine toric variety
  To:   2-d toric variety covered by 4 affine patches
  Defn: Defined on coordinates by sending [x : s] to [x : s : 1 : 1]
```

The patch above was specifically chosen to coincide with our representation of the affine plane before, but you can get the other three patches as well. (While any cone of a fan will correspond to an affine toric variety, the main interest is usually in the generating fans as "the biggest" affine subvarieties, and these are precisely the patches that you can get from *affine_patch()*.)

All two-dimensional toric varieties are "quite nice" because any two-dimensional cone is generated by exactly two rays. From the point of view of the corresponding toric varieties, this means that they have at worst quotient singularities:

```
sage: P1xP1.is_orbifold()
True
sage: P1xP1.is_smooth()
True
sage: TV = ToricVariety(NormalFan(diamond))
sage: TV.fan().rays()
N( 1,  1),        N( 1, -1),
N(-1, -1),        N(-1,  1)
in 2-d lattice N
sage: TV.is_orbifold()
True
sage: TV.is_smooth()
False
```

```
>>> from sage.all import *
>>> P1xP1.is_orbifold()
True
>>> P1xP1.is_smooth()
True
>>> TV = ToricVariety(NormalFan(diamond))
>>> TV.fan().rays()
N( 1,  1),        N( 1, -1),
N(-1, -1),        N(-1,  1)
```

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```
in 2-d lattice N
>>> TV.is_orbifold()
True
>>> TV.is_smooth()
False
```

In higher dimensions worse things can happen:

```
sage: TV3 = ToricVariety(NormalFan(lattice_polytope.cross_polytope(3)))
sage: TV3.fan().rays()
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: TV3.is_orbifold()
False
```

```
>>> from sage.all import *
>>> TV3 = ToricVariety(NormalFan(lattice_polytope.cross_polytope(Integer(3))))
>>> TV3.fan().rays()
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
>>> TV3.is_orbifold()
False
```

Fortunately, we can perform a (partial) resolution:

```
sage: TV3_res = TV3.resolve_to_orbifold()
sage: TV3_res.is_orbifold()
True
sage: TV3_res.fan().ngenerating_cones()
12
sage: TV3.fan().ngenerating_cones()
6
```

```
>>> from sage.all import *
>>> TV3_res = TV3.resolve_to_orbifold()
>>> TV3_res.is_orbifold()
True
>>> TV3_res.fan().ngenerating_cones()
12
>>> TV3.fan().ngenerating_cones()
6
```

In this example we had to double the number of affine patches. The result is still singular:

```
sage: TV3_res.is_smooth()
False
```

```
>>> from sage.all import *
>>> TV3_res.is_smooth()
False
```

You can resolve it further using *resolve()* method, but (at least for now) you will have to specify which rays should be inserted into the fan. See also *CPRFanoToricVariety()*, which can construct some other "nice partial resolutions."

The intersection theory on toric varieties is very well understood, and there are explicit algorithms to compute many quantities of interest. The most important tools are the *cohomology ring* and the *Chow group*. For d-dimensional compact toric varieties with at most orbifold singularities, the rational cohomology ring $H^*(X, \mathbf{Q})$ and the rational Chow ring $A^*(X, \mathbf{Q}) = A_{d-*}(X) \otimes \mathbf{Q}$ are isomorphic except for a doubling in degree. More precisely, the Chow group has the same rank

$$A_{d-k}(X) \otimes \mathbf{Q} \simeq H^{2k}(X, \mathbf{Q})$$

and the intersection in of Chow cycles matches the cup product in cohomology.

In this case, you should work with the cohomology ring description because it is much faster. For example, here is a weighted projective space with a curve of $\mathbf{Z}_3$-orbifold singularities:

```
sage: P4_11133 = toric_varieties.P4_11133()
sage: P4_11133.is_smooth(), P4_11133.is_orbifold()
(False, True)
sage: cone = P4_11133.fan(3)[9]
sage: cone.is_smooth(), cone.is_simplicial()
(False, True)
sage: HH = P4_11133.cohomology_ring();  HH
Rational cohomology ring of a 4-d CPR-Fano toric variety covered by 5 affine patches
sage: P4_11133.cohomology_basis()                                              #␣
↪needs sage.libs.singular
(([1],), ([z4],), ([z4^2],), ([z4^3],), ([z4^4],))
```

```
>>> from sage.all import *
>>> P4_11133 = toric_varieties.P4_11133()
>>> P4_11133.is_smooth(), P4_11133.is_orbifold()
(False, True)
>>> cone = P4_11133.fan(Integer(3))[Integer(9)]
>>> cone.is_smooth(), cone.is_simplicial()
(False, True)
>>> HH = P4_11133.cohomology_ring();  HH
Rational cohomology ring of a 4-d CPR-Fano toric variety covered by 5 affine patches
>>> P4_11133.cohomology_basis()                                                #␣
↪needs sage.libs.singular
(([1],), ([z4],), ([z4^2],), ([z4^3],), ([z4^4],))
```

Every cone defines a torus orbit closure, and hence a (co)homology class:

```
sage: # needs sage.libs.singular
sage: HH.gens()
([3*z4], [3*z4], [z4], [z4], [z4])
sage: list(map(HH, P4_11133.fan(1)))
[[3*z4], [3*z4], [z4], [z4], [z4]]
sage: list(map(HH, P4_11133.fan(4)))
[[9*z4^4], [9*z4^4], [9*z4^4], [9*z4^4], [9*z4^4]]
sage: HH(cone)
[3*z4^3]
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> HH.gens()
([3*z4], [3*z4], [z4], [z4], [z4])
>>> list(map(HH, P4_11133.fan(Integer(1))))
[[3*z4], [3*z4], [z4], [z4], [z4]]
>>> list(map(HH, P4_11133.fan(Integer(4))))
[[9*z4^4], [9*z4^4], [9*z4^4], [9*z4^4], [9*z4^4]]
>>> HH(cone)
[3*z4^3]
```

We can compute intersection numbers by integrating top-dimensional cohomology classes:

```
sage: # needs sage.libs.singular
sage: D = P4_11133.divisor(0)
sage: HH(D)
[3*z4]
sage: P4_11133.integrate(HH(D)^4)
9
sage: P4_11133.integrate(HH(D) * HH(cone))
1
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> D = P4_11133.divisor(Integer(0))
>>> HH(D)
[3*z4]
>>> P4_11133.integrate(HH(D)**Integer(4))
9
>>> P4_11133.integrate(HH(D) * HH(cone))
1
```

Although computationally less efficient, we can do the same computations with the rational Chow group:

```
sage: AA = P4_11133.Chow_group(QQ)
sage: list(map(AA, P4_11133.fan(1)))  # long time (5s on sage.math, 2012)
[( 0 | 0 | 0 | 3 | 0 ), ( 0 | 0 | 0 | 3 | 0 ),
 ( 0 | 0 | 0 | 1 | 0 ), ( 0 | 0 | 0 | 1 | 0 ), ( 0 | 0 | 0 | 1 | 0 )]
sage: list(map(AA, P4_11133.fan(4)))  # long time (5s on sage.math, 2012)
[( 1 | 0 | 0 | 0 | 0 ), ( 1 | 0 | 0 | 0 | 0 ),
 ( 1 | 0 | 0 | 0 | 0 ), ( 1 | 0 | 0 | 0 | 0 ), ( 1 | 0 | 0 | 0 | 0 )]
sage: AA(cone).intersection_with_divisor(D)  # long time (4s on sage.math, 2013)    #␣
↪needs sage.libs.singular
( 1 | 0 | 0 | 0 | 0 )
sage: AA(cone).intersection_with_divisor(D).count_points()  # long time             #␣
↪needs sage.libs.singular
1
```

```
>>> from sage.all import *
>>> AA = P4_11133.Chow_group(QQ)
>>> list(map(AA, P4_11133.fan(Integer(1))))  # long time (5s on sage.math, 2012)
[( 0 | 0 | 0 | 3 | 0 ), ( 0 | 0 | 0 | 3 | 0 ),
 ( 0 | 0 | 0 | 1 | 0 ), ( 0 | 0 | 0 | 1 | 0 ), ( 0 | 0 | 0 | 1 | 0 )]
```

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```
>>> list(map(AA, P4_11133.fan(Integer(4))))  # long time (5s on sage.math, 2012)
[( 1 | 0 | 0 | 0 | 0 ), ( 1 | 0 | 0 | 0 | 0 ),
 ( 1 | 0 | 0 | 0 | 0 ), ( 1 | 0 | 0 | 0 | 0 ), ( 1 | 0 | 0 | 0 | 0 )]
>>> AA(cone).intersection_with_divisor(D)  # long time (4s on sage.math, 2013)     #␣
↪needs sage.libs.singular
( 1 | 0 | 0 | 0 | 0 )
>>> AA(cone).intersection_with_divisor(D).count_points()  # long time              #␣
↪needs sage.libs.singular
1
```

The real advantage of the Chow group is that

- it works just as well over **Z**, so torsion information is also easily available, and
- its combinatorial description also works over worse-than-orbifold singularities. By contrast, the cohomology groups can become very complicated to compute in this case, and one usually only has a spectral sequence but no toric algorithm.

Below you will find detailed descriptions of available functions. If you are familiar with toric geometry, you will likely see that many important objects and operations are unavailable. However, this module is under active development and hopefully will improve in future releases of Sage. If there are some particular features that you would like to see implemented ASAP, please consider reporting them to the Sage Development Team or even implementing them on your own as a patch for inclusion!

sage.schemes.toric.variety.**AffineToricVariety**(*cone*, **args*, ***kwds*)

Construct an affine toric variety.

INPUT:

- cone – strictly convex rational polyhedral cone

This cone will be used to construct a rational polyhedral fan, which will be passed to *ToricVariety()* with the rest of positional and keyword arguments.

OUTPUT: a *toric variety*

Note

The generating rays of the fan of this variety are guaranteed to be listed in the same order as the rays of the original cone.

EXAMPLES:

We will create the affine plane as an affine toric variety:

```
sage: quadrant = Cone([(1,0), (0,1)])
sage: A2 = AffineToricVariety(quadrant)
sage: origin = A2(0,0)
sage: origin
[0 : 0]
sage: parent(origin)
Set of rational points of 2-d affine toric variety
```

```
>>> from sage.all import *
>>> quadrant = Cone([(Integer(1),Integer(0)), (Integer(0),Integer(1))])
```

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```
>>> A2 = AffineToricVariety(quadrant)
>>> origin = A2(Integer(0),Integer(0))
>>> origin
[0 : 0]
>>> parent(origin)
Set of rational points of 2-d affine toric variety
```

Only affine toric varieties have points whose (homogeneous) coordinates are all zero.

class sage.schemes.toric.variety.**CohomologyClass**(*cohomology_ring*, *representative*)

Bases: QuotientRingElement

An element of the *CohomologyRing*.

Warning

You should not create instances of this class manually. The generators of the cohomology ring as well as the cohomology classes associated to cones of the fan can be obtained from *ToricVariety_field.cohomology_ring()*.

EXAMPLES:

```
sage: # needs sage.libs.singular
sage: P2 = toric_varieties.P2()
sage: P2.cohomology_ring().gen(0)
[z]
sage: HH = P2.cohomology_ring()
sage: HH.gen(0)
[z]
sage: cone = P2.fan(1)[0];  HH(cone)
[z]
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> P2 = toric_varieties.P2()
>>> P2.cohomology_ring().gen(Integer(0))
[z]
>>> HH = P2.cohomology_ring()
>>> HH.gen(Integer(0))
[z]
>>> cone = P2.fan(Integer(1))[Integer(0)];  HH(cone)
[z]
```

deg()

The degree of the cohomology class.

OUTPUT:

An integer d such that the cohomology class is in degree $2d$. If the cohomology class is of mixed degree, the highest degree is returned.

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: P2.cohomology_ring().gen(0).deg()                                    #␣
↪needs sage.libs.singular
1
sage: P2.cohomology_ring().zero().deg()                                    #␣
↪needs sage.libs.singular
-1
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> P2.cohomology_ring().gen(Integer(0)).deg()                                ␣
↪     # needs sage.libs.singular
1
>>> P2.cohomology_ring().zero().deg()                                      #␣
↪needs sage.libs.singular
-1
```

exp()

Exponentiate `self`.

Note

The exponential $\exp(x)$ of a rational number x is usually not rational. Therefore, the cohomology class must not have a constant (degree zero) part. The coefficients in the Taylor series of exp are rational, so any cohomology class without constant term can be exponentiated.

OUTPUT:

The cohomology class exp(`self`) if the constant part vanishes, otherwise a `ValueError` is raised.

EXAMPLES:

```
sage: # needs sage.libs.singular
sage: P2 = toric_varieties.P2()
sage: H_class = P2.cohomology_ring().gen(0)
sage: H_class
[z]
sage: H_class.exp()
[1/2*z^2 + z + 1]
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> P2 = toric_varieties.P2()
>>> H_class = P2.cohomology_ring().gen(Integer(0))
>>> H_class
[z]
>>> H_class.exp()
[1/2*z^2 + z + 1]
```

part_of_degree(d)

Project the (mixed-degree) cohomology class to the given degree.

$$pr_d : \ H^\bullet(X_\Delta, \mathbf{Q}) \to H^{2d}(X_\Delta, \mathbf{Q})$$

INPUT:

- An integer `d`

OUTPUT: the degree-`2d` part of the cohomology class

EXAMPLES:

```
sage: # needs sage.libs.singular
sage: P1xP1 = toric_varieties.P1xP1()
sage: t = P1xP1.cohomology_ring().gen(0)
sage: y = P1xP1.cohomology_ring().gen(2)
sage: 3*t + 4*t^2*y + y + t*y + t + 1
[t*y + 4*t + y + 1]
sage: (3*t + 4*t^2*y + y + t*y + t + 1).part_of_degree(1)
[4*t + y]
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> P1xP1 = toric_varieties.P1xP1()
>>> t = P1xP1.cohomology_ring().gen(Integer(0))
>>> y = P1xP1.cohomology_ring().gen(Integer(2))
>>> Integer(3)*t + Integer(4)*t**Integer(2)*y + y + t*y + t + Integer(1)
[t*y + 4*t + y + 1]
>>> (Integer(3)*t + Integer(4)*t**Integer(2)*y + y + t*y + t + Integer(1)).
↪part_of_degree(Integer(1))
[4*t + y]
```

class sage.schemes.toric.variety.**CohomologyRing**(*variety*)

Bases: `QuotientRing_generic`, `UniqueRepresentation`

The (even) cohomology ring of a toric variety.

Irregardles of the variety's base ring, we always work with the variety over **C** and its topology.

The cohomology is always the singular cohomology with **Q**-coefficients. Note, however, that the cohomology of smooth toric varieties is torsion-free, so there is no loss of information in that case.

Currently, the toric variety must not be "too singular". See *`ToricVariety_field.cohomology_ring()`* for a detailed description of which toric varieties are admissible. For such varieties the odd-dimensional cohomology groups vanish.

Warning

You should not create instances of this class manually. Use *`ToricVariety_field.cohomology_ring()`* to generate the cohomology ring.

INPUT:

- `variety` – a toric variety. Currently, the toric variety must be at least an orbifold. See *`ToricVariety_field.cohomology_ring()`* for a detailed description of which toric varieties are admissible.

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: P2.cohomology_ring()
Rational cohomology ring of a 2-d CPR-Fano toric variety covered by 3 affine␣
↪patches
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> P2.cohomology_ring()
Rational cohomology ring of a 2-d CPR-Fano toric variety covered by 3 affine␣
↪patches
```

This is equivalent to:

```
sage: from sage.schemes.toric.variety import CohomologyRing
sage: CohomologyRing(P2)
Rational cohomology ring of a 2-d CPR-Fano toric variety covered by 3 affine␣
↪patches
```

```
>>> from sage.all import *
>>> from sage.schemes.toric.variety import CohomologyRing
>>> CohomologyRing(P2)
Rational cohomology ring of a 2-d CPR-Fano toric variety covered by 3 affine␣
↪patches
```

gen(*i*)

Return a generator of the cohomology ring.

INPUT:

- `i` – integer

OUTPUT:

The `i`-th generator of the cohomology ring. If we denote the toric variety by `X`, then this generator is associated to the ray `X.fan().ray(i)`, which spans the one-cone `X.fan(1)[i]`

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: P2.cohomology_ring().gen(2)                                              #␣
↪needs sage.libs.singular
[z]
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> P2.cohomology_ring().gen(Integer(2))                                       ␣
↪     # needs sage.libs.singular
[z]
```

gens()

Return the generators of the cohomology ring.

OUTPUT:

A tuple of generators, one for each toric divisor of the toric variety `X`. The order is the same as the ordering of the rays of the fan `X.fan().rays()`, which is also the same as the ordering of the one-cones in `X.fan(1)`

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: P2.cohomology_ring().gens()                                              #␣
↪needs sage.libs.singular
([z], [z], [z])
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> P2.cohomology_ring().gens()                                                #␣
↪needs sage.libs.singular
([z], [z], [z])
```

sage.schemes.toric.variety.**ToricVariety**(*fan*, *coordinate_names=None*, *names=None*, *coordinate_indices=None*, *base_ring=Rational Field*, *base_field=None*)

Construct a toric variety.

INPUT:

- `fan` – `rational polyhedral fan`
- `coordinate_names` – names of variables for the coordinate ring, see *`normalize_names()`* for acceptable formats. If not given, indexed variable names will be created automatically.
- `names` – an alias of `coordinate_names` for internal use. You may specify either `names` or `coordinate_names`, but not both.
- `coordinate_indices` – list of integers, indices for indexed variables. If not given, the index of each variable will coincide with the index of the corresponding ray of the fan.
- `base_ring` – base ring of the toric variety (default: **Q**); must be a field
- `base_field` – alias for `base_ring`; takes precedence if both are specified

OUTPUT: a *`toric variety`*

EXAMPLES:

We will create the product of two projective lines:

```
sage: fan = FaceFan(lattice_polytope.cross_polytope(2))
sage: fan.rays()
M( 1,  0),
M( 0,  1),
M(-1,  0),
M( 0, -1)
in 2-d lattice M
sage: P1xP1 = ToricVariety(fan)
sage: P1xP1.gens()
(z0, z1, z2, z3)
```

```
>>> from sage.all import *
>>> fan = FaceFan(lattice_polytope.cross_polytope(Integer(2)))
>>> fan.rays()
M( 1,  0),
M( 0,  1),
M(-1,  0),
M( 0, -1)
in 2-d lattice M
>>> P1xP1 = ToricVariety(fan)
```

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```
>>> P1xP1.gens()
(z0, z1, z2, z3)
```

Let's create some points:

```
sage: P1xP1(1,1,1,1)
[1 : 1 : 1 : 1]
sage: P1xP1(0,1,1,1)
[0 : 1 : 1 : 1]
sage: P1xP1(0,1,0,1)
Traceback (most recent call last):
...
TypeError: coordinates (0, 1, 0, 1) are in the exceptional set
```

```
>>> from sage.all import *
>>> P1xP1(Integer(1),Integer(1),Integer(1),Integer(1))
[1 : 1 : 1 : 1]
>>> P1xP1(Integer(0),Integer(1),Integer(1),Integer(1))
[0 : 1 : 1 : 1]
>>> P1xP1(Integer(0),Integer(1),Integer(0),Integer(1))
Traceback (most recent call last):
...
TypeError: coordinates (0, 1, 0, 1) are in the exceptional set
```

We cannot set to zero both coordinates of the same projective line!

Let's change the names of the variables. We have to re-create our toric variety:

```
sage: P1xP1 = ToricVariety(fan, "x s y t")
sage: P1xP1.gens()
(x, s, y, t)
```

```
>>> from sage.all import *
>>> P1xP1 = ToricVariety(fan, "x s y t")
>>> P1xP1.gens()
(x, s, y, t)
```

Now (x, y) correspond to one line and (s, t) to the other one.

```
sage: P1xP1.inject_variables()
Defining x, s, y, t
sage: P1xP1.subscheme(x*s - y*t)
Closed subscheme of 2-d toric variety covered by 4 affine patches defined by:
  x*s - y*t
```

```
>>> from sage.all import *
>>> P1xP1.inject_variables()
Defining x, s, y, t
>>> P1xP1.subscheme(x*s - y*t)
Closed subscheme of 2-d toric variety covered by 4 affine patches defined by:
  x*s - y*t
```

Here is a shorthand for defining the toric variety and homogeneous coordinates in one go:

```
sage: P1xP1.<a,b,c,d> = ToricVariety(fan)
sage: (a^2+b^2) * (c+d)
a^2*c + b^2*c + a^2*d + b^2*d
```

```
>>> from sage.all import *
>>> P1xP1 = ToricVariety(fan, names=('a', 'b', 'c', 'd',)); (a, b, c, d,) = P1xP1.
↪_first_ngens(4)
>>> (a**Integer(2)+b**Integer(2)) * (c+d)
a^2*c + b^2*c + a^2*d + b^2*d
```

class sage.schemes.toric.variety.**ToricVariety_field**(*fan*, *coordinate_names*, *coordinate_indices*, *base_field*)

Bases: *AmbientSpace*

Construct a toric variety associated to a rational polyhedral fan.

Warning

This class does not perform any checks of correctness of input. Use *ToricVariety()* and *AffineToricVariety()* to construct toric varieties.

INPUT:

- `fan` – `rational polyhedral fan`
- `coordinate_names` – names of variables, see *normalize_names()* for acceptable formats. If `None`, indexed variable names will be created automatically.
- `coordinate_indices` – list of integers, indices for indexed variables. If `None`, the index of each variable will coincide with the index of the corresponding ray of the fan.
- `base_field` – base field of the toric variety

OUTPUT: a *toric variety*

Aut_dimension()

Return the dimension of the automorphism group.

There are three kinds of symmetries of toric varieties:

- Toric automorphisms (rescaling of homogeneous coordinates)
- Demazure roots. These are translations $x_i \to x_i + \epsilon x^m$ of a homogeneous coordinate x_i by a monomial x^m of the same homogeneous degree.
- Symmetries of the fan. These yield discrete subgroups.

OUTPUT:

An integer. The dimension of the automorphism group. Equals the dimension of the M-lattice plus the number of Demazure roots.

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: P2.Aut_dimension()
8
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> P2.Aut_dimension()
8
```

Chern_character(*deg=None*)

Return the Chern character (of the tangent bundle) of the toric variety.

INPUT:

- `deg` – integer (optional); the degree of the Chern character

OUTPUT:

- If the degree is specified, the degree-`deg` part of the Chern character.
- If no degree is specified, the total Chern character.

REFERENCES:

- Wikipedia article Chern_character#The_Chern_character

EXAMPLES:

```
sage: # needs sage.libs.singular
sage: dP6 = toric_varieties.dP6()
sage: dP6.Chern_character()
[3*w^2 + y + 2*v + 2*z + w + 2]
sage: dP6.ch()
[3*w^2 + y + 2*v + 2*z + w + 2]
sage: dP6.ch(1) == dP6.c(1)
True
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> dP6 = toric_varieties.dP6()
>>> dP6.Chern_character()
[3*w^2 + y + 2*v + 2*z + w + 2]
>>> dP6.ch()
[3*w^2 + y + 2*v + 2*z + w + 2]
>>> dP6.ch(Integer(1)) == dP6.c(Integer(1))
True
```

Chern_class(*deg=None*)

Return Chern classes of the (tangent bundle of the) toric variety.

INPUT:

- `deg` – integer (optional); the degree of the Chern class

OUTPUT: if the degree is specified, the `deg`-th Chern class

- If no degree is specified, the total Chern class.

REFERENCES:

- Wikipedia article Chern_class

EXAMPLES:

```
sage: # needs sage.libs.singular
sage: X = toric_varieties.dP6()
sage: X.Chern_class()
[-6*w^2 + y + 2*v + 2*z + w + 1]
sage: X.c()
[-6*w^2 + y + 2*v + 2*z + w + 1]
sage: X.c(1)
[y + 2*v + 2*z + w]
sage: X.c(2)
[-6*w^2]
sage: X.integrate( X.c(2) )
6
sage: X.integrate( X.c(2) ) == X.Euler_number()
True
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> X = toric_varieties.dP6()
>>> X.Chern_class()
[-6*w^2 + y + 2*v + 2*z + w + 1]
>>> X.c()
[-6*w^2 + y + 2*v + 2*z + w + 1]
>>> X.c(Integer(1))
[y + 2*v + 2*z + w]
>>> X.c(Integer(2))
[-6*w^2]
>>> X.integrate( X.c(Integer(2)) )
6
>>> X.integrate( X.c(Integer(2)) ) == X.Euler_number()
True
```

Chow_group(*base_ring=Integer Ring*)

Return the toric Chow group.

INPUT:

- `base_ring` – either `ZZ` (default) or `QQ`; the coefficient ring of the Chow group

OUTPUT: a *sage.schemes.toric.chow_group.ChowGroup_class*

EXAMPLES:

```
sage: A = toric_varieties.P2().Chow_group(); A
Chow group of 2-d CPR-Fano toric variety covered by 3 affine patches
sage: A.gens()
(( 0 | 0 | 1 ), ( 0 | 1 | 0 ), ( 1 | 0 | 0 ))
```

```
>>> from sage.all import *
>>> A = toric_varieties.P2().Chow_group(); A
Chow group of 2-d CPR-Fano toric variety covered by 3 affine patches
>>> A.gens()
(( 0 | 0 | 1 ), ( 0 | 1 | 0 ), ( 1 | 0 | 0 ))
```

Demazure_roots()

Return the Demazure roots.

OUTPUT: the roots as points of the M-lattice

REFERENCES:

- [De1970]
- [Baz2011]

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: P2.Demazure_roots()
(M(-1, 0), M(-1, 1), M(0, -1), M(0, 1), M(1, -1), M(1, 0))
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> P2.Demazure_roots()
(M(-1, 0), M(-1, 1), M(0, -1), M(0, 1), M(1, -1), M(1, 0))
```

Here are the remaining three examples listed in [Baz2011], Example 2.1 and 2.3:

```
sage: s = 3
sage: cones = [(0,1), (1,2), (2,3), (3,0)]
sage: Hs = ToricVariety(Fan(rays=[(1,0), (0,-1), (-1,s), (0,1)], cones=cones))
sage: Hs.Demazure_roots()
(M(-1, 0), M(1, 0), M(0, 1), M(1, 1), M(2, 1), M(3, 1))

sage: P11s = ToricVariety(Fan(rays=[(1,0), (0,-1), (-1,s)],
....:                         cones=[(0,1), (1,2), (2,0)]))
sage: P11s.Demazure_roots()
(M(-1, 0), M(1, 0), M(0, 1), M(1, 1), M(2, 1), M(3, 1))
sage: P11s.Demazure_roots() == Hs.Demazure_roots()
True

sage: Bs = ToricVariety(Fan(rays=[(s,1), (s,-1), (-s,-1), (-s,1)],␣
↪cones=cones))
sage: Bs.Demazure_roots()
()
```

```
>>> from sage.all import *
>>> s = Integer(3)
>>> cones = [(Integer(0),Integer(1)), (Integer(1),Integer(2)), (Integer(2),
↪Integer(3)), (Integer(3),Integer(0))]
>>> Hs = ToricVariety(Fan(rays=[(Integer(1),Integer(0)), (Integer(0),-
↪Integer(1)), (-Integer(1),s), (Integer(0),Integer(1))], cones=cones))
>>> Hs.Demazure_roots()
(M(-1, 0), M(1, 0), M(0, 1), M(1, 1), M(2, 1), M(3, 1))

>>> P11s = ToricVariety(Fan(rays=[(Integer(1),Integer(0)), (Integer(0),-
↪Integer(1)), (-Integer(1),s)],
...                         cones=[(Integer(0),Integer(1)), (Integer(1),
↪Integer(2)), (Integer(2),Integer(0))]))
>>> P11s.Demazure_roots()
(M(-1, 0), M(1, 0), M(0, 1), M(1, 1), M(2, 1), M(3, 1))
>>> P11s.Demazure_roots() == Hs.Demazure_roots()
```

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```
True

>>> Bs = ToricVariety(Fan(rays=[(s,Integer(1)), (s,-Integer(1)), (-s,-
↪Integer(1)), (-s,Integer(1))], cones=cones))
>>> Bs.Demazure_roots()
()
```

Euler_number()

Return the topological Euler number of the toric variety.

Sometimes, this is also called the Euler characteristic. *chi()* is a synonym for *Euler_number()*.

REFERENCES:

- Wikipedia article Euler_characteristic

EXAMPLES:

```
sage: # needs sage.libs.singular
sage: P1xP1 = toric_varieties.P1xP1()
sage: P1xP1.Euler_number()
4
sage: P1xP1.chi()
4
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> P1xP1 = toric_varieties.P1xP1()
>>> P1xP1.Euler_number()
4
>>> P1xP1.chi()
4
```

K()

Return the canonical divisor of the toric variety.

EXAMPLES:

Lets test that the del Pezzo surface dP_6 has degree 6, as its name implies:

```
sage: dP6 = toric_varieties.dP6()
sage: HH = dP6.cohomology_ring()
sage: dP6.K()
-V(x) - V(u) - V(y) - V(v) - V(z) - V(w)
sage: dP6.integrate( HH(dP6.K())^2 )                                    #␣
↪needs sage.libs.singular
6
```

```
>>> from sage.all import *
>>> dP6 = toric_varieties.dP6()
>>> HH = dP6.cohomology_ring()
>>> dP6.K()
-V(x) - V(u) - V(y) - V(v) - V(z) - V(w)
>>> dP6.integrate( HH(dP6.K())**Integer(2) )                            ␣
```

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```
↪      # needs sage.libs.singular
6
```

Kaehler_cone()

Return the closure of the Kähler cone of `self`.

OUTPUT: `cone`

Note

This cone sits in the rational divisor class group of `self` and the choice of coordinates agrees with *rational_class_group()*.

EXAMPLES:

```
sage: P1xP1 = toric_varieties.P1xP1()
sage: Kc = P1xP1.Kaehler_cone()
sage: Kc
2-d cone in 2-d lattice
sage: Kc.rays()
Divisor class [0, 1],
Divisor class [1, 0]
in Basis lattice of The toric rational divisor class group
of a 2-d CPR-Fano toric variety covered by 4 affine patches
sage: [ divisor_class.lift() for divisor_class in Kc.rays() ]
[V(y), V(t)]
sage: Kc.lattice()
Basis lattice of The toric rational divisor class group of a
2-d CPR-Fano toric variety covered by 4 affine patches
```

```
>>> from sage.all import *
>>> P1xP1 = toric_varieties.P1xP1()
>>> Kc = P1xP1.Kaehler_cone()
>>> Kc
2-d cone in 2-d lattice
>>> Kc.rays()
Divisor class [0, 1],
Divisor class [1, 0]
in Basis lattice of The toric rational divisor class group
of a 2-d CPR-Fano toric variety covered by 4 affine patches
>>> [ divisor_class.lift() for divisor_class in Kc.rays() ]
[V(y), V(t)]
>>> Kc.lattice()
Basis lattice of The toric rational divisor class group of a
2-d CPR-Fano toric variety covered by 4 affine patches
```

Mori_cone()

Return the Mori cone of `self`.

OUTPUT: `cone`

Note

- The Mori cone is dual to the Kähler cone.
- We think of the Mori cone as living inside the row span of the Gale transform matrix (computed by `self.fan().Gale_transform()`).
- The points in the Mori cone are the effective curves in the variety.
- The `i`-th entry in each Mori vector is the intersection number of the curve corresponding to the generator of the `i`-th ray of the fan with the corresponding divisor class. The very last entry is associated to the origin of the fan lattice.
- The Mori vectors are also known as the gauged linear sigma model charge vectors.

EXAMPLES:

```
sage: P4_11169 = toric_varieties.P4_11169_resolved()
sage: P4_11169.Mori_cone()
2-d cone in 7-d lattice
sage: P4_11169.Mori_cone().rays()
(3, 2, 0, 0, 0,  1, -6),
(0, 0, 1, 1, 1, -3,  0)
in Ambient free module of rank 7 over the principal ideal domain Integer Ring
```

```
>>> from sage.all import *
>>> P4_11169 = toric_varieties.P4_11169_resolved()
>>> P4_11169.Mori_cone()
2-d cone in 7-d lattice
>>> P4_11169.Mori_cone().rays()
(3, 2, 0, 0, 0,  1, -6),
(0, 0, 1, 1, 1, -3,  0)
in Ambient free module of rank 7 over the principal ideal domain Integer Ring
```

Spec(*cone=None*, *names=None*)

Return the spectrum associated to the dual cone.

Let $\sigma \in N_{\mathbf{R}}$ be a cone and $\sigma^\vee \cap M$ the associated semigroup of lattice points in the dual cone. Then

$$S = \mathbf{C}[\sigma^\vee \cap M]$$

is a $\mathbf{C}$-algebra. It is spanned over $\mathbf{C}$ by the points of $\sigma \cap N$, addition is formal linear combination of lattice points, and multiplication of lattice points is the semigroup law (that is, addition of lattice points). The $\mathbf{C}$-algebra S then defines a scheme $Spec(S)$.

For example, if $\sigma = \{(x, y) | x \geq 0, y \geq 0\}$ is the first quadrant then S is the polynomial ring in two variables. The associated scheme is $Spec(S) = \mathbf{C}^2$.

The same construction works over any base field, this introduction only used $\mathbf{C}$ for simplicity.

INPUT:

- `cone` – a `Cone`. Can be omitted for an affine toric variety, in which case the (unique) generating cone is used.
- `names` – (optional). Names of variables for the semigroup ring, see *`normalize_names()`* for acceptable formats. If not given, indexed variable names will be created automatically.

OUTPUT: the spectrum of the semigroup ring $\mathbf{C}[\sigma^\vee \cap M]$

EXAMPLES:

```
sage: quadrant = Cone([(1,0), (0,1)])
sage: AffineToricVariety(quadrant).Spec()
Spectrum of Multivariate Polynomial Ring in z0, z1 over Rational Field
```

```
>>> from sage.all import *
>>> quadrant = Cone([(Integer(1),Integer(0)), (Integer(0),Integer(1))])
>>> AffineToricVariety(quadrant).Spec()
Spectrum of Multivariate Polynomial Ring in z0, z1 over Rational Field
```

A more interesting example:

```
sage: A2Z2 = Cone([(0,1), (2,1)])
sage: AffineToricVariety(A2Z2).Spec(names='u,v,t')                              #␣
↪needs fpylll sage.libs.singular
Spectrum of Quotient of Multivariate Polynomial Ring
in u, v, t over Rational Field by the ideal (-u*v + t^2)
```

```
>>> from sage.all import *
>>> A2Z2 = Cone([(Integer(0),Integer(1)), (Integer(2),Integer(1))])
>>> AffineToricVariety(A2Z2).Spec(names='u,v,t')                               #␣
↪needs fpylll sage.libs.singular
Spectrum of Quotient of Multivariate Polynomial Ring
in u, v, t over Rational Field by the ideal (-u*v + t^2)
```

Stanley_Reisner_ideal()

Return the Stanley-Reisner ideal.

OUTPUT:

- The Stanley-Reisner ideal in the polynomial ring over $\mathbf{Q}$ generated by the homogeneous coordinates.

EXAMPLES:

```
sage: fan = Fan([[0,1,3], [3,4], [2,0], [1,2,4]],
....:           [(-3, -2, 1), (0, 0, 1), (3, -2, 1), (-1, -1, 1), (1, -1, 1)])
sage: X = ToricVariety(fan, coordinate_names='A B C D E', base_field=GF(5))
sage: SR = X.Stanley_Reisner_ideal(); SR
Ideal (A*E, C*D, A*B*C, B*D*E) of
 Multivariate Polynomial Ring in A, B, C, D, E over Rational Field
```

```
>>> from sage.all import *
>>> fan = Fan([[Integer(0),Integer(1),Integer(3)], [Integer(3),Integer(4)],␣
↪[Integer(2),Integer(0)], [Integer(1),Integer(2),Integer(4)]],
...           [(-Integer(3), -Integer(2), Integer(1)), (Integer(0),␣
↪Integer(0), Integer(1)), (Integer(3), -Integer(2), Integer(1)), (-
↪Integer(1), -Integer(1), Integer(1)), (Integer(1), -Integer(1),␣
↪Integer(1))])
>>> X = ToricVariety(fan, coordinate_names='A B C D E', base_
↪field=GF(Integer(5)))
>>> SR = X.Stanley_Reisner_ideal(); SR
```

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```
Ideal (A*E, C*D, A*B*C, B*D*E) of
 Multivariate Polynomial Ring in A, B, C, D, E over Rational Field
```

Td(*deg=None*)

Return the Todd class (of the tangent bundle) of the toric variety.

INPUT:

- `deg` – integer (optional); the desired degree part

OUTPUT:

- If the degree is specified, the degree-`deg` part of the Todd class.
- If no degree is specified, the total Todd class.

REFERENCES:

- Wikipedia article Todd_class

EXAMPLES:

```
sage: # needs sage.libs.singular
sage: dP6 = toric_varieties.dP6()
sage: dP6.Todd_class()
[-w^2 + 1/2*y + v + z + 1/2*w + 1]
sage: dP6.Td()
[-w^2 + 1/2*y + v + z + 1/2*w + 1]
sage: dP6.integrate( dP6.Td() )
1
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> dP6 = toric_varieties.dP6()
>>> dP6.Todd_class()
[-w^2 + 1/2*y + v + z + 1/2*w + 1]
>>> dP6.Td()
[-w^2 + 1/2*y + v + z + 1/2*w + 1]
>>> dP6.integrate( dP6.Td() )
1
```

Todd_class(*deg=None*)

Return the Todd class (of the tangent bundle) of the toric variety.

INPUT:

- `deg` – integer (optional); the desired degree part

OUTPUT:

- If the degree is specified, the degree-`deg` part of the Todd class.
- If no degree is specified, the total Todd class.

REFERENCES:

- Wikipedia article Todd_class

EXAMPLES:

```
sage: # needs sage.libs.singular
sage: dP6 = toric_varieties.dP6()
sage: dP6.Todd_class()
[-w^2 + 1/2*y + v + z + 1/2*w + 1]
sage: dP6.Td()
[-w^2 + 1/2*y + v + z + 1/2*w + 1]
sage: dP6.integrate( dP6.Td() )
1
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> dP6 = toric_varieties.dP6()
>>> dP6.Todd_class()
[-w^2 + 1/2*y + v + z + 1/2*w + 1]
>>> dP6.Td()
[-w^2 + 1/2*y + v + z + 1/2*w + 1]
>>> dP6.integrate( dP6.Td() )
1
```

affine_algebraic_patch(*cone=None*, *names=None*)

Return the patch corresponding to `cone` as an affine algebraic subvariety.

INPUT:

- `cone` – a `Cone` σ of the fan. It can be omitted for an affine toric variety, in which case the single generating cone is used.

OUTPUT:

A *affine algebraic subscheme* corresponding to the patch $Spec(\sigma^\vee \cap M)$ associated to the cone σ.

See also *affine_patch()*, which expresses the patches as subvarieties of affine toric varieties instead.

EXAMPLES:

```
sage: cone = Cone([(0,1), (2,1)])
sage: A2Z2 = AffineToricVariety(cone)
sage: A2Z2.affine_algebraic_patch()                                             #␣
↪needs fpylll sage.libs.singular
Closed subscheme of Affine Space of dimension 3 over Rational Field defined␣
↪by:
  -z0*z1 + z2^2
sage: A2Z2.affine_algebraic_patch(Cone([(0,1)]), names='x, y, t')               #␣
↪needs fpylll sage.libs.singular
Closed subscheme of Affine Space of dimension 3 over Rational Field defined␣
↪by:
  1
```

```
>>> from sage.all import *
>>> cone = Cone([(Integer(0),Integer(1)), (Integer(2),Integer(1))])
>>> A2Z2 = AffineToricVariety(cone)
>>> A2Z2.affine_algebraic_patch()                                               #␣
↪needs fpylll sage.libs.singular
Closed subscheme of Affine Space of dimension 3 over Rational Field defined␣
↪by:
```

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```
  -z0*z1 + z2^2
>>> A2Z2.affine_algebraic_patch(Cone([(Integer(0),Integer(1))]), names='x, y,␣
↪t')           # needs fpylll sage.libs.singular
Closed subscheme of Affine Space of dimension 3 over Rational Field defined␣
↪by:
  1
```

affine_patch(*i*)

Return the `i`-th affine patch of `self`.

INPUT:

- `i` – integer; index of a generating cone of the fan of `self`

OUTPUT:

- affine *toric variety* corresponding to the `i`-th generating cone of the fan of `self`.

The result is cached, so the `i`-th patch is always the same object in memory.

See also *affine_algebraic_patch()*, which expresses the patches as subvarieties of affine space instead.

EXAMPLES:

```
sage: fan = FaceFan(lattice_polytope.cross_polytope(2))
sage: P1xP1 = ToricVariety(fan, "x s y t")
sage: patch0 = P1xP1.affine_patch(0)
sage: patch0
2-d affine toric variety
sage: patch0.embedding_morphism()
Scheme morphism:
  From: 2-d affine toric variety
  To:   2-d toric variety covered by 4 affine patches
  Defn: Defined on coordinates by sending [y : t] to [1 : 1 : y : t]
sage: patch1 = P1xP1.affine_patch(1)
sage: patch1.embedding_morphism()
Scheme morphism:
  From: 2-d affine toric variety
  To:   2-d toric variety covered by 4 affine patches
  Defn: Defined on coordinates by sending [s : y] to [1 : s : y : 1]
sage: patch1 is P1xP1.affine_patch(1)
True
```

```
>>> from sage.all import *
>>> fan = FaceFan(lattice_polytope.cross_polytope(Integer(2)))
>>> P1xP1 = ToricVariety(fan, "x s y t")
>>> patch0 = P1xP1.affine_patch(Integer(0))
>>> patch0
2-d affine toric variety
>>> patch0.embedding_morphism()
Scheme morphism:
  From: 2-d affine toric variety
  To:   2-d toric variety covered by 4 affine patches
  Defn: Defined on coordinates by sending [y : t] to [1 : 1 : y : t]
>>> patch1 = P1xP1.affine_patch(Integer(1))
```

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```
>>> patch1.embedding_morphism()
Scheme morphism:
  From: 2-d affine toric variety
  To:   2-d toric variety covered by 4 affine patches
  Defn: Defined on coordinates by sending [s : y] to [1 : s : y : 1]
>>> patch1 is P1xP1.affine_patch(Integer(1))
True
```

c(*deg=None*)

Return Chern classes of the (tangent bundle of the) toric variety.

INPUT:

- `deg` – integer (optional); the degree of the Chern class

OUTPUT: if the degree is specified, the `deg`-th Chern class

- If no degree is specified, the total Chern class.

REFERENCES:

- Wikipedia article Chern_class

EXAMPLES:

```
sage: # needs sage.libs.singular
sage: X = toric_varieties.dP6()
sage: X.Chern_class()
[-6*w^2 + y + 2*v + 2*z + w + 1]
sage: X.c()
[-6*w^2 + y + 2*v + 2*z + w + 1]
sage: X.c(1)
[y + 2*v + 2*z + w]
sage: X.c(2)
[-6*w^2]
sage: X.integrate( X.c(2) )
6
sage: X.integrate( X.c(2) ) == X.Euler_number()
True
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> X = toric_varieties.dP6()
>>> X.Chern_class()
[-6*w^2 + y + 2*v + 2*z + w + 1]
>>> X.c()
[-6*w^2 + y + 2*v + 2*z + w + 1]
>>> X.c(Integer(1))
[y + 2*v + 2*z + w]
>>> X.c(Integer(2))
[-6*w^2]
>>> X.integrate( X.c(Integer(2)) )
6
>>> X.integrate( X.c(Integer(2)) ) == X.Euler_number()
True
```

cartesian_product(*other*, *coordinate_names=None*, *coordinate_indices=None*)

Return the Cartesian product of `self` with `other`.

INPUT:

- `other` – a *toric variety*
- `coordinate_names` – names of variables for the coordinate ring, see *normalize_names()* for acceptable formats. If not given, indexed variable names will be created automatically.
- `coordinate_indices` – list of integers, indices for indexed variables. If not given, the index of each variable will coincide with the index of the corresponding ray of the fan.

OUTPUT: a *toric variety*

EXAMPLES:

```
sage: P1 = ToricVariety(Fan([Cone([(1,)]), Cone([(-1,)])]))
sage: P1xP1 = P1.cartesian_product(P1); P1xP1
2-d toric variety covered by 4 affine patches
sage: P1xP1.fan().rays()
N+N(-1,  0),      N+N( 1,  0),
N+N( 0, -1),      N+N( 0,  1)
in 2-d lattice N+N
```

```
>>> from sage.all import *
>>> P1 = ToricVariety(Fan([Cone([(Integer(1),)]), Cone([(-Integer(1),)])]))
>>> P1xP1 = P1.cartesian_product(P1); P1xP1
2-d toric variety covered by 4 affine patches
>>> P1xP1.fan().rays()
N+N(-1,  0),      N+N( 1,  0),
N+N( 0, -1),      N+N( 0,  1)
in 2-d lattice N+N
```

ch(*deg=None*)

Return the Chern character (of the tangent bundle) of the toric variety.

INPUT:

- `deg` – integer (optional); the degree of the Chern character

OUTPUT:

- If the degree is specified, the degree-`deg` part of the Chern character.
- If no degree is specified, the total Chern character.

REFERENCES:

- Wikipedia article Chern_character#The_Chern_character

EXAMPLES:

```
sage: # needs sage.libs.singular
sage: dP6 = toric_varieties.dP6()
sage: dP6.Chern_character()
[3*w^2 + y + 2*v + 2*z + w + 2]
sage: dP6.ch()
[3*w^2 + y + 2*v + 2*z + w + 2]
```

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```
sage: dP6.ch(1) == dP6.c(1)
True
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> dP6 = toric_varieties.dP6()
>>> dP6.Chern_character()
[3*w^2 + y + 2*v + 2*z + w + 2]
>>> dP6.ch()
[3*w^2 + y + 2*v + 2*z + w + 2]
>>> dP6.ch(Integer(1)) == dP6.c(Integer(1))
True
```

change_ring(*F*)

Return a toric variety over `F` and otherwise the same as `self`.

INPUT:

- `F` – field

OUTPUT: *toric variety* over `F`

Note

There is no need to have any relation between `F` and the base field of `self`. If you do want to have such a relation, use `base_extend()` instead.

EXAMPLES:

```
sage: P1xA1 = toric_varieties.P1xA1()
sage: P1xA1.base_ring()
Rational Field
sage: P1xA1_RR = P1xA1.change_ring(RR)
sage: P1xA1_RR.base_ring()
Real Field with 53 bits of precision
sage: P1xA1_QQ = P1xA1_RR.change_ring(QQ)
sage: P1xA1_QQ.base_ring()
Rational Field
sage: P1xA1_RR.base_extend(QQ)
Traceback (most recent call last):
...
ValueError: no natural map from the base ring
(=Real Field with 53 bits of precision) to R (=Rational Field)!
sage: R = PolynomialRing(QQ, 2, 'a')
sage: P1xA1.change_ring(R)
Traceback (most recent call last):
...
TypeError: need a field to construct a toric variety;
got Multivariate Polynomial Ring in a0, a1 over Rational Field
```

```
>>> from sage.all import *
>>> P1xA1 = toric_varieties.P1xA1()
```

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```
>>> P1xA1.base_ring()
Rational Field
>>> P1xA1_RR = P1xA1.change_ring(RR)
>>> P1xA1_RR.base_ring()
Real Field with 53 bits of precision
>>> P1xA1_QQ = P1xA1_RR.change_ring(QQ)
>>> P1xA1_QQ.base_ring()
Rational Field
>>> P1xA1_RR.base_extend(QQ)
Traceback (most recent call last):
...
ValueError: no natural map from the base ring
(=Real Field with 53 bits of precision) to R (=Rational Field)!
>>> R = PolynomialRing(QQ, Integer(2), 'a')
>>> P1xA1.change_ring(R)
Traceback (most recent call last):
...
TypeError: need a field to construct a toric variety;
got Multivariate Polynomial Ring in a0, a1 over Rational Field
```

chi()

Return the topological Euler number of the toric variety.

Sometimes, this is also called the Euler characteristic. *chi()* is a synonym for *Euler_number()*.

REFERENCES:

- Wikipedia article Euler_characteristic

EXAMPLES:

```
sage: # needs sage.libs.singular
sage: P1xP1 = toric_varieties.P1xP1()
sage: P1xP1.Euler_number()
4
sage: P1xP1.chi()
4
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> P1xP1 = toric_varieties.P1xP1()
>>> P1xP1.Euler_number()
4
>>> P1xP1.chi()
4
```

cohomology_basis(*d=None*)

Return a basis for the cohomology of the toric variety.

INPUT:

- `d` – (optional) integer

OUTPUT:

- Without the optional argument, a list whose d-th entry is a basis for $H^{2d}(X, \mathbf{Q})$

- If the argument is an integer `d`, returns basis for $H^{2d}(X, \mathbf{Q})$

EXAMPLES:

```
sage: # needs sage.libs.singular
sage: X = toric_varieties.dP8()
sage: X.cohomology_basis()
(([1],), ([z], [y]), ([y*z],))
sage: X.cohomology_basis(1)
([z], [y])
sage: X.cohomology_basis(dimension(X))[0] == X.volume_class()
True
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> X = toric_varieties.dP8()
>>> X.cohomology_basis()
(([1],), ([z], [y]), ([y*z],))
>>> X.cohomology_basis(Integer(1))
([z], [y])
>>> X.cohomology_basis(dimension(X))[Integer(0)] == X.volume_class()
True
```

cohomology_ring()

Return the cohomology ring of the toric variety.

OUTPUT:

- If the toric variety is over $\mathbf{C}$ and has at most finite orbifold singularities: $H^\bullet(X, \mathbf{Q})$ as a polynomial quotient ring.
- Other cases are not handled yet.

Note

- Toric varieties over any field of characteristic 0 are treated as if they were varieties over $\mathbf{C}$.
- The integral cohomology of smooth toric varieties is torsion-free, so in this case there is no loss of information when going to rational coefficients.
- `self.cohomology_ring().gen(i)` is the divisor class corresponding to the `i`-th ray of the fan.

EXAMPLES:

```
sage: X = toric_varieties.dP6()
sage: X.cohomology_ring()
Rational cohomology ring of a 2-d CPR-Fano toric variety covered by 6 affine␣
↪patches
sage: X.cohomology_ring().defining_ideal()
Ideal (-u - y + z + w, x - y - v + w, x*y, x*v, x*z, u*v, u*z, u*w, y*z, y*w,␣
↪v*w)
 of Multivariate Polynomial Ring in x, u, y, v, z, w over Rational Field
sage: X.cohomology_ring().defining_ideal().ring()
Multivariate Polynomial Ring in x, u, y, v, z, w over Rational Field
```

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```
sage: X.variable_names()
('x', 'u', 'y', 'v', 'z', 'w')
sage: X.cohomology_ring().gens()                                              #␣
↪needs sage.libs.singular
([y + v - w], [-y + z + w], [y], [v], [z], [w])
```

```
>>> from sage.all import *
>>> X = toric_varieties.dP6()
>>> X.cohomology_ring()
Rational cohomology ring of a 2-d CPR-Fano toric variety covered by 6 affine␣
↪patches
>>> X.cohomology_ring().defining_ideal()
Ideal (-u - y + z + w, x - y - v + w, x*y, x*v, x*z, u*v, u*z, u*w, y*z, y*w,␣
↪v*w)
 of Multivariate Polynomial Ring in x, u, y, v, z, w over Rational Field
>>> X.cohomology_ring().defining_ideal().ring()
Multivariate Polynomial Ring in x, u, y, v, z, w over Rational Field
>>> X.variable_names()
('x', 'u', 'y', 'v', 'z', 'w')
>>> X.cohomology_ring().gens()                                                #␣
↪needs sage.libs.singular
([y + v - w], [-y + z + w], [y], [v], [z], [w])
```

coordinate_ring()

Return the coordinate ring of `self`.

For toric varieties this is the homogeneous coordinate ring (a.k.a. Cox's ring and total ring).

OUTPUT: a polynomial ring

EXAMPLES:

```
sage: P1xP1 = toric_varieties.P1xP1()
sage: P1xP1.coordinate_ring()
Multivariate Polynomial Ring in s, t, x, y over Rational Field
```

```
>>> from sage.all import *
>>> P1xP1 = toric_varieties.P1xP1()
>>> P1xP1.coordinate_ring()
Multivariate Polynomial Ring in s, t, x, y over Rational Field
```

count_points()

Return the number of points of `self`.

This is an alias for `point_set().cardinality()`, see *cardinality()* for details.

EXAMPLES:

```
sage: o = lattice_polytope.cross_polytope(3)
sage: V = ToricVariety(FaceFan(o))
sage: V2 = V.change_ring(GF(2))
sage: V2.point_set().cardinality()
27
```

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```
sage: V2.count_points()
27
```

```
>>> from sage.all import *
>>> o = lattice_polytope.cross_polytope(Integer(3))
>>> V = ToricVariety(FaceFan(o))
>>> V2 = V.change_ring(GF(Integer(2)))
>>> V2.point_set().cardinality()
27
>>> V2.count_points()
27
```

dimension_singularities()

Return the dimension of the singular set.

OUTPUT:

Integer. The dimension of the singular set of the toric variety. Often the singular set is a reducible subvariety, and this method will return the dimension of the largest-dimensional component.

This returns -1 if the toric variety is smooth.

EXAMPLES:

```
sage: toric_varieties.P4_11169().dimension_singularities()
1
sage: toric_varieties.Conifold().dimension_singularities()
0
sage: toric_varieties.P2().dimension_singularities()
-1
```

```
>>> from sage.all import *
>>> toric_varieties.P4_11169().dimension_singularities()
1
>>> toric_varieties.Conifold().dimension_singularities()
0
>>> toric_varieties.P2().dimension_singularities()
-1
```

divisor(*arg*, *base_ring=None*, *check=True*, *reduce=True*)

Return a divisor.

INPUT:

The arguments are the same as in *sage.schemes.toric.divisor.ToricDivisor()*, with the exception of defining a divisor with a single integer: this method considers it to be the index of a ray of the *fan()* of `self`.

OUTPUT: a *sage.schemes.toric.divisor.ToricDivisor_generic*

EXAMPLES:

```
sage: dP6 = toric_varieties.dP6()
sage: dP6.coordinate_ring()
Multivariate Polynomial Ring in x, u, y, v, z, w over Rational Field
```

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```
sage: dP6.divisor(list(range(6)))
V(u) + 2*V(y) + 3*V(v) + 4*V(z) + 5*V(w)
sage: dP6.inject_variables()
Defining x, u, y, v, z, w
sage: dP6.divisor(x*u^3)
V(x) + 3*V(u)
```

```
>>> from sage.all import *
>>> dP6 = toric_varieties.dP6()
>>> dP6.coordinate_ring()
Multivariate Polynomial Ring in x, u, y, v, z, w over Rational Field
>>> dP6.divisor(list(range(Integer(6))))
V(u) + 2*V(y) + 3*V(v) + 4*V(z) + 5*V(w)
>>> dP6.inject_variables()
Defining x, u, y, v, z, w
>>> dP6.divisor(x*u**Integer(3))
V(x) + 3*V(u)
```

You can also construct divisors based on ray indices:

```
sage: dP6.divisor(0)
V(x)
sage: for i in range(dP6.fan().nrays()):
....:     print('{} : generated by ray {}'.format(dP6.divisor(i),
....:           dP6.fan().ray(i)))
V(x) : generated by ray N(0, 1)
V(u) : generated by ray N(-1, 0)
V(y) : generated by ray N(-1, -1)
V(v) : generated by ray N(0, -1)
V(z) : generated by ray N(1, 0)
V(w) : generated by ray N(1, 1)
```

```
>>> from sage.all import *
>>> dP6.divisor(Integer(0))
V(x)
>>> for i in range(dP6.fan().nrays()):
...     print('{} : generated by ray {}'.format(dP6.divisor(i),
...           dP6.fan().ray(i)))
V(x) : generated by ray N(0, 1)
V(u) : generated by ray N(-1, 0)
V(y) : generated by ray N(-1, -1)
V(v) : generated by ray N(0, -1)
V(z) : generated by ray N(1, 0)
V(w) : generated by ray N(1, 1)
```

divisor_group(*base_ring=Integer Ring*)

Return the group of Weil divisors.

INPUT:

- `base_ring` – the coefficient ring, usually `ZZ` (default) or `QQ`

OUTPUT:

The (free abelian) group of Cartier divisors, that is, formal linear combinations of polynomial equations over the coefficient ring `base_ring`.

These need not be toric (=defined by monomials), but allow general polynomials. The output will be an instance of *sage.schemes.generic.divisor_group.DivisorGroup_generic*.

Warning

You almost certainly want the group of toric divisors, see *toric_divisor_group()*. The toric divisor group is generated by the rays of the fan. The general divisor group has no toric functionality implemented.

EXAMPLES:

```
sage: dP6 = toric_varieties.dP6()
sage: Div = dP6.divisor_group(); Div
Group of ZZ-Divisors on 2-d CPR-Fano toric variety covered by 6 affine patches
sage: Div(x)                                                                #␣
↪needs sage.symbolic
V(x)
```

```
>>> from sage.all import *
>>> dP6 = toric_varieties.dP6()
>>> Div = dP6.divisor_group(); Div
Group of ZZ-Divisors on 2-d CPR-Fano toric variety covered by 6 affine patches
>>> Div(x)                                                                  #␣
↪needs sage.symbolic
V(x)
```

embedding_morphism()

Return the default embedding morphism of `self`.

Such a morphism is always defined for an affine patch of a toric variety (which is also a toric varieties itself).

OUTPUT:

- `scheme morphism` if the default embedding morphism was defined for `self`, otherwise a `ValueError` exception is raised.

EXAMPLES:

```
sage: fan = FaceFan(lattice_polytope.cross_polytope(2))
sage: P1xP1 = ToricVariety(fan, "x s y t")
sage: P1xP1.embedding_morphism()
Traceback (most recent call last):
...
ValueError: no default embedding was defined for this toric variety
sage: patch = P1xP1.affine_patch(0)
sage: patch
2-d affine toric variety
sage: patch.embedding_morphism()
Scheme morphism:
  From: 2-d affine toric variety
  To:   2-d toric variety covered by 4 affine patches
  Defn: Defined on coordinates by sending [y : t] to [1 : 1 : y : t]
```

```
>>> from sage.all import *
>>> fan = FaceFan(lattice_polytope.cross_polytope(Integer(2)))
>>> P1xP1 = ToricVariety(fan, "x s y t")
>>> P1xP1.embedding_morphism()
Traceback (most recent call last):
...
ValueError: no default embedding was defined for this toric variety
>>> patch = P1xP1.affine_patch(Integer(0))
>>> patch
2-d affine toric variety
>>> patch.embedding_morphism()
Scheme morphism:
  From: 2-d affine toric variety
  To:   2-d toric variety covered by 4 affine patches
  Defn: Defined on coordinates by sending [y : t] to [1 : 1 : y : t]
```

fan(*dim=None*, *codim=None*)

Return the underlying fan of `self` or its cones.

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: fan = FaceFan(lattice_polytope.cross_polytope(2))
sage: P1xP1 = ToricVariety(fan)
sage: P1xP1.fan()
Rational polyhedral fan in 2-d lattice M
sage: P1xP1.fan() is fan
True
sage: P1xP1.fan(1)[0]
1-d cone of Rational polyhedral fan in 2-d lattice M
```

```
>>> from sage.all import *
>>> fan = FaceFan(lattice_polytope.cross_polytope(Integer(2)))
>>> P1xP1 = ToricVariety(fan)
>>> P1xP1.fan()
Rational polyhedral fan in 2-d lattice M
>>> P1xP1.fan() is fan
True
>>> P1xP1.fan(Integer(1))[Integer(0)]
1-d cone of Rational polyhedral fan in 2-d lattice M
```

inject_coefficients(*scope=None*, *verbose=True*)

Inject generators of the base field of `self` into `scope`.

This function is useful if the base field is the field of rational functions.

INPUT:

- `scope` – namespace (default: global, not just the scope from which this function was called)
- `verbose` – if `True` (default), names of injected generators will be printed

OUTPUT: none

EXAMPLES:

```
sage: fan = FaceFan(lattice_polytope.cross_polytope(2))
sage: F = QQ["a, b"].fraction_field()
sage: P1xP1 = ToricVariety(fan, base_field=F)
sage: P1xP1.inject_coefficients()
Defining a, b
```

```
>>> from sage.all import *
>>> fan = FaceFan(lattice_polytope.cross_polytope(Integer(2)))
>>> F = QQ["a, b"].fraction_field()
>>> P1xP1 = ToricVariety(fan, base_field=F)
>>> P1xP1.inject_coefficients()
Defining a, b
```

We check that we can use names `a` and `b`, Issue #10498 is fixed:

```
sage: a + b
a + b
sage: a + b in P1xP1.coordinate_ring()
True
```

```
>>> from sage.all import *
>>> a + b
a + b
>>> a + b in P1xP1.coordinate_ring()
True
```

integrate(*cohomology_class*)

Integrate a cohomology class over the toric variety.

INPUT:

- `cohomology_class` – a cohomology class given as a polynomial in `self.cohomology_ring()`

OUTPUT:

The integral of the cohomology class over the variety. The volume normalization is given by *volume_class()*, that is, `self.integrate(self.volume_class())` is always one (if the volume class exists).

EXAMPLES:

```
sage: # needs sage.libs.singular
sage: dP6 = toric_varieties.dP6()
sage: HH = dP6.cohomology_ring()
sage: D = [ HH(c) for c in dP6.fan(dim=1) ]
sage: matrix([ [ D[i]*D[j] for i in range(0,6) ] for j in range(0,6) ])
[ [w^2] [-w^2]    [0]    [0]    [0] [-w^2]]
[[-w^2]  [w^2] [-w^2]    [0]    [0]    [0]]
[   [0] [-w^2]  [w^2] [-w^2]    [0]    [0]]
```

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```
[   [0]    [0] [-w^2]  [w^2] [-w^2]    [0]]
[   [0]    [0]    [0] [-w^2]  [w^2] [-w^2]]
[[-w^2]    [0]    [0]    [0] [-w^2]  [w^2]]
sage: matrix([ [ dP6.integrate(D[i]*D[j]) for i in range(0,6) ] for j in␣
↪range(0,6) ])
[-1  1  0  0  0  1]
[ 1 -1  1  0  0  0]
[ 0  1 -1  1  0  0]
[ 0  0  1 -1  1  0]
[ 0  0  0  1 -1  1]
[ 1  0  0  0  1 -1]
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> dP6 = toric_varieties.dP6()
>>> HH = dP6.cohomology_ring()
>>> D = [ HH(c) for c in dP6.fan(dim=Integer(1)) ]
>>> matrix([ [ D[i]*D[j] for i in range(Integer(0),Integer(6)) ] for j in␣
↪range(Integer(0),Integer(6)) ])
[ [w^2] [-w^2]    [0]    [0]    [0] [-w^2]]
[[-w^2]  [w^2] [-w^2]    [0]    [0]    [0]]
[   [0] [-w^2]  [w^2] [-w^2]    [0]    [0]]
[   [0]    [0] [-w^2]  [w^2] [-w^2]    [0]]
[   [0]    [0]    [0] [-w^2]  [w^2] [-w^2]]
[[-w^2]    [0]    [0]    [0] [-w^2]  [w^2]]
>>> matrix([ [ dP6.integrate(D[i]*D[j]) for i in range(Integer(0),Integer(6))␣
↪] for j in range(Integer(0),Integer(6)) ])
[-1  1  0  0  0  1]
[ 1 -1  1  0  0  0]
[ 0  1 -1  1  0  0]
[ 0  0  1 -1  1  0]
[ 0  0  0  1 -1  1]
[ 1  0  0  0  1 -1]
```

If the toric variety is an orbifold, the intersection numbers are usually fractional:

```
sage: # needs sage.libs.singular
sage: P2_123 = toric_varieties.P2_123()
sage: HH = P2_123.cohomology_ring()
sage: D = [ HH(c) for c in P2_123.fan(dim=1) ]
sage: matrix([ [ P2_123.integrate(D[i]*D[j]) for i in range(0,3) ] for j in␣
↪range(0,3) ])
[2/3   1 1/3]
[  1 3/2 1/2]
[1/3 1/2 1/6]
sage: A = P2_123.Chow_group(QQ)
sage: matrix([ [ A(P2_123.divisor(i))
....:            .intersection_with_divisor(P2_123.divisor(j))
....:            .count_points() for i in range(0,3) ] for j in range(0,3) ])
[2/3   1 1/3]
[  1 3/2 1/2]
[1/3 1/2 1/6]
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> P2_123 = toric_varieties.P2_123()
>>> HH = P2_123.cohomology_ring()
>>> D = [ HH(c) for c in P2_123.fan(dim=Integer(1)) ]
>>> matrix([ [ P2_123.integrate(D[i]*D[j]) for i in range(Integer(0),
↪Integer(3)) ] for j in range(Integer(0),Integer(3)) ])
[2/3   1 1/3]
[  1 3/2 1/2]
[1/3 1/2 1/6]
>>> A = P2_123.Chow_group(QQ)
>>> matrix([ [ A(P2_123.divisor(i))
...            .intersection_with_divisor(P2_123.divisor(j))
...            .count_points() for i in range(Integer(0),Integer(3)) ] for j␣
↪in range(Integer(0),Integer(3)) ])
[2/3   1 1/3]
[  1 3/2 1/2]
[1/3 1/2 1/6]
```

is_affine()

Check if `self` is an affine toric variety.

An affine toric variety is a toric variety whose fan is the face lattice of a single cone. See also *AffineToricVariety()*.

OUTPUT: boolean

EXAMPLES:

```
sage: toric_varieties.A2().is_affine()
True
sage: toric_varieties.P1xA1().is_affine()
False
```

```
>>> from sage.all import *
>>> toric_varieties.A2().is_affine()
True
>>> toric_varieties.P1xA1().is_affine()
False
```

is_complete()

Check if `self` is complete.

OUTPUT: `True` if `self` is complete and `False` otherwise

EXAMPLES:

```
sage: P1xP1 = toric_varieties.P1xP1()
sage: P1xP1.is_complete()
True
sage: P1xP1.affine_patch(0).is_complete()
False
```

```
>>> from sage.all import *
>>> P1xP1 = toric_varieties.P1xP1()
```

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```
>>> P1xP1.is_complete()
True
>>> P1xP1.affine_patch(Integer(0)).is_complete()
False
```

is_homogeneous(*polynomial*)

Check if `polynomial` is homogeneous.

The coordinate ring of a toric variety is multigraded by relations between generating rays of the underlying fan.

INPUT:

- `polynomial` – polynomial in the coordinate ring of `self` or its quotient

OUTPUT: `True` if `polynomial` is homogeneous and `False` otherwise

EXAMPLES:

We will use the product of two projective lines with coordinates (x, y) for one and (s, t) for the other:

```
sage: P1xP1.<x,y,s,t> = toric_varieties.P1xP1()
sage: P1xP1.is_homogeneous(x - y)
True
sage: P1xP1.is_homogeneous(x*s + y*t)
True
sage: P1xP1.is_homogeneous(x - t)
False
sage: P1xP1.is_homogeneous(1)
True
```

```
>>> from sage.all import *
>>> P1xP1 = toric_varieties.P1xP1(names=('x', 'y', 's', 't',)); (x, y, s, t,)␣
↪= P1xP1._first_ngens(4)
>>> P1xP1.is_homogeneous(x - y)
True
>>> P1xP1.is_homogeneous(x*s + y*t)
True
>>> P1xP1.is_homogeneous(x - t)
False
>>> P1xP1.is_homogeneous(Integer(1))
True
```

Note that by homogeneous, we mean well-defined with respect to the homogeneous rescalings of `self`. So a polynomial that you would usually not call homogeneous can be homogeneous if there are no homogeneous rescalings, for example:

```
sage: A1.<z> = toric_varieties.A1()
sage: A1.is_homogeneous(z^3 + z^7)
True
```

```
>>> from sage.all import *
>>> A1 = toric_varieties.A1(names=('z',)); (z,) = A1._first_ngens(1)
>>> A1.is_homogeneous(z**Integer(3) + z**Integer(7))
True
```

Finally, the degree group is really the Chow group $A_{d-1}(X)$ and can contain torsion. For example, take $\mathbf{C}^2/\mathbf{Z}_2$. Here, the Chow group is $A_{d-1}(\mathbf{C}^2/\mathbf{Z}_2) = \mathbf{Z}_2$ and distinguishes even-degree homogeneous polynomials from odd-degree homogeneous polynomials:

```
sage: A2_Z2.<x,y> = toric_varieties.A2_Z2()
sage: A2_Z2.is_homogeneous(x + y + x^3 + y^5 + x^3*y^4)
True
sage: A2_Z2.is_homogeneous(x^2 + x*y + y^4 + (x*y)^5 + x^4*y^4)
True
sage: A2_Z2.is_homogeneous(x + y^2)
False
```

```
>>> from sage.all import *
>>> A2_Z2 = toric_varieties.A2_Z2(names=('x', 'y',)); (x, y,) = A2_Z2._first_
↪ngens(2)
>>> A2_Z2.is_homogeneous(x + y + x**Integer(3) + y**Integer(5) +␣
↪x**Integer(3)*y**Integer(4))
True
>>> A2_Z2.is_homogeneous(x**Integer(2) + x*y + y**Integer(4) +␣
↪(x*y)**Integer(5) + x**Integer(4)*y**Integer(4))
True
>>> A2_Z2.is_homogeneous(x + y**Integer(2))
False
```

is_isomorphic(*another*)

Check if `self` is isomorphic to `another`.

INPUT:

- `another` – *toric variety*

OUTPUT:

- `True` if `self` and `another` are isomorphic, `False` otherwise.

EXAMPLES:

```
sage: TV1 = toric_varieties.P1xA1()
sage: TV2 = toric_varieties.P1xP1()
```

```
>>> from sage.all import *
>>> TV1 = toric_varieties.P1xA1()
>>> TV2 = toric_varieties.P1xP1()
```

Only the most trivial case is implemented so far:

```
sage: TV1.is_isomorphic(TV1)
True
sage: TV1.is_isomorphic(TV2)
Traceback (most recent call last):
...
NotImplementedError: isomorphism check is not yet implemented
```

```
>>> from sage.all import *
>>> TV1.is_isomorphic(TV1)
```

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```
True
>>> TV1.is_isomorphic(TV2)
Traceback (most recent call last):
...
NotImplementedError: isomorphism check is not yet implemented
```

is_orbifold()

Check if `self` has only quotient singularities.

A toric variety with at most orbifold singularities (in this sense) is often called a simplicial toric variety. In this package, we generally try to avoid this term since it mixes up differential geometry and cone terminology.

OUTPUT:

- `True` if `self` has at most quotient singularities by finite groups, `False` otherwise.

EXAMPLES:

```
sage: fan1 = FaceFan(lattice_polytope.cross_polytope(2))
sage: P1xP1 = ToricVariety(fan1)
sage: P1xP1.is_orbifold()
True
sage: fan2 = NormalFan(lattice_polytope.cross_polytope(3))
sage: TV = ToricVariety(fan2)
sage: TV.is_orbifold()
False
```

```
>>> from sage.all import *
>>> fan1 = FaceFan(lattice_polytope.cross_polytope(Integer(2)))
>>> P1xP1 = ToricVariety(fan1)
>>> P1xP1.is_orbifold()
True
>>> fan2 = NormalFan(lattice_polytope.cross_polytope(Integer(3)))
>>> TV = ToricVariety(fan2)
>>> TV.is_orbifold()
False
```

is_smooth()

Check if `self` is smooth.

OUTPUT: `True` if `self` is smooth and `False` otherwise

EXAMPLES:

```
sage: fan1 = FaceFan(lattice_polytope.cross_polytope(2))
sage: P1xP1 = ToricVariety(fan1)
sage: P1xP1.is_smooth()
True
sage: fan2 = NormalFan(lattice_polytope.cross_polytope(2))
sage: TV = ToricVariety(fan2)
sage: TV.is_smooth()
False
```

```
>>> from sage.all import *
>>> fan1 = FaceFan(lattice_polytope.cross_polytope(Integer(2)))
>>> P1xP1 = ToricVariety(fan1)
>>> P1xP1.is_smooth()
True
>>> fan2 = NormalFan(lattice_polytope.cross_polytope(Integer(2)))
>>> TV = ToricVariety(fan2)
>>> TV.is_smooth()
False
```

linear_equivalence_ideal()

Return the ideal generated by linear relations.

OUTPUT:

- The ideal generated by the linear relations of the rays in the polynomial ring over $\mathbf{Q}$ generated by the homogeneous coordinates.

EXAMPLES:

```
sage: fan = Fan([[0,1,3], [3,4], [2,0], [1,2,4]],
....:           [(-3, -2, 1), (0, 0, 1), (3, -2, 1), (-1, -1, 1), (1, -1, 1)])
sage: X = ToricVariety(fan, coordinate_names='A B C D E', base_field=GF(5))
sage: lin = X.linear_equivalence_ideal(); lin
Ideal (-3*A + 3*C - D + E, -2*A - 2*C - D - E, A + B + C + D + E) of
 Multivariate Polynomial Ring in A, B, C, D, E over Rational Field
```

```
>>> from sage.all import *
>>> fan = Fan([[Integer(0),Integer(1),Integer(3)], [Integer(3),Integer(4)],␣
↪[Integer(2),Integer(0)], [Integer(1),Integer(2),Integer(4)]],
...           [(-Integer(3), -Integer(2), Integer(1)), (Integer(0),␣
↪Integer(0), Integer(1)), (Integer(3), -Integer(2), Integer(1)), (-
↪Integer(1), -Integer(1), Integer(1)), (Integer(1), -Integer(1),␣
↪Integer(1))])
>>> X = ToricVariety(fan, coordinate_names='A B C D E', base_
↪field=GF(Integer(5)))
>>> lin = X.linear_equivalence_ideal(); lin
Ideal (-3*A + 3*C - D + E, -2*A - 2*C - D - E, A + B + C + D + E) of
 Multivariate Polynomial Ring in A, B, C, D, E over Rational Field
```

orbit_closure(*cone*)

Return the orbit closure of `cone`.

The cones σ of a fan Σ are in one-to-one correspondence with the torus orbits $O(\sigma)$ of the corresponding toric variety X_Σ. Each orbit is isomorphic to a lower dimensional torus (of dimension equal to the codimension of σ). Just like the toric variety X_Σ itself, these orbits are (partially) compactified by lower-dimensional orbits. In particular, one can define the closure $V(\sigma)$ of the torus orbit $O(\sigma)$ in the ambient toric variety X_Σ, which is again a toric variety.

See Proposition 3.2.7 of [CLS2011] for more details.

INPUT:

- `cone` – a `cone` of the fan

OUTPUT:

- a torus orbit closure associated to `cone` as a *toric variety*.

EXAMPLES:

```
sage: P1xP1 = toric_varieties.P1xP1()
sage: H = P1xP1.fan(1)[0]
sage: V = P1xP1.orbit_closure(H);  V
1-d toric variety covered by 2 affine patches
sage: V.embedding_morphism()
Scheme morphism:
  From: 1-d toric variety covered by 2 affine patches
  To:   2-d CPR-Fano toric variety covered by 4 affine patches
  Defn: Defined by embedding the torus closure associated to the 1-d
        cone of Rational polyhedral fan in 2-d lattice N.
sage: V.embedding_morphism().as_polynomial_map()
Scheme morphism:
  From: 1-d toric variety covered by 2 affine patches
  To:   2-d CPR-Fano toric variety covered by 4 affine patches
  Defn: Defined on coordinates by sending [z0 : z1] to [0 : 1 : z1 : z0]
```

```
>>> from sage.all import *
>>> P1xP1 = toric_varieties.P1xP1()
>>> H = P1xP1.fan(Integer(1))[Integer(0)]
>>> V = P1xP1.orbit_closure(H);  V
1-d toric variety covered by 2 affine patches
>>> V.embedding_morphism()
Scheme morphism:
  From: 1-d toric variety covered by 2 affine patches
  To:   2-d CPR-Fano toric variety covered by 4 affine patches
  Defn: Defined by embedding the torus closure associated to the 1-d
        cone of Rational polyhedral fan in 2-d lattice N.
>>> V.embedding_morphism().as_polynomial_map()
Scheme morphism:
  From: 1-d toric variety covered by 2 affine patches
  To:   2-d CPR-Fano toric variety covered by 4 affine patches
  Defn: Defined on coordinates by sending [z0 : z1] to [0 : 1 : z1 : z0]
```

plot(***options*)

Plot `self`, i.e. the corresponding fan.

INPUT:

- any options for toric plots (see `toric_plotter.options`), none are mandatory.

OUTPUT: a plot

Note

The difference between `X.plot()` and `X.fan().plot()` is that in the first case default ray labels correspond to variables of `X`.

EXAMPLES:

```
sage: X = toric_varieties.Cube_deformation(4)
sage: X.plot()                                                              #␣
↪needs sage.plot
Graphics3d Object
```

```
>>> from sage.all import *
>>> X = toric_varieties.Cube_deformation(Integer(4))
>>> X.plot()                                                                #␣
↪needs sage.plot
Graphics3d Object
```

rational_class_group()

Return the rational divisor class group of `self`.

Let X be a toric variety.

The **Weil divisor class group** $Cl(X)$ is a finitely generated abelian group and can contain torsion. Its rank equals the number of rays in the fan of X minus the dimension of X.

The **rational divisor class group** is $Cl(X) \otimes_{\mathbf{Z}} \mathbf{Q}$ and never includes torsion. If X is *smooth*, this equals the **Picard group** of X, whose elements are the isomorphism classes of line bundles on X. The group law (which we write as addition) is the tensor product of the line bundles. The Picard group of a toric variety is always torsion-free.

OUTPUT: *rational divisor class group*.

Note

- Coordinates correspond to the rows of `self.fan().gale_transform()`.
- *Kaehler_cone()* yields a cone in this group.

EXAMPLES:

```
sage: P1xA1 = toric_varieties.P1xA1()
sage: P1xA1.rational_class_group()
The toric rational divisor class group
of a 2-d toric variety covered by 2 affine patches
```

```
>>> from sage.all import *
>>> P1xA1 = toric_varieties.P1xA1()
>>> P1xA1.rational_class_group()
The toric rational divisor class group
of a 2-d toric variety covered by 2 affine patches
```

resolve(***kwds*)

Construct a toric variety whose fan subdivides the fan of `self`.

The name of this function reflects the fact that usually such subdivisions are done for resolving singularities of the original variety.

INPUT:

This function accepts only keyword arguments, none of which are mandatory.

- coordinate_names – names for coordinates of the new variety. If not given, will be constructed from the coordinate names of self and necessary indexed ones. See *normalize_names()* for the description of acceptable formats.
- coordinate_indices – coordinate indices which should be used for indexed variables of the new variety
- all other arguments will be passed to subdivide() method of the underlying rational polyhedral fan, see its documentation for the available options.

OUTPUT: a *toric variety*

EXAMPLES:

First we will "manually" resolve a simple orbifold singularity:

```
sage: cone = Cone([(1,1), (-1,1)])
sage: fan = Fan([cone])
sage: TV = ToricVariety(fan)
sage: TV.is_smooth()
False
sage: TV_res = TV.resolve(new_rays=[(0,1)])
sage: TV_res.is_smooth()
True
sage: TV_res.fan().rays()
N( 1, 1),
N(-1, 1),
N( 0, 1)
in 2-d lattice N
sage: [cone.ambient_ray_indices() for cone in TV_res.fan()]
[(0, 2), (1, 2)]
```

```
>>> from sage.all import *
>>> cone = Cone([(Integer(1),Integer(1)), (-Integer(1),Integer(1))])
>>> fan = Fan([cone])
>>> TV = ToricVariety(fan)
>>> TV.is_smooth()
False
>>> TV_res = TV.resolve(new_rays=[(Integer(0),Integer(1))])
>>> TV_res.is_smooth()
True
>>> TV_res.fan().rays()
N( 1, 1),
N(-1, 1),
N( 0, 1)
in 2-d lattice N
>>> [cone.ambient_ray_indices() for cone in TV_res.fan()]
[(0, 2), (1, 2)]
```

Now let's "automatically" partially resolve a more complicated fan:

```
sage: fan = NormalFan(lattice_polytope.cross_polytope(3))
sage: TV = ToricVariety(fan)
sage: TV.is_smooth()
False
sage: TV.is_orbifold()
```

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```
False
sage: TV.fan().nrays()
8
sage: TV.fan().ngenerating_cones()
6
sage: TV_res = TV.resolve(make_simplicial=True)
sage: TV_res.is_smooth()
False
sage: TV_res.is_orbifold()
True
sage: TV_res.fan().nrays()
8
sage: TV_res.fan().ngenerating_cones()
12
sage: TV.gens()
(z0, z1, z2, z3, z4, z5, z6, z7)
sage: TV_res.gens()
(z0, z1, z2, z3, z4, z5, z6, z7)
sage: TV_res = TV.resolve(coordinate_names='x+',
....:                     make_simplicial=True)
sage: TV_res.gens()
(x0, x1, x2, x3, x4, x5, x6, x7)
```

```
>>> from sage.all import *
>>> fan = NormalFan(lattice_polytope.cross_polytope(Integer(3)))
>>> TV = ToricVariety(fan)
>>> TV.is_smooth()
False
>>> TV.is_orbifold()
False
>>> TV.fan().nrays()
8
>>> TV.fan().ngenerating_cones()
6
>>> TV_res = TV.resolve(make_simplicial=True)
>>> TV_res.is_smooth()
False
>>> TV_res.is_orbifold()
True
>>> TV_res.fan().nrays()
8
>>> TV_res.fan().ngenerating_cones()
12
>>> TV.gens()
(z0, z1, z2, z3, z4, z5, z6, z7)
>>> TV_res.gens()
(z0, z1, z2, z3, z4, z5, z6, z7)
>>> TV_res = TV.resolve(coordinate_names='x+',
...                     make_simplicial=True)
>>> TV_res.gens()
(x0, x1, x2, x3, x4, x5, x6, x7)
```

resolve_to_orbifold(***kwds*)

Construct an orbifold whose fan subdivides the fan of `self`.

It is a synonym for *resolve()* with `make_simplicial=True` option.

INPUT:

- this function accepts only keyword arguments. See *resolve()* for documentation.

OUTPUT: a *toric variety*

EXAMPLES:

```
sage: fan = NormalFan(lattice_polytope.cross_polytope(3))
sage: TV = ToricVariety(fan)
sage: TV.is_orbifold()
False
sage: TV.fan().nrays()
8
sage: TV.fan().ngenerating_cones()
6
sage: TV_res = TV.resolve_to_orbifold()
sage: TV_res.is_orbifold()
True
sage: TV_res.fan().nrays()
8
sage: TV_res.fan().ngenerating_cones()
12
```

```
>>> from sage.all import *
>>> fan = NormalFan(lattice_polytope.cross_polytope(Integer(3)))
>>> TV = ToricVariety(fan)
>>> TV.is_orbifold()
False
>>> TV.fan().nrays()
8
>>> TV.fan().ngenerating_cones()
6
>>> TV_res = TV.resolve_to_orbifold()
>>> TV_res.is_orbifold()
True
>>> TV_res.fan().nrays()
8
>>> TV_res.fan().ngenerating_cones()
12
```

property sheaves

Return the factory object for sheaves on the toric variety.

See *sage.schemes.toric.sheaf.constructor.SheafLibrary* for details.

EXAMPLES:

```
sage: dP6 = toric_varieties.dP6()
sage: dP6.sheaves
Sheaf constructor on 2-d CPR-Fano toric variety covered by 6 affine patches
```

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```
sage: dP6.sheaves.trivial_bundle()
Rank 1 bundle on 2-d CPR-Fano toric variety covered by 6 affine patches.
```

```
>>> from sage.all import *
>>> dP6 = toric_varieties.dP6()
>>> dP6.sheaves
Sheaf constructor on 2-d CPR-Fano toric variety covered by 6 affine patches
>>> dP6.sheaves.trivial_bundle()
Rank 1 bundle on 2-d CPR-Fano toric variety covered by 6 affine patches.
```

subscheme (*polynomials*)

Return the subscheme of `self` defined by `polynomials`.

INPUT:

- `polynomials` – list of polynomials in the coordinate ring of `self`

OUTPUT: a *subscheme of a toric variety*.

EXAMPLES:

We will construct a subscheme of the product of two projective lines with coordinates (x, y) for one and (s, t) for the other:

```
sage: P1xP1.<x,y,s,t> = toric_varieties.P1xP1()
sage: X = P1xP1.subscheme([x*s + y*t, x^3 + y^3])
sage: X
Closed subscheme of 2-d CPR-Fano toric variety
covered by 4 affine patches defined by:
  x*s + y*t,
  x^3 + y^3
sage: X.defining_polynomials()
(x*s + y*t, x^3 + y^3)
sage: X.defining_ideal()
Ideal (x*s + y*t, x^3 + y^3) of
 Multivariate Polynomial Ring in x, y, s, t over Rational Field
sage: X.base_ring()
Rational Field
sage: X.base_scheme()
Spectrum of Rational Field
sage: X.structure_morphism()
Scheme morphism:
  From: Closed subscheme of 2-d CPR-Fano toric variety
        covered by 4 affine patches defined by: x*s + y*t, x^3 + y^3
  To:   Spectrum of Rational Field
  Defn: Structure map
```

```
>>> from sage.all import *
>>> P1xP1 = toric_varieties.P1xP1(names=('x', 'y', 's', 't',)); (x, y, s, t,)␣
↪= P1xP1._first_ngens(4)
>>> X = P1xP1.subscheme([x*s + y*t, x**Integer(3) + y**Integer(3)])
>>> X
Closed subscheme of 2-d CPR-Fano toric variety
covered by 4 affine patches defined by:
```

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```
  x*s + y*t,
  x^3 + y^3
>>> X.defining_polynomials()
(x*s + y*t, x^3 + y^3)
>>> X.defining_ideal()
Ideal (x*s + y*t, x^3 + y^3) of
 Multivariate Polynomial Ring in x, y, s, t over Rational Field
>>> X.base_ring()
Rational Field
>>> X.base_scheme()
Spectrum of Rational Field
>>> X.structure_morphism()
Scheme morphism:
  From: Closed subscheme of 2-d CPR-Fano toric variety
        covered by 4 affine patches defined by: x*s + y*t, x^3 + y^3
  To:   Spectrum of Rational Field
  Defn: Structure map
```

toric_divisor_group(*base_ring=Integer Ring*)

Return the group of toric (T-Weil) divisors.

INPUT:

- `base_ring` – the coefficient ring, usually `ZZ` (default) or `QQ`

OUTPUT:

The free Abelian agroup of toric Weil divisors, that is, formal `base_ring`-linear combinations of codimension-one toric subvarieties. The output will be an instance of *sage.schemes.toric.divisor.ToricDivisorGroup*.

The i-th generator of the divisor group is the divisor where the i-th homogeneous coordinate vanishes, $\{z_i = 0\}$.

EXAMPLES:

```
sage: dP6 = toric_varieties.dP6()
sage: TDiv = dP6.toric_divisor_group(); TDiv
Group of toric ZZ-Weil divisors on 2-d CPR-Fano toric variety
covered by 6 affine patches
sage: TDiv == dP6.toric_divisor_group()
True
sage: TDiv.gens()
(V(x), V(u), V(y), V(v), V(z), V(w))
sage: dP6.coordinate_ring()
Multivariate Polynomial Ring in x, u, y, v, z, w over Rational Field
```

```
>>> from sage.all import *
>>> dP6 = toric_varieties.dP6()
>>> TDiv = dP6.toric_divisor_group(); TDiv
Group of toric ZZ-Weil divisors on 2-d CPR-Fano toric variety
covered by 6 affine patches
>>> TDiv == dP6.toric_divisor_group()
True
>>> TDiv.gens()
```

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```
(V(x), V(u), V(y), V(v), V(z), V(w))
>>> dP6.coordinate_ring()
Multivariate Polynomial Ring in x, u, y, v, z, w over Rational Field
```

volume_class()

Return the cohomology class of the volume form on the toric variety.

Note that we are using cohomology with compact supports. If the variety is non-compact this is dual to homology without any support condition. In particular, for non-compact varieties the volume form dVol $= \wedge_i(dx_i \wedge dy_i)$ does not define a (nonzero) cohomology class.

OUTPUT:

A *CohomologyClass*. If it exists, it is the class of the (properly normalized) volume form, that is, it is the Poincaré dual of a single point. If it does not exist, a ValueError is raised.

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: P2.volume_class()                                                    #␣
↪needs sage.libs.singular
[z^2]

sage: A2_Z2 = toric_varieties.A2_Z2()
sage: A2_Z2.volume_class()                                                 #␣
↪needs sage.libs.singular
Traceback (most recent call last):
...
ValueError: volume class does not exist
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> P2.volume_class()                                                      #␣
↪needs sage.libs.singular
[z^2]

>>> A2_Z2 = toric_varieties.A2_Z2()
>>> A2_Z2.volume_class()                                                   #␣
↪needs sage.libs.singular
Traceback (most recent call last):
...
ValueError: volume class does not exist
```

If none of the maximal cones is smooth things get more tricky. In this case no torus-fixed point is smooth. If we want to count an ordinary point as 1, then a G-orbifold point needs to count as $\frac{1}{|G|}$. For example, take $\mathbb{P}^1 \times \mathbb{P}^1$ with inhomogeneous coordinates (t, y). Take the quotient by the action $(t, y) \mapsto (-t, -y)$. The $\mathbf{Z}_2$-invariant Weil divisors $\{t = 0\}$ and $\{y = 0\}$ intersect in a $\mathbf{Z}_2$-fixed point, so they ought to have intersection number $\frac{1}{2}$. This means that the cohomology class $[t] \cap [y]$ should be $\frac{1}{2}$ times the volume class. Note that this is different from the volume normalization chosen in [KS]:

```
sage: P1xP1_Z2 = toric_varieties.P1xP1_Z2()
sage: Dt = P1xP1_Z2.divisor(1);  Dt
V(t)
sage: Dy = P1xP1_Z2.divisor(3);  Dy
```

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```
V(y)
sage: P1xP1_Z2.volume_class()                                                #␣
↪needs sage.libs.singular
[2*t*y]

sage: HH = P1xP1_Z2.cohomology_ring()
sage: HH(Dt) * HH(Dy) == 1/2 * P1xP1_Z2.volume_class()                       #␣
↪needs sage.libs.singular
True
```

```
>>> from sage.all import *
>>> P1xP1_Z2 = toric_varieties.P1xP1_Z2()
>>> Dt = P1xP1_Z2.divisor(Integer(1));  Dt
V(t)
>>> Dy = P1xP1_Z2.divisor(Integer(3));  Dy
V(y)
>>> P1xP1_Z2.volume_class()                                                  #␣
↪needs sage.libs.singular
[2*t*y]

>>> HH = P1xP1_Z2.cohomology_ring()
>>> HH(Dt) * HH(Dy) == Integer(1)/Integer(2) * P1xP1_Z2.volume_class()       ␣
↪              # needs sage.libs.singular
True
```

The fractional coefficients are also necessary to match the normalization in the rational Chow group for simplicial toric varieties:

```
sage: A = P1xP1_Z2.Chow_group(QQ)
sage: A(Dt).intersection_with_divisor(Dy).count_points()
1/2
```

```
>>> from sage.all import *
>>> A = P1xP1_Z2.Chow_group(QQ)
>>> A(Dt).intersection_with_divisor(Dy).count_points()
1/2
```

sage.schemes.toric.variety.**is_CohomologyClass**(*x*)

Check whether `x` is a cohomology class of a toric variety.

INPUT:

- `x` – anything

OUTPUT:

`True` or `False` depending on whether `x` is an instance of *CohomologyClass*

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: HH = P2.cohomology_ring()
sage: from sage.schemes.toric.variety import is_CohomologyClass
sage: is_CohomologyClass( HH.one() )                                         #␣
```

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```
↪needs sage.libs.singular
doctest:warning...
DeprecationWarning: The function is_CohomologyClass is deprecated;
use 'isinstance(..., CohomologyClass)' instead.
See https://github.com/sagemath/sage/issues/38277 for details.
True
sage: is_CohomologyClass( HH(P2.fan(1)[0]) )                                    #␣
↪needs sage.libs.singular
True
sage: is_CohomologyClass('z')
False
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> HH = P2.cohomology_ring()
>>> from sage.schemes.toric.variety import is_CohomologyClass
>>> is_CohomologyClass( HH.one() )                                              #␣
↪needs sage.libs.singular
doctest:warning...
DeprecationWarning: The function is_CohomologyClass is deprecated;
use 'isinstance(..., CohomologyClass)' instead.
See https://github.com/sagemath/sage/issues/38277 for details.
True
>>> is_CohomologyClass( HH(P2.fan(Integer(1))[Integer(0)]) )                    ␣
↪              # needs sage.libs.singular
True
>>> is_CohomologyClass('z')
False
```

sage.schemes.toric.variety.**is_ToricVariety**(*x*)

Check if `x` is a toric variety.

INPUT:

- `x` – anything

OUTPUT:

- `True` if `x` is a *toric variety* and `False` otherwise.

Note

While projective spaces are toric varieties mathematically, they are not toric varieties in Sage due to efficiency considerations, so this function will return `False`.

EXAMPLES:

```
sage: from sage.schemes.toric.variety import is_ToricVariety
sage: is_ToricVariety(1)
doctest:warning...
DeprecationWarning: The function is_ToricVariety is deprecated; use 'isinstance(..
↪., ToricVariety_field)' instead.
See https://github.com/sagemath/sage/issues/38022 for details.
```

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```
False
sage: fan = FaceFan(lattice_polytope.cross_polytope(2))
sage: P = ToricVariety(fan)
sage: P
2-d toric variety covered by 4 affine patches
sage: is_ToricVariety(P)
True
sage: is_ToricVariety(ProjectiveSpace(2))
False
```

```
>>> from sage.all import *
>>> from sage.schemes.toric.variety import is_ToricVariety
>>> is_ToricVariety(Integer(1))
doctest:warning...
DeprecationWarning: The function is_ToricVariety is deprecated; use 'isinstance(..
↪., ToricVariety_field)' instead.
See https://github.com/sagemath/sage/issues/38022 for details.
False
>>> fan = FaceFan(lattice_polytope.cross_polytope(Integer(2)))
>>> P = ToricVariety(fan)
>>> P
2-d toric variety covered by 4 affine patches
>>> is_ToricVariety(P)
True
>>> is_ToricVariety(ProjectiveSpace(Integer(2)))
False
```

sage.schemes.toric.variety.**normalize_names**(*names=None*, *ngens=None*, *prefix=None*, *indices=None*, *return_prefix=False*)

Return a list of names in the standard form.

INPUT:

All input parameters are optional.

- `names` – names given either as a single string (with individual names separated by commas or spaces) or a list of strings with each string specifying a name. If the last name ends with the plus sign, "+", this name will be used as `prefix` (even if `prefix` was given explicitly).
- `ngens` – number of names to be returned
- `prefix` – prefix for the indexed names given as a string
- `indices` – list of integers (default: `range(ngens)`) used as indices for names with `prefix`. If given, must be of length `ngens`.
- `return_prefix` – if `True`, the last element of the returned list will contain the prefix determined from `names` or given as the parameter `prefix`. This is useful if you may need more names in the future.

OUTPUT: list of names given as strings

These names are constructed in the following way:

1. If necessary, split `names` into separate names.
2. If the last name ends with "+", put it into `prefix`.

3. If `ngens` was given, add to the names obtained so far as many indexed names as necessary to get this number. If the `k`-th name of the *total* list of names is indexed, it is `prefix + str(indices[k])`. If there were already more names than `ngens`, discard "extra" ones.
4. Check if constructed names are valid. See `certify_names()` for details.
5. If the option `return_prefix=True` was given, add `prefix` to the end of the list.

EXAMPLES:

As promised, all parameters are optional:

```
sage: from sage.schemes.toric.variety import normalize_names
sage: normalize_names()
[]
```

```
>>> from sage.all import *
>>> from sage.schemes.toric.variety import normalize_names
>>> normalize_names()
[]
```

One of the most common uses is probably this one:

```
sage: normalize_names("x+", 4)
['x0', 'x1', 'x2', 'x3']
```

```
>>> from sage.all import *
>>> normalize_names("x+", Integer(4))
['x0', 'x1', 'x2', 'x3']
```

Now suppose that you want to enumerate your variables starting with one instead of zero:

```
sage: normalize_names("x+", 4, indices=list(range(1,5)))
['x1', 'x2', 'x3', 'x4']
```

```
>>> from sage.all import *
>>> normalize_names("x+", Integer(4), indices=list(range(Integer(1),Integer(5))))
['x1', 'x2', 'x3', 'x4']
```

You may actually have an arbitrary enumeration scheme:

```
sage: normalize_names("x+", 4, indices=[1, 10, 100, 1000])
['x1', 'x10', 'x100', 'x1000']
```

```
>>> from sage.all import *
>>> normalize_names("x+", Integer(4), indices=[Integer(1), Integer(10),␣
↪Integer(100), Integer(1000)])
['x1', 'x10', 'x100', 'x1000']
```

Now let's add some "explicit" names:

```
sage: normalize_names("x y z t+", 4)
['x', 'y', 'z', 't3']
```

```
>>> from sage.all import *
>>> normalize_names("x y z t+", Integer(4))
['x', 'y', 'z', 't3']
```

Note that the "automatic" name is `t3` instead of `t0`. This may seem weird, but the reason for this behaviour is that the fourth name in this list will be the same no matter how many explicit names were given:

```
sage: normalize_names("x y t+", 4)
['x', 'y', 't2', 't3']
```

```
>>> from sage.all import *
>>> normalize_names("x y t+", Integer(4))
['x', 'y', 't2', 't3']
```

This is especially useful if you get `names` from a user but want to specify all default names:

```
sage: normalize_names("x, y", 4, prefix='t')
['x', 'y', 't2', 't3']
```

```
>>> from sage.all import *
>>> normalize_names("x, y", Integer(4), prefix='t')
['x', 'y', 't2', 't3']
```

In this format, the user can easily override your choice for automatic names:

```
sage: normalize_names("x y s+", 4, prefix='t')
['x', 'y', 's2', 's3']
```

```
>>> from sage.all import *
>>> normalize_names("x y s+", Integer(4), prefix='t')
['x', 'y', 's2', 's3']
```

Let's now use all parameters at once:

```
sage: normalize_names("x, y, s+", 4, prefix='t',
....:     indices=list(range(1,5)), return_prefix=True)
['x', 'y', 's3', 's4', 's']
```

```
>>> from sage.all import *
>>> normalize_names("x, y, s+", Integer(4), prefix='t',
...     indices=list(range(Integer(1),Integer(5))), return_prefix=True)
['x', 'y', 's3', 's4', 's']
```

Note that you still need to give indices for all names, even if some of the first ones will be "wasted" because of the explicit names. The reason is the same as before - this ensures consistency of automatically generated names, no matter how many explicit names were given.

The prefix is discarded if `ngens` was not given:

```
sage: normalize_names("alpha, beta, gamma, zeta+")
['alpha', 'beta', 'gamma']
```

```
>>> from sage.all import *
>>> normalize_names("alpha, beta, gamma, zeta+")
['alpha', 'beta', 'gamma']
```

Finally, let's take a look at some possible mistakes:

```
sage: normalize_names("123")
Traceback (most recent call last):
...
ValueError: variable name '123' does not start with a letter
```

```
>>> from sage.all import *
>>> normalize_names("123")
Traceback (most recent call last):
...
ValueError: variable name '123' does not start with a letter
```

A more subtle one:

```
sage: normalize_names("x1", 4, prefix='x')
Traceback (most recent call last):
...
ValueError: variable name 'x1' appears more than once
```

```
>>> from sage.all import *
>>> normalize_names("x1", Integer(4), prefix='x')
Traceback (most recent call last):
...
ValueError: variable name 'x1' appears more than once
```

16.2 Fano toric varieties

This module provides support for (Crepant Partial Resolutions of) Fano toric varieties, corresponding to crepant subdivisions of face fans of reflexive `lattice polytopes`. The interface is provided via *CPRFanoToricVariety()*.

A careful exposition of different flavours of Fano varieties can be found in the paper by Benjamin Nill [Nil2005]. The main goal of this module is to support work with **Gorenstein weak Fano toric varieties**. Such a variety corresponds to a **coherent crepant refinement of the normal fan of a reflexive polytope** Δ, where crepant means that primitive generators of the refining rays lie on the facets of the polar polytope Δ° and coherent (a.k.a. regular or projective) means that there exists a strictly upper convex piecewise linear function whose domains of linearity are precisely the maximal cones of the subdivision. These varieties are important for string theory in physics, as they serve as ambient spaces for mirror pairs of Calabi-Yau manifolds via constructions due to Victor V. Batyrev [Bat1994] and Lev A. Borisov [Bor1993].

From the combinatorial point of view "crepant" requirement is much more simple and natural to work with than "coherent." For this reason, the code in this module will allow work with arbitrary crepant subdivisions without checking whether they are coherent or not. We refer to corresponding toric varieties as **CPR-Fano toric varieties**.

REFERENCES:

- [Bat1994]
- [Bor1993]
- [CD2007]
- [Nil2005]

AUTHORS:

- Andrey Novoseltsev (2010-05-18): initial version.

EXAMPLES:

Most of the functions available for Fano toric varieties are the same as for general toric varieties, so here we will concentrate only on Calabi-Yau subvarieties, which were the primary goal for creating this module.

For our first example we realize the projective plane as a Fano toric variety:

```
sage: simplex = LatticePolytope([(1,0), (0,1), (-1,-1)])
sage: P2 = CPRFanoToricVariety(Delta_polar=simplex)
```

```
>>> from sage.all import *
>>> simplex = LatticePolytope([(Integer(1),Integer(0)), (Integer(0),Integer(1)), (-
↪Integer(1),-Integer(1))])
>>> P2 = CPRFanoToricVariety(Delta_polar=simplex)
```

Its anticanonical "hypersurface" is a one-dimensional Calabi-Yau manifold:

```
sage: P2.anticanonical_hypersurface(monomial_points='all')
Closed subscheme of 2-d CPR-Fano toric variety covered by 3 affine patches defined by:
  a0*z0^3 + a9*z0^2*z1 + a7*z0*z1^2 + a1*z1^3 + a8*z0^2*z2 + a6*z0*z1*z2
  + a4*z1^2*z2 + a5*z0*z2^2 + a3*z1*z2^2 + a2*z2^3
```

```
>>> from sage.all import *
>>> P2.anticanonical_hypersurface(monomial_points='all')
Closed subscheme of 2-d CPR-Fano toric variety covered by 3 affine patches defined by:
  a0*z0^3 + a9*z0^2*z1 + a7*z0*z1^2 + a1*z1^3 + a8*z0^2*z2 + a6*z0*z1*z2
  + a4*z1^2*z2 + a5*z0*z2^2 + a3*z1*z2^2 + a2*z2^3
```

In many cases it is sufficient to work with the "simplified polynomial moduli space" of anticanonical hypersurfaces:

```
sage: P2.anticanonical_hypersurface(monomial_points='simplified')
Closed subscheme of 2-d CPR-Fano toric variety covered by 3 affine patches defined by:
  a0*z0^3 + a1*z1^3 + a6*z0*z1*z2 + a2*z2^3
```

```
>>> from sage.all import *
>>> P2.anticanonical_hypersurface(monomial_points='simplified')
Closed subscheme of 2-d CPR-Fano toric variety covered by 3 affine patches defined by:
  a0*z0^3 + a1*z1^3 + a6*z0*z1*z2 + a2*z2^3
```

The mirror family to these hypersurfaces lives inside the Fano toric variety obtained using `simplex` as `Delta` instead of `Delta_polar`:

```
sage: FTV = CPRFanoToricVariety(Delta=simplex, coordinate_points='all')
sage: FTV.anticanonical_hypersurface(monomial_points='simplified')
Closed subscheme of 2-d CPR-Fano toric variety covered by 9 affine patches defined by:
  a2*z2^3*z3^2*z4*z5^2*z8 + a1*z1^3*z3*z4^2*z7^2*z9
  + a3*z0*z1*z2*z3*z4*z5*z7*z8*z9 + a0*z0^3*z5*z7*z8^2*z9^2
```

```
>>> from sage.all import *
>>> FTV = CPRFanoToricVariety(Delta=simplex, coordinate_points='all')
>>> FTV.anticanonical_hypersurface(monomial_points='simplified')
```

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```
Closed subscheme of 2-d CPR-Fano toric variety covered by 9 affine patches defined by:
  a2*z2^3*z3^2*z4*z5^2*z8 + a1*z1^3*z3*z4^2*z7^2*z9
  + a3*z0*z1*z2*z3*z4*z5*z7*z8*z9 + a0*z0^3*z5*z7*z8^2*z9^2
```

Here we have taken the resolved version of the ambient space for the mirror family, but in fact we don't have to resolve singularities corresponding to the interior points of facets - they are singular points which do not lie on a generic anticanonical hypersurface:

```
sage: FTV = CPRFanoToricVariety(Delta=simplex, coordinate_points="all but facets")
sage: FTV.anticanonical_hypersurface(monomial_points='simplified')
Closed subscheme of 2-d CPR-Fano toric variety covered by 3 affine patches defined by:
  a0*z0^3 + a1*z1^3 + a3*z0*z1*z2 + a2*z2^3
```

```
>>> from sage.all import *
>>> FTV = CPRFanoToricVariety(Delta=simplex, coordinate_points="all but facets")
>>> FTV.anticanonical_hypersurface(monomial_points='simplified')
Closed subscheme of 2-d CPR-Fano toric variety covered by 3 affine patches defined by:
  a0*z0^3 + a1*z1^3 + a3*z0*z1*z2 + a2*z2^3
```

This looks very similar to our second version of the anticanonical hypersurface of the projective plane, as expected, since all one-dimensional Calabi-Yau manifolds are elliptic curves!

Now let's take a look at a toric realization of M-polarized K3 surfaces studied by Adrian Clingher and Charles F. Doran in [CD2007]:

```
sage: p4318 = ReflexivePolytope(3, 4318)
sage: FTV = CPRFanoToricVariety(Delta_polar=p4318)
sage: FTV.anticanonical_hypersurface()
Closed subscheme of 3-d CPR-Fano toric variety covered by 4 affine patches defined by:
  a0*z2^12 + a4*z2^6*z3^6 + a3*z3^12 + a8*z0*z1*z2*z3 + a2*z1^3 + a1*z0^2
```

```
>>> from sage.all import *
>>> p4318 = ReflexivePolytope(Integer(3), Integer(4318))
>>> FTV = CPRFanoToricVariety(Delta_polar=p4318)
>>> FTV.anticanonical_hypersurface()
Closed subscheme of 3-d CPR-Fano toric variety covered by 4 affine patches defined by:
  a0*z2^12 + a4*z2^6*z3^6 + a3*z3^12 + a8*z0*z1*z2*z3 + a2*z1^3 + a1*z0^2
```

Below you will find detailed descriptions of available functions. Current functionality of this module is very basic, but it is under active development and hopefully will improve in future releases of Sage. If there are some particular features that you would like to see implemented ASAP, please consider reporting them to the Sage Development Team or even implementing them on your own as a patch for inclusion!

class sage.schemes.toric.fano_variety.**AnticanonicalHypersurface**(*P_Delta*, *monomial_points=None*, *coefficient_names=None*, *coefficient_name_indices=None*, *coefficients=None*)

Bases: *AlgebraicScheme_subscheme_toric*

Construct an anticanonical hypersurface of a CPR-Fano toric variety.

INPUT:

- `P_Delta` – *CPR-Fano toric variety* associated to a reflexive polytope Δ

- see *CPRFanoToricVariety_field.anticanonical_hypersurface()* for documentation on all other acceptable parameters

OUTPUT:

anticanonical hypersurface of `P_Delta` (with the extended base field, if necessary).

EXAMPLES:

```
sage: P1xP1 = toric_varieties.P1xP1()
sage: import sage.schemes.toric.fano_variety as ftv
sage: ftv.AnticanonicalHypersurface(P1xP1)
Closed subscheme of 2-d CPR-Fano toric variety
 covered by 4 affine patches defined by:
  a0*s^2*x^2 + a3*t^2*x^2 + a6*s*t*x*y + a1*s^2*y^2 + a2*t^2*y^2
```

```
>>> from sage.all import *
>>> P1xP1 = toric_varieties.P1xP1()
>>> import sage.schemes.toric.fano_variety as ftv
>>> ftv.AnticanonicalHypersurface(P1xP1)
Closed subscheme of 2-d CPR-Fano toric variety
 covered by 4 affine patches defined by:
  a0*s^2*x^2 + a3*t^2*x^2 + a6*s*t*x*y + a1*s^2*y^2 + a2*t^2*y^2
```

See *anticanonical_hypersurface()* for a more elaborate example.

sage.schemes.toric.fano_variety.**CPRFanoToricVariety**(*Delta=None*, *Delta_polar=None*, *coordinate_points=None*, *charts=None*, *coordinate_names=None*, *names=None*, *coordinate_name_indices=None*, *make_simplicial=False*, *base_ring=None*, *base_field=None*, *check=True*)

Construct a CPR-Fano toric variety.

Note

See documentation of the module *fano_variety* for the used definitions and supported varieties.

Due to the large number of available options, it is recommended to always use keyword parameters.

INPUT:

- `Delta` – reflexive `lattice polytope`. The fan of the constructed CPR-Fano toric variety will be a crepant subdivision of the *normal fan* of `Delta`. Either `Delta` or `Delta_polar` must be given, but not both at the same time, since one is completely determined by another via `polar` method.
- `Delta_polar` – reflexive `lattice polytope`. The fan of the constructed CPR-Fano toric variety will be a crepant subdivision of the *face fan* of `Delta_polar`. Either `Delta` or `Delta_polar` must be given, but not both at the same time, since one is completely determined by another via `polar` method.
- `coordinate_points` – list of integers or string. A list will be interpreted as indices of (boundary) points of `Delta_polar` which should be used as rays of the underlying fan. It must include all vertices of `Delta_polar` and no repetitions are allowed. A string must be one of the following descriptions of points of `Delta_polar`:
  - "vertices" (default),
  - "all" (will not include the origin),

  - "all but facets" (will not include points in the relative interior of facets);

- `charts` – list of lists of elements from `coordinate_points`. Each of these lists must define a generating cone of a fan subdividing the normal fan of `Delta`. Default `charts` correspond to the normal fan of `Delta` without subdivision. The fan specified by `charts` will be subdivided to include all of the requested `coordinate_points`.
- `coordinate_names` – names of variables for the coordinate ring, see *`normalize_names()`* for acceptable formats. If not given, indexed variable names will be created automatically.
- `names` – an alias of `coordinate_names` for internal use. You may specify either `names` or `coordinate_names`, but not both.
- `coordinate_name_indices` – list of integers, indices for indexed variables. If not given, the index of each variable will coincide with the index of the corresponding point of `Delta_polar`.
- `make_simplicial` – if `True`, the underlying fan will be made simplicial (default: `False`)
- `base_ring` – base field of the CPR-Fano toric variety (default: $\mathbf{Q}$)
- `base_field` – alias for `base_ring`. Takes precedence if both are specified.
- `check` – by default the input data will be checked for correctness (e.g. that `charts` do form a subdivision of the normal fan of `Delta`). If you know for sure that the input is valid, you may significantly decrease construction time using `check=False` option.

OUTPUT: *`CPR-Fano toric variety`*

EXAMPLES:

We start with the product of two projective lines:

```
sage: diamond = lattice_polytope.cross_polytope(2)
sage: diamond.vertices()
M( 1,  0),        M( 0,  1),
M(-1,  0),        M( 0, -1)
in 2-d lattice M
sage: P1xP1 = CPRFanoToricVariety(Delta_polar=diamond)
sage: P1xP1
2-d CPR-Fano toric variety covered by 4 affine patches
sage: P1xP1.fan()
Rational polyhedral fan in 2-d lattice M
sage: P1xP1.fan().rays()
M( 1,  0),        M( 0,  1),
M(-1,  0),        M( 0, -1)
in 2-d lattice M
```

```
>>> from sage.all import *
>>> diamond = lattice_polytope.cross_polytope(Integer(2))
>>> diamond.vertices()
M( 1,  0),        M( 0,  1),
M(-1,  0),        M( 0, -1)
in 2-d lattice M
>>> P1xP1 = CPRFanoToricVariety(Delta_polar=diamond)
>>> P1xP1
2-d CPR-Fano toric variety covered by 4 affine patches
>>> P1xP1.fan()
Rational polyhedral fan in 2-d lattice M
>>> P1xP1.fan().rays()
```

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```
M( 1,  0),        M( 0,  1),
M(-1,  0),        M( 0, -1)
in 2-d lattice M
```

"Unfortunately," this variety is smooth to start with and we cannot perform any subdivisions of the underlying fan without leaving the category of CPR-Fano toric varieties. Our next example starts with a square:

```
sage: square = diamond.polar()
sage: square.vertices()
N( 1,  1),        N( 1, -1),
N(-1, -1),        N(-1,  1)
in 2-d lattice N
sage: square.points()
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
```

```
>>> from sage.all import *
>>> square = diamond.polar()
>>> square.vertices()
N( 1,  1),        N( 1, -1),
N(-1, -1),        N(-1,  1)
in 2-d lattice N
>>> square.points()
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
```

We will construct several varieties associated to it:

```
sage: FTV = CPRFanoToricVariety(Delta_polar=square)
sage: FTV.fan().rays()
N( 1,  1),        N( 1, -1),
N(-1, -1),        N(-1,  1)
in 2-d lattice N
sage: FTV.gens()
(z0, z1, z2, z3)

sage: FTV = CPRFanoToricVariety(Delta_polar=square,
....:                           coordinate_points=[0,1,2,3,8])
sage: FTV.fan().rays()
N( 1,  1),        N( 1, -1),        N(-1, -1),
N(-1,  1),        N( 1,  0)
in 2-d lattice N
sage: FTV.gens()
(z0, z1, z2, z3, z8)

sage: FTV = CPRFanoToricVariety(Delta_polar=square,
....:                           coordinate_points=[8,0,2,1,3],
....:                           coordinate_names='x+')
```

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```
sage: FTV.fan().rays()
N( 1,  0),        N( 1,  1),        N(-1, -1),
N( 1, -1),        N(-1,  1)
in 2-d lattice N
sage: FTV.gens()
(x8, x0, x2, x1, x3)

sage: FTV = CPRFanoToricVariety(Delta_polar=square,
....:                           coordinate_points='all',
....:                           coordinate_names="x y Z+")
sage: FTV.fan().rays()
N( 1,  1),        N( 1, -1),        N(-1, -1),        N(-1,  1),
N(-1,  0),        N( 0, -1),        N( 0,  1),        N( 1,  0)
in 2-d lattice N
sage: FTV.gens()
(x, y, Z2, Z3, Z4, Z5, Z7, Z8)
```

```
>>> from sage.all import *
>>> FTV = CPRFanoToricVariety(Delta_polar=square)
>>> FTV.fan().rays()
N( 1,  1),        N( 1, -1),
N(-1, -1),        N(-1,  1)
in 2-d lattice N
>>> FTV.gens()
(z0, z1, z2, z3)

>>> FTV = CPRFanoToricVariety(Delta_polar=square,
...                           coordinate_points=[Integer(0),Integer(1),Integer(2),
↪Integer(3),Integer(8)])
>>> FTV.fan().rays()
N( 1,  1),        N( 1, -1),        N(-1, -1),
N(-1,  1),        N( 1,  0)
in 2-d lattice N
>>> FTV.gens()
(z0, z1, z2, z3, z8)

>>> FTV = CPRFanoToricVariety(Delta_polar=square,
...                           coordinate_points=[Integer(8),Integer(0),Integer(2),
↪Integer(1),Integer(3)],
...                           coordinate_names='x+')
>>> FTV.fan().rays()
N( 1,  0),        N( 1,  1),        N(-1, -1),
N( 1, -1),        N(-1,  1)
in 2-d lattice N
>>> FTV.gens()
(x8, x0, x2, x1, x3)

>>> FTV = CPRFanoToricVariety(Delta_polar=square,
...                           coordinate_points='all',
...                           coordinate_names="x y Z+")
>>> FTV.fan().rays()
N( 1,  1),        N( 1, -1),        N(-1, -1),        N(-1,  1),
```

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```
N(-1,  0),        N( 0, -1),        N( 0,  1),        N( 1,  0)
in 2-d lattice N
>>> FTV.gens()
(x, y, Z2, Z3, Z4, Z5, Z7, Z8)
```

Note that `Z6` is "missing". This is due to the fact that the 6-th point of `square` is the origin, and all automatically created names have the same indices as corresponding points of *`Delta_polar()`*. This is usually very convenient, especially if you have to work with several partial resolutions of the same Fano toric variety. However, you can change it, if you want:

```
sage: FTV = CPRFanoToricVariety(Delta_polar=square,
....:                           coordinate_points='all',
....:                           coordinate_names="x y Z+",
....:                           coordinate_name_indices=list(range(8)))
sage: FTV.gens()
(x, y, Z2, Z3, Z4, Z5, Z6, Z7)
```

```
>>> from sage.all import *
>>> FTV = CPRFanoToricVariety(Delta_polar=square,
...                           coordinate_points='all',
...                           coordinate_names="x y Z+",
...                           coordinate_name_indices=list(range(Integer(8))))
>>> FTV.gens()
(x, y, Z2, Z3, Z4, Z5, Z6, Z7)
```

Note that you have to provide indices for *all* variables, including those that have "completely custom" names. Again, this is usually convenient, because you can add or remove "custom" variables without disturbing too much "automatic" ones:

```
sage: FTV = CPRFanoToricVariety(Delta_polar=square,
....:                           coordinate_points='all',
....:                           coordinate_names="x Z+",
....:                           coordinate_name_indices=list(range(8)))
sage: FTV.gens()
(x, Z1, Z2, Z3, Z4, Z5, Z6, Z7)
```

```
>>> from sage.all import *
>>> FTV = CPRFanoToricVariety(Delta_polar=square,
...                           coordinate_points='all',
...                           coordinate_names="x Z+",
...                           coordinate_name_indices=list(range(Integer(8))))
>>> FTV.gens()
(x, Z1, Z2, Z3, Z4, Z5, Z6, Z7)
```

If you prefer to always start from zero, you will have to shift indices accordingly:

```
sage: FTV = CPRFanoToricVariety(Delta_polar=square,
....:                           coordinate_points='all',
....:                           coordinate_names="x Z+",
....:                           coordinate_name_indices=[0] + list(range(7)))
sage: FTV.gens()
(x, Z0, Z1, Z2, Z3, Z4, Z5, Z6)
```

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```
sage: FTV = CPRFanoToricVariety(Delta_polar=square,
....:                           coordinate_points='all',
....:                           coordinate_names="x y Z+",
....:                           coordinate_name_indices=[0]*2 + list(range(6)))
sage: FTV.gens()
(x, y, Z0, Z1, Z2, Z3, Z4, Z5)
```

```
>>> from sage.all import *
>>> FTV = CPRFanoToricVariety(Delta_polar=square,
...                           coordinate_points='all',
...                           coordinate_names="x Z+",
...                           coordinate_name_indices=[Integer(0)] +␣
↪list(range(Integer(7))))
>>> FTV.gens()
(x, Z0, Z1, Z2, Z3, Z4, Z5, Z6)

>>> FTV = CPRFanoToricVariety(Delta_polar=square,
...                           coordinate_points='all',
...                           coordinate_names="x y Z+",
...                           coordinate_name_indices=[Integer(0)]*Integer(2) +␣
↪list(range(Integer(6))))
>>> FTV.gens()
(x, y, Z0, Z1, Z2, Z3, Z4, Z5)
```

So you always can get any names you want, somewhat complicated default behaviour was designed with the hope that in most cases you will have no desire to provide different names.

Now we will use the possibility to specify initial charts:

```
sage: charts = [(0,1), (1,2), (2,3), (3,0)]
```

```
>>> from sage.all import *
>>> charts = [(Integer(0),Integer(1)), (Integer(1),Integer(2)), (Integer(2),
↪Integer(3)), (Integer(3),Integer(0))]
```

(these charts actually form exactly the face fan of our square)

```
sage: FTV = CPRFanoToricVariety(Delta_polar=square,
....:                           coordinate_points=[0,1,2,3,4],
....:                           charts=charts)
sage: FTV.fan().rays()
N( 1,  1),        N( 1, -1),        N(-1, -1),
N(-1,  1),        N(-1,  0)
in 2-d lattice N
sage: [cone.ambient_ray_indices() for cone in FTV.fan()]
[(0, 1), (1, 2), (2, 4), (3, 4), (0, 3)]
```

```
>>> from sage.all import *
>>> FTV = CPRFanoToricVariety(Delta_polar=square,
...                           coordinate_points=[Integer(0),Integer(1),Integer(2),
↪Integer(3),Integer(4)],
```

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```
...                             charts=charts)
>>> FTV.fan().rays()
N( 1,  1),        N( 1, -1),        N(-1, -1),
N(-1,  1),        N(-1,  0)
in 2-d lattice N
>>> [cone.ambient_ray_indices() for cone in FTV.fan()]
[(0, 1), (1, 2), (2, 4), (3, 4), (0, 3)]
```

If charts are wrong, it should be detected:

```
sage: bad_charts = charts + [(3,0)]
sage: FTV = CPRFanoToricVariety(Delta_polar=square,
....:                           coordinate_points=[0,1,2,3,4],
....:                           charts=bad_charts)
Traceback (most recent call last):
...
ValueError: you have provided 5 cones, but only 4 of them are maximal!
Use discard_faces=True if you indeed need to construct a fan from these cones.
```

```
>>> from sage.all import *
>>> bad_charts = charts + [(Integer(3),Integer(0))]
>>> FTV = CPRFanoToricVariety(Delta_polar=square,
...                           coordinate_points=[Integer(0),Integer(1),Integer(2),
↪Integer(3),Integer(4)],
...                           charts=bad_charts)
Traceback (most recent call last):
...
ValueError: you have provided 5 cones, but only 4 of them are maximal!
Use discard_faces=True if you indeed need to construct a fan from these cones.
```

These charts are technically correct, they just happened to list one of them twice, but it is assumed that such a situation will not happen. It is especially important when you try to speed up your code:

```
sage: FTV = CPRFanoToricVariety(Delta_polar=square,
....:                           coordinate_points=[0,1,2,3,4],
....:                           charts=bad_charts,
....:                           check=False)
Traceback (most recent call last):
...
IndexError: list assignment index out of range
```

```
>>> from sage.all import *
>>> FTV = CPRFanoToricVariety(Delta_polar=square,
...                           coordinate_points=[Integer(0),Integer(1),Integer(2),
↪Integer(3),Integer(4)],
...                           charts=bad_charts,
...                           check=False)
Traceback (most recent call last):
...
IndexError: list assignment index out of range
```

In this case you still get an error message, but it is harder to figure out what is going on. It may also happen that "everything will still work" in the sense of not crashing, but work with such an invalid variety may lead to

mathematically wrong results, so use `check=False` carefully!

Here are some other possible mistakes:

```
sage: bad_charts = charts + [(0,2)]
sage: FTV = CPRFanoToricVariety(Delta_polar=square,
....:                           coordinate_points=[0,1,2,3,4],
....:                           charts=bad_charts)
Traceback (most recent call last):
...
ValueError: (0, 2) does not form a chart of a subdivision of
the face fan of 2-d reflexive polytope #14 in 2-d lattice N!

sage: bad_charts = charts[:-1]
sage: FTV = CPRFanoToricVariety(Delta_polar=square,
....:                           coordinate_points=[0,1,2,3,4],
....:                           charts=bad_charts)
Traceback (most recent call last):
...
ValueError: given charts do not form a complete fan!

sage: FTV = CPRFanoToricVariety(Delta_polar=square,
....:                           coordinate_points=[1,2,3,4])
Traceback (most recent call last):
...
ValueError: all 4 vertices of Delta_polar must be used for coordinates!
Got: [1, 2, 3, 4]

sage: FTV = CPRFanoToricVariety(Delta_polar=square,
....:                           coordinate_points=[0,0,1,2,3,4])
Traceback (most recent call last):
...
ValueError: no repetitions are allowed for coordinate points!
Got: [0, 0, 1, 2, 3, 4]

sage: FTV = CPRFanoToricVariety(Delta_polar=square,
....:                           coordinate_points=[0,1,2,3,6])
Traceback (most recent call last):
...
ValueError: the origin (point #6) cannot be used for a coordinate!
Got: [0, 1, 2, 3, 6]
```

```
>>> from sage.all import *
>>> bad_charts = charts + [(Integer(0),Integer(2))]
>>> FTV = CPRFanoToricVariety(Delta_polar=square,
...                           coordinate_points=[Integer(0),Integer(1),Integer(2),
↪Integer(3),Integer(4)],
...                           charts=bad_charts)
Traceback (most recent call last):
...
ValueError: (0, 2) does not form a chart of a subdivision of
the face fan of 2-d reflexive polytope #14 in 2-d lattice N!

>>> bad_charts = charts[:-Integer(1)]
```

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```
>>> FTV = CPRFanoToricVariety(Delta_polar=square,
...                           coordinate_points=[Integer(0),Integer(1),Integer(2),
↪Integer(3),Integer(4)],
...                           charts=bad_charts)
Traceback (most recent call last):
...
ValueError: given charts do not form a complete fan!

>>> FTV = CPRFanoToricVariety(Delta_polar=square,
...                           coordinate_points=[Integer(1),Integer(2),Integer(3),
↪Integer(4)])
Traceback (most recent call last):
...
ValueError: all 4 vertices of Delta_polar must be used for coordinates!
Got: [1, 2, 3, 4]

>>> FTV = CPRFanoToricVariety(Delta_polar=square,
...                           coordinate_points=[Integer(0),Integer(0),Integer(1),
↪Integer(2),Integer(3),Integer(4)])
Traceback (most recent call last):
...
ValueError: no repetitions are allowed for coordinate points!
Got: [0, 0, 1, 2, 3, 4]

>>> FTV = CPRFanoToricVariety(Delta_polar=square,
...                           coordinate_points=[Integer(0),Integer(1),Integer(2),
↪Integer(3),Integer(6)])
Traceback (most recent call last):
...
ValueError: the origin (point #6) cannot be used for a coordinate!
Got: [0, 1, 2, 3, 6]
```

Here is a shorthand for defining the toric variety and homogeneous coordinates in one go:

```
sage: P1xP1.<a,b,c,d> = CPRFanoToricVariety(Delta_polar=diamond)
sage: (a^2+b^2) * (c+d)
a^2*c + b^2*c + a^2*d + b^2*d
```

```
>>> from sage.all import *
>>> P1xP1 = CPRFanoToricVariety(Delta_polar=diamond, names=('a', 'b', 'c', 'd',));
↪ (a, b, c, d,) = P1xP1._first_ngens(4)
>>> (a**Integer(2)+b**Integer(2)) * (c+d)
a^2*c + b^2*c + a^2*d + b^2*d
```

class sage.schemes.toric.fano_variety.**CPRFanoToricVariety_field**(*Delta_polar*, *fan*, *coordinate_points*, *point_to_ray*, *coordinate_names*, *coordinate_name_indices*, *base_field*)

Bases: *ToricVariety_field*

Construct a CPR-Fano toric variety associated to a reflexive polytope.

Warning

This class does not perform any checks of correctness of input and it does assume that the internal structure of the given parameters is coordinated in a certain way. Use *CPRFanoToricVariety()* to construct CPR-Fano toric varieties.

Note

See documentation of the module *fano_variety* for the used definitions and supported varieties.

INPUT:

- `Delta_polar` – reflexive polytope
- `fan` – rational polyhedral fan subdividing the face fan of `Delta_polar`
- `coordinate_points` – list of indices of points of `Delta_polar` used for rays of `fan`
- `point_to_ray` – dictionary mapping the index of a coordinate point to the index of the corresponding ray
- `coordinate_names` – names of the variables of the coordinate ring in the format accepted by *normalize_names()*
- `coordinate_name_indices` – indices for indexed variables, if `None`, will be equal to `coordinate_points`
- `base_field` – base field of the CPR-Fano toric variety

OUTPUT: *CPR-Fano toric variety*

Delta()

Return the reflexive polytope associated to `self`.

OUTPUT:

- reflexive `lattice polytope`. The underlying fan of `self` is a coherent subdivision of the *normal fan* of this polytope.

EXAMPLES:

```
sage: diamond = lattice_polytope.cross_polytope(2)
sage: P1xP1 = CPRFanoToricVariety(Delta_polar=diamond)
sage: P1xP1.Delta()
2-d reflexive polytope #14 in 2-d lattice N
sage: P1xP1.Delta() is diamond.polar()
True
```

```
>>> from sage.all import *
>>> diamond = lattice_polytope.cross_polytope(Integer(2))
>>> P1xP1 = CPRFanoToricVariety(Delta_polar=diamond)
>>> P1xP1.Delta()
2-d reflexive polytope #14 in 2-d lattice N
>>> P1xP1.Delta() is diamond.polar()
True
```

Delta_polar()

Return polar of *Delta()*.

OUTPUT:

- reflexive lattice polytope. The underlying fan of self is a coherent subdivision of the *face fan* of this polytope.

EXAMPLES:

```
sage: diamond = lattice_polytope.cross_polytope(2)
sage: P1xP1 = CPRFanoToricVariety(Delta_polar=diamond)
sage: P1xP1.Delta_polar()
2-d reflexive polytope #3 in 2-d lattice M
sage: P1xP1.Delta_polar() is diamond
True
sage: P1xP1.Delta_polar() is P1xP1.Delta().polar()
True
```

```
>>> from sage.all import *
>>> diamond = lattice_polytope.cross_polytope(Integer(2))
>>> P1xP1 = CPRFanoToricVariety(Delta_polar=diamond)
>>> P1xP1.Delta_polar()
2-d reflexive polytope #3 in 2-d lattice M
>>> P1xP1.Delta_polar() is diamond
True
>>> P1xP1.Delta_polar() is P1xP1.Delta().polar()
True
```

anticanonical_hypersurface(***kwds*)

Return an anticanonical hypersurface of self.

Note

The returned hypersurface may be actually a subscheme of **another** CPR-Fano toric variety: if the base field of self does not include all of the required names for generic monomial coefficients, it will be automatically extended.

Below Δ is the reflexive polytope corresponding to self, i.e. the fan of self is a refinement of the normal fan of Δ. This function accepts only keyword parameters.

INPUT:

- monomial_points – list of integers or a string. A list will be interpreted as indices of points of Δ which should be used for monomials of this hypersurface. A string must be one of the following descriptions of points of Δ:
  - "vertices",
  - "vertices+origin",
  - "all",
  - "simplified" (default) – all points of Δ except for the interior points of facets, this choice corresponds to working with the "simplified polynomial moduli space" of anticanonical hypersurfaces;
- coefficient_names – names for the monomial coefficients, see *normalize_names()* for acceptable formats. If not given, indexed coefficient names will be created automatically.

- `coefficient_name_indices` – list of integers, indices for indexed coefficients. If not given, the index of each coefficient will coincide with the index of the corresponding point of Δ.
- `coefficients` – as an alternative to specifying coefficient names and/or indices, you can give the coefficients themselves as arbitrary expressions and/or strings. Using strings allows you to easily add "parameters": the base field of `self` will be extended to include all necessary names.

OUTPUT:

- an *anticanonical hypersurface* of `self` (with the extended base field, if necessary).

EXAMPLES:

We realize the projective plane as a Fano toric variety:

```
sage: simplex = LatticePolytope([(1,0), (0,1), (-1,-1)])
sage: P2 = CPRFanoToricVariety(Delta_polar=simplex)
```

```
>>> from sage.all import *
>>> simplex = LatticePolytope([(Integer(1),Integer(0)), (Integer(0),
↪Integer(1)), (-Integer(1),-Integer(1))])
>>> P2 = CPRFanoToricVariety(Delta_polar=simplex)
```

Its anticanonical "hypersurface" is a one-dimensional Calabi-Yau manifold:

```
sage: P2.anticanonical_hypersurface(monomial_points='all')
Closed subscheme of 2-d CPR-Fano toric variety
 covered by 3 affine patches defined by:
  a0*z0^3 + a9*z0^2*z1 + a7*z0*z1^2 + a1*z1^3 + a8*z0^2*z2 + a6*z0*z1*z2
  + a4*z1^2*z2 + a5*z0*z2^2 + a3*z1*z2^2 + a2*z2^3
```

```
>>> from sage.all import *
>>> P2.anticanonical_hypersurface(monomial_points='all')
Closed subscheme of 2-d CPR-Fano toric variety
 covered by 3 affine patches defined by:
  a0*z0^3 + a9*z0^2*z1 + a7*z0*z1^2 + a1*z1^3 + a8*z0^2*z2 + a6*z0*z1*z2
  + a4*z1^2*z2 + a5*z0*z2^2 + a3*z1*z2^2 + a2*z2^3
```

In many cases it is sufficient to work with the "simplified polynomial moduli space" of anticanonical hypersurfaces:

```
sage: P2.anticanonical_hypersurface(monomial_points='simplified')
Closed subscheme of 2-d CPR-Fano toric variety
 covered by 3 affine patches defined by:
  a0*z0^3 + a1*z1^3 + a6*z0*z1*z2 + a2*z2^3
```

```
>>> from sage.all import *
>>> P2.anticanonical_hypersurface(monomial_points='simplified')
Closed subscheme of 2-d CPR-Fano toric variety
 covered by 3 affine patches defined by:
  a0*z0^3 + a1*z1^3 + a6*z0*z1*z2 + a2*z2^3
```

The mirror family to these hypersurfaces lives inside the Fano toric variety obtained using `simplex` as `Delta` instead of `Delta_polar`:

```
sage: FTV = CPRFanoToricVariety(Delta=simplex,
....:                           coordinate_points='all')
sage: FTV.anticanonical_hypersurface(monomial_points='simplified')
Closed subscheme of 2-d CPR-Fano toric variety
 covered by 9 affine patches defined by:
  a2*z2^3*z3^2*z4*z5^2*z8 + a1*z1^3*z3*z4^2*z7^2*z9
  + a3*z0*z1*z2*z3*z4*z5*z7*z8*z9 + a0*z0^3*z5*z7*z8^2*z9^2
```

```
>>> from sage.all import *
>>> FTV = CPRFanoToricVariety(Delta=simplex,
...                           coordinate_points='all')
>>> FTV.anticanonical_hypersurface(monomial_points='simplified')
Closed subscheme of 2-d CPR-Fano toric variety
 covered by 9 affine patches defined by:
  a2*z2^3*z3^2*z4*z5^2*z8 + a1*z1^3*z3*z4^2*z7^2*z9
  + a3*z0*z1*z2*z3*z4*z5*z7*z8*z9 + a0*z0^3*z5*z7*z8^2*z9^2
```

Here we have taken the resolved version of the ambient space for the mirror family, but in fact we don't have to resolve singularities corresponding to the interior points of facets - they are singular points which do not lie on a generic anticanonical hypersurface:

```
sage: FTV = CPRFanoToricVariety(Delta=simplex,
....:                           coordinate_points="all but facets")
sage: FTV.anticanonical_hypersurface(monomial_points='simplified')
Closed subscheme of 2-d CPR-Fano toric variety
 covered by 3 affine patches defined by:
  a0*z0^3 + a1*z1^3 + a3*z0*z1*z2 + a2*z2^3
```

```
>>> from sage.all import *
>>> FTV = CPRFanoToricVariety(Delta=simplex,
...                           coordinate_points="all but facets")
>>> FTV.anticanonical_hypersurface(monomial_points='simplified')
Closed subscheme of 2-d CPR-Fano toric variety
 covered by 3 affine patches defined by:
  a0*z0^3 + a1*z1^3 + a3*z0*z1*z2 + a2*z2^3
```

This looks very similar to our second anticanonical hypersurface of the projective plane, as expected, since all one-dimensional Calabi-Yau manifolds are elliptic curves!

All anticanonical hypersurfaces constructed above were generic with automatically generated coefficients. If you want, you can specify your own names

```
sage: FTV.anticanonical_hypersurface(coefficient_names="a b c d")
Closed subscheme of 2-d CPR-Fano toric variety
 covered by 3 affine patches defined by:
  a*z0^3 + b*z1^3 + d*z0*z1*z2 + c*z2^3
```

```
>>> from sage.all import *
>>> FTV.anticanonical_hypersurface(coefficient_names="a b c d")
Closed subscheme of 2-d CPR-Fano toric variety
 covered by 3 affine patches defined by:
  a*z0^3 + b*z1^3 + d*z0*z1*z2 + c*z2^3
```

or give concrete coefficients

```
sage: FTV.anticanonical_hypersurface(coefficients=[1, 2, 3, 4])
Closed subscheme of 2-d CPR-Fano toric variety
 covered by 3 affine patches defined by:
  z0^3 + 2*z1^3 + 4*z0*z1*z2 + 3*z2^3
```

```
>>> from sage.all import *
>>> FTV.anticanonical_hypersurface(coefficients=[Integer(1), Integer(2),␣
↪Integer(3), Integer(4)])
Closed subscheme of 2-d CPR-Fano toric variety
 covered by 3 affine patches defined by:
  z0^3 + 2*z1^3 + 4*z0*z1*z2 + 3*z2^3
```

or even mix numerical coefficients with some expressions

```
sage: H = FTV.anticanonical_hypersurface(
....:   coefficients=[0, "t", "1/t", "psi/(psi^2 + phi)"])
sage: H
Closed subscheme of 2-d CPR-Fano toric variety
 covered by 3 affine patches defined by:
  t*z1^3 + psi/(phi + psi^2)*z0*z1*z2 + 1/t*z2^3
sage: R = H.ambient_space().base_ring()
sage: R
Fraction Field of
 Multivariate Polynomial Ring in phi, psi, t over Rational Field
```

```
>>> from sage.all import *
>>> H = FTV.anticanonical_hypersurface(
...   coefficients=[Integer(0), "t", "1/t", "psi/(psi^2 + phi)"])
>>> H
Closed subscheme of 2-d CPR-Fano toric variety
 covered by 3 affine patches defined by:
  t*z1^3 + psi/(phi + psi^2)*z0*z1*z2 + 1/t*z2^3
>>> R = H.ambient_space().base_ring()
>>> R
Fraction Field of
 Multivariate Polynomial Ring in phi, psi, t over Rational Field
```

cartesian_product(*other*, *coordinate_names=None*, *coordinate_indices=None*)

Return the Cartesian product of `self` with `other`.

INPUT:

- `other` – a (possibly *CPR-Fano*) *toric variety*
- `coordinate_names` – names of variables for the coordinate ring, see *normalize_names()* for acceptable formats. If not given, indexed variable names will be created automatically.
- `coordinate_indices` – list of integers, indices for indexed variables. If not given, the index of each variable will coincide with the index of the corresponding ray of the fan.

OUTPUT:

- a *toric variety*, which is *CPR-Fano* if `other` was.

EXAMPLES:

```
sage: P1 = toric_varieties.P1()
sage: P2 = toric_varieties.P2()
sage: P1xP2 = P1.cartesian_product(P2); P1xP2
3-d CPR-Fano toric variety covered by 6 affine patches
sage: P1xP2.fan().rays()
N+N( 1,  0,  0),        N+N(-1,  0,  0),        N+N( 0,  1,  0),
N+N( 0,  0,  1),        N+N( 0, -1, -1)
in 3-d lattice N+N
sage: P1xP2.Delta_polar()
3-d reflexive polytope in 3-d lattice N+N
```

```
>>> from sage.all import *
>>> P1 = toric_varieties.P1()
>>> P2 = toric_varieties.P2()
>>> P1xP2 = P1.cartesian_product(P2); P1xP2
3-d CPR-Fano toric variety covered by 6 affine patches
>>> P1xP2.fan().rays()
N+N( 1,  0,  0),        N+N(-1,  0,  0),        N+N( 0,  1,  0),
N+N( 0,  0,  1),        N+N( 0, -1, -1)
in 3-d lattice N+N
>>> P1xP2.Delta_polar()
3-d reflexive polytope in 3-d lattice N+N
```

change_ring(*F*)

Return a CPR-Fano toric variety over field `F`, otherwise the same as `self`.

INPUT:

- `F` – field

OUTPUT: *CPR-Fano toric variety* over `F`

Note

There is no need to have any relation between `F` and the base field of `self`. If you do want to have such a relation, use `base_extend()` instead.

EXAMPLES:

```
sage: P1xP1 = toric_varieties.P1xP1()
sage: P1xP1.base_ring()
Rational Field
sage: P1xP1_RR = P1xP1.change_ring(RR)
sage: P1xP1_RR.base_ring()
Real Field with 53 bits of precision
sage: P1xP1_QQ = P1xP1_RR.change_ring(QQ)
sage: P1xP1_QQ.base_ring()
Rational Field
sage: P1xP1_RR.base_extend(QQ)
Traceback (most recent call last):
...
ValueError: no natural map from the base ring
(=Real Field with 53 bits of precision) to R (=Rational Field)!
```

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```
sage: R = PolynomialRing(QQ, 2, 'a')
sage: P1xP1.change_ring(R)
Traceback (most recent call last):
...
TypeError: need a field to construct a Fano toric variety!
Got Multivariate Polynomial Ring in a0, a1 over Rational Field
```

```
>>> from sage.all import *
>>> P1xP1 = toric_varieties.P1xP1()
>>> P1xP1.base_ring()
Rational Field
>>> P1xP1_RR = P1xP1.change_ring(RR)
>>> P1xP1_RR.base_ring()
Real Field with 53 bits of precision
>>> P1xP1_QQ = P1xP1_RR.change_ring(QQ)
>>> P1xP1_QQ.base_ring()
Rational Field
>>> P1xP1_RR.base_extend(QQ)
Traceback (most recent call last):
...
ValueError: no natural map from the base ring
(=Real Field with 53 bits of precision) to R (=Rational Field)!
>>> R = PolynomialRing(QQ, Integer(2), 'a')
>>> P1xP1.change_ring(R)
Traceback (most recent call last):
...
TypeError: need a field to construct a Fano toric variety!
Got Multivariate Polynomial Ring in a0, a1 over Rational Field
```

coordinate_point_to_coordinate(*point*)

Return the variable of the coordinate ring corresponding to `point`.

INPUT:

- `point` – integer from the list of *coordinate_points()*

OUTPUT: the corresponding generator of the coordinate ring of `self`

EXAMPLES:

```
sage: diamond = lattice_polytope.cross_polytope(2)
sage: FTV = CPRFanoToricVariety(diamond, coordinate_points=[0,1,2,3,8])
sage: FTV.coordinate_points()
(0, 1, 2, 3, 8)
sage: FTV.gens()
(z0, z1, z2, z3, z8)
sage: FTV.coordinate_point_to_coordinate(8)
z8
```

```
>>> from sage.all import *
>>> diamond = lattice_polytope.cross_polytope(Integer(2))
>>> FTV = CPRFanoToricVariety(diamond, coordinate_points=[Integer(0),
↪Integer(1),Integer(2),Integer(3),Integer(8)])
```

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```
>>> FTV.coordinate_points()
(0, 1, 2, 3, 8)
>>> FTV.gens()
(z0, z1, z2, z3, z8)
>>> FTV.coordinate_point_to_coordinate(Integer(8))
z8
```

coordinate_points()

Return indices of points of *Delta_polar()* used for coordinates.

OUTPUT: `tuple` of integers

EXAMPLES:

```
sage: diamond = lattice_polytope.cross_polytope(2)
sage: square = diamond.polar()
sage: FTV = CPRFanoToricVariety(Delta_polar=square,
....:                           coordinate_points=[0,1,2,3,8])
sage: FTV.coordinate_points()
(0, 1, 2, 3, 8)
sage: FTV.gens()
(z0, z1, z2, z3, z8)

sage: FTV = CPRFanoToricVariety(Delta_polar=square,
....:                           coordinate_points='all')
sage: FTV.coordinate_points()
(0, 1, 2, 3, 4, 5, 7, 8)
sage: FTV.gens()
(z0, z1, z2, z3, z4, z5, z7, z8)
```

```
>>> from sage.all import *
>>> diamond = lattice_polytope.cross_polytope(Integer(2))
>>> square = diamond.polar()
>>> FTV = CPRFanoToricVariety(Delta_polar=square,
...                           coordinate_points=[Integer(0),Integer(1),
↪Integer(2),Integer(3),Integer(8)])
>>> FTV.coordinate_points()
(0, 1, 2, 3, 8)
>>> FTV.gens()
(z0, z1, z2, z3, z8)

>>> FTV = CPRFanoToricVariety(Delta_polar=square,
...                           coordinate_points='all')
>>> FTV.coordinate_points()
(0, 1, 2, 3, 4, 5, 7, 8)
>>> FTV.gens()
(z0, z1, z2, z3, z4, z5, z7, z8)
```

Note that one point is missing, namely

```
sage: square.origin()
6
```

```
>>> from sage.all import *
>>> square.origin()
6
```

nef_complete_intersection(*nef_partition*, ***kwds*)

Return a nef complete intersection in `self`.

Note

The returned complete intersection may be actually a subscheme of **another** CPR-Fano toric variety: if the base field of `self` does not include all of the required names for monomial coefficients, it will be automatically extended.

Below Δ is the reflexive polytope corresponding to `self`, i.e. the fan of `self` is a refinement of the normal fan of Δ. Other polytopes are described in the documentation of `nef-partitions` of `reflexive polytopes`.

Except for the first argument, `nef_partition`, this method accepts only keyword parameters.

INPUT:

- `nef_partition` – a k-part `nef-partition` of Δ°, all other parameters (if given) must be lists of length k
- `monomial_points` – the i-th element of this list is either a list of integers or a string. A list will be interpreted as indices of points of Δ_i which should be used for monomials of the i-th polynomial of this complete intersection. A string must be one of the following descriptions of points of Δ_i:
  - "vertices",
  - "vertices+origin",
  - "all" (default),

  when using this description, it is also OK to pass a single string as `monomial_points` instead of repeating it k times.
- `coefficient_names` – the i-th element of this list specifies names for the monomial coefficients of the i-th polynomial, see *`normalize_names()`* for acceptable formats. If not given, indexed coefficient names will be created automatically.
- `coefficient_name_indices` – the i-th element of this list specifies indices for indexed coefficients of the i-th polynomial. If not given, the index of each coefficient will coincide with the index of the corresponding point of Δ_i.
- `coefficients` – as an alternative to specifying coefficient names and/or indices, you can give the coefficients themselves as arbitrary expressions and/or strings. Using strings allows you to easily add "parameters": the base field of `self` will be extended to include all necessary names.

OUTPUT:

- a *`nef complete intersection`* of `self` (with the extended base field, if necessary).

EXAMPLES:

We construct several complete intersections associated to the same nef-partition of the 3-dimensional reflexive polytope #2254:

```
sage: p = ReflexivePolytope(3, 2254)
sage: np = p.nef_partitions()[1]; np
Nef-partition {2, 3, 4, 7, 8} ⊔ {0, 1, 5, 6}
sage: X = CPRFanoToricVariety(Delta_polar=p)
sage: X.nef_complete_intersection(np)
Closed subscheme of 3-d CPR-Fano toric variety
 covered by 10 affine patches defined by:
  a0*z1*z4^2*z5^2*z7^3 + a2*z2*z4*z5*z6*z7^2*z8^2
  + a3*z2*z3*z4*z7*z8 + a1*z0*z2,
  b3*z1*z4*z5^2*z6^2*z7^2*z8^2 + b0*z2*z5*z6^3*z7*z8^4
  + b5*z1*z3*z4*z5*z6*z7*z8 + b2*z2*z3*z6^2*z8^3
  + b1*z1*z3^2*z4 + b4*z0*z1*z5*z6
```

```
>>> from sage.all import *
>>> p = ReflexivePolytope(Integer(3), Integer(2254))
>>> np = p.nef_partitions()[Integer(1)]; np
Nef-partition {2, 3, 4, 7, 8} ⊔ {0, 1, 5, 6}
>>> X = CPRFanoToricVariety(Delta_polar=p)
>>> X.nef_complete_intersection(np)
Closed subscheme of 3-d CPR-Fano toric variety
 covered by 10 affine patches defined by:
  a0*z1*z4^2*z5^2*z7^3 + a2*z2*z4*z5*z6*z7^2*z8^2
  + a3*z2*z3*z4*z7*z8 + a1*z0*z2,
  b3*z1*z4*z5^2*z6^2*z7^2*z8^2 + b0*z2*z5*z6^3*z7*z8^4
  + b5*z1*z3*z4*z5*z6*z7*z8 + b2*z2*z3*z6^2*z8^3
  + b1*z1*z3^2*z4 + b4*z0*z1*z5*z6
```

Now we include only monomials associated to vertices of Δ_i:

```
sage: X.nef_complete_intersection(np, monomial_points='vertices')
Closed subscheme of 3-d CPR-Fano toric variety
 covered by 10 affine patches defined by:
  a0*z1*z4^2*z5^2*z7^3 + a2*z2*z4*z5*z6*z7^2*z8^2
  + a3*z2*z3*z4*z7*z8 + a1*z0*z2,
  b3*z1*z4*z5^2*z6^2*z7^2*z8^2 + b0*z2*z5*z6^3*z7*z8^4
  + b2*z2*z3*z6^2*z8^3 + b1*z1*z3^2*z4 + b4*z0*z1*z5*z6
```

```
>>> from sage.all import *
>>> X.nef_complete_intersection(np, monomial_points='vertices')
Closed subscheme of 3-d CPR-Fano toric variety
 covered by 10 affine patches defined by:
  a0*z1*z4^2*z5^2*z7^3 + a2*z2*z4*z5*z6*z7^2*z8^2
  + a3*z2*z3*z4*z7*z8 + a1*z0*z2,
  b3*z1*z4*z5^2*z6^2*z7^2*z8^2 + b0*z2*z5*z6^3*z7*z8^4
  + b2*z2*z3*z6^2*z8^3 + b1*z1*z3^2*z4 + b4*z0*z1*z5*z6
```

(effectively, we set `b5=0`). Next we provide coefficients explicitly instead of using default generic names:

```
sage: X.nef_complete_intersection(np,
....:       monomial_points='vertices',
....:       coefficients=[("a", "a^2", "a/e", "c_i"), list(range(1,6))])
Closed subscheme of 3-d CPR-Fano toric variety
 covered by 10 affine patches defined by:
```

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```
  a*z1*z4^2*z5^2*z7^3 + a/e*z2*z4*z5*z6*z7^2*z8^2
  + (c_i)*z2*z3*z4*z7*z8 + (a^2)*z0*z2,
  4*z1*z4*z5^2*z6^2*z7^2*z8^2 + z2*z5*z6^3*z7*z8^4
  + 3*z2*z3*z6^2*z8^3 + 2*z1*z3^2*z4 + 5*z0*z1*z5*z6
```

```
>>> from sage.all import *
>>> X.nef_complete_intersection(np,
...       monomial_points='vertices',
...       coefficients=[("a", "a^2", "a/e", "c_i"), list(range(Integer(1),
↪Integer(6)))])
Closed subscheme of 3-d CPR-Fano toric variety
 covered by 10 affine patches defined by:
  a*z1*z4^2*z5^2*z7^3 + a/e*z2*z4*z5*z6*z7^2*z8^2
  + (c_i)*z2*z3*z4*z7*z8 + (a^2)*z0*z2,
  4*z1*z4*z5^2*z6^2*z7^2*z8^2 + z2*z5*z6^3*z7*z8^4
  + 3*z2*z3*z6^2*z8^3 + 2*z1*z3^2*z4 + 5*z0*z1*z5*z6
```

Finally, we take a look at the generic representative of these complete intersections in a completely resolved ambient toric variety:

```
sage: X = CPRFanoToricVariety(Delta_polar=p,
....:                         coordinate_points='all')
sage: X.nef_complete_intersection(np)
Closed subscheme of 3-d CPR-Fano toric variety
 covered by 22 affine patches defined by:
  a2*z2*z4*z5*z6*z7^2*z8^2*z9^2*z10^2*z11*z12*z13
  + a0*z1*z4^2*z5^2*z7^3*z9*z10^2*z12*z13
  + a3*z2*z3*z4*z7*z8*z9*z10*z11*z12 + a1*z0*z2,
  b0*z2*z5*z6^3*z7*z8^4*z9^3*z10^2*z11^2*z12*z13^2
  + b3*z1*z4*z5^2*z6^2*z7^2*z8^2*z9^2*z10^2*z11*z12*z13^2
  + b2*z2*z3*z6^2*z8^3*z9^2*z10*z11^2*z12*z13
  + b5*z1*z3*z4*z5*z6*z7*z8*z9*z10*z11*z12*z13
  + b1*z1*z3^2*z4*z11*z12 + b4*z0*z1*z5*z6*z13
```

```
>>> from sage.all import *
>>> X = CPRFanoToricVariety(Delta_polar=p,
...                         coordinate_points='all')
>>> X.nef_complete_intersection(np)
Closed subscheme of 3-d CPR-Fano toric variety
 covered by 22 affine patches defined by:
  a2*z2*z4*z5*z6*z7^2*z8^2*z9^2*z10^2*z11*z12*z13
  + a0*z1*z4^2*z5^2*z7^3*z9*z10^2*z12*z13
  + a3*z2*z3*z4*z7*z8*z9*z10*z11*z12 + a1*z0*z2,
  b0*z2*z5*z6^3*z7*z8^4*z9^3*z10^2*z11^2*z12*z13^2
  + b3*z1*z4*z5^2*z6^2*z7^2*z8^2*z9^2*z10^2*z11*z12*z13^2
  + b2*z2*z3*z6^2*z8^3*z9^2*z10*z11^2*z12*z13
  + b5*z1*z3*z4*z5*z6*z7*z8*z9*z10*z11*z12*z13
  + b1*z1*z3^2*z4*z11*z12 + b4*z0*z1*z5*z6*z13
```

resolve(***kwds*)

Construct a toric variety whose fan subdivides the fan of `self`.

This function accepts only keyword arguments, none of which are mandatory.

INPUT:

- `new_points` – list of integers, indices of boundary points of *`Delta_polar()`*, which should be added as rays to the subdividing fan
- all other arguments will be passed to *`resolve()`* method of (general) toric varieties; see its documentation for details

OUTPUT:

- *`CPR-Fano toric variety`* if there was no `new_rays` argument and *`toric variety`* otherwise.

EXAMPLES:

```
sage: diamond = lattice_polytope.cross_polytope(2)
sage: FTV = CPRFanoToricVariety(Delta=diamond)
sage: FTV.coordinate_points()
(0, 1, 2, 3)
sage: FTV.gens()
(z0, z1, z2, z3)
sage: FTV_res = FTV.resolve(new_points=[6,8])
Traceback (most recent call last):
...
ValueError: the origin (point #6)
cannot be used for subdivision!
sage: FTV_res = FTV.resolve(new_points=[8,5]); FTV_res
2-d CPR-Fano toric variety covered by 6 affine patches
sage: FTV_res.coordinate_points()
(0, 1, 2, 3, 8, 5)
sage: FTV_res.gens()
(z0, z1, z2, z3, z8, z5)

sage: TV_res = FTV.resolve(new_rays=[(1,2)]); TV_res
2-d toric variety covered by 5 affine patches
sage: TV_res.gens()
(z0, z1, z2, z3, z4)
```

```
>>> from sage.all import *
>>> diamond = lattice_polytope.cross_polytope(Integer(2))
>>> FTV = CPRFanoToricVariety(Delta=diamond)
>>> FTV.coordinate_points()
(0, 1, 2, 3)
>>> FTV.gens()
(z0, z1, z2, z3)
>>> FTV_res = FTV.resolve(new_points=[Integer(6),Integer(8)])
Traceback (most recent call last):
...
ValueError: the origin (point #6)
cannot be used for subdivision!
>>> FTV_res = FTV.resolve(new_points=[Integer(8),Integer(5)]); FTV_res
2-d CPR-Fano toric variety covered by 6 affine patches
>>> FTV_res.coordinate_points()
(0, 1, 2, 3, 8, 5)
>>> FTV_res.gens()
(z0, z1, z2, z3, z8, z5)
```

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```
>>> TV_res = FTV.resolve(new_rays=[(Integer(1),Integer(2))]); TV_res
2-d toric variety covered by 5 affine patches
>>> TV_res.gens()
(z0, z1, z2, z3, z4)
```

class sage.schemes.toric.fano_variety.**NefCompleteIntersection**(*P_Delta*, *nef_partition*, *monomial_points='all'*, *coefficient_names=None*, *coefficient_name_indices=None*, *coefficients=None*)

Bases: *AlgebraicScheme_subscheme_toric*

Construct a nef complete intersection in a CPR-Fano toric variety.

INPUT:

- `P_Delta` – a *CPR-Fano toric variety* associated to a reflexive polytope Δ
- see *CPRFanoToricVariety_field.nef_complete_intersection()* for documentation on all other acceptable parameters

OUTPUT:

- a *nef complete intersection* of `P_Delta` (with the extended base field, if necessary).

EXAMPLES:

```
sage: o = lattice_polytope.cross_polytope(3)
sage: np = o.nef_partitions()[0]; np
Nef-partition {0, 1, 3} ⊔ {2, 4, 5}
sage: X = CPRFanoToricVariety(Delta_polar=o)
sage: X.nef_complete_intersection(np)
Closed subscheme of 3-d CPR-Fano toric variety
 covered by 8 affine patches defined by:
  a2*z0^2*z1 + a5*z0*z1*z3 + a1*z1*z3^2 + a3*z0^2*z4 + a4*z0*z3*z4 + a0*z3^2*z4,
  b1*z1*z2^2 + b2*z2^2*z4 + b5*z1*z2*z5 + b4*z2*z4*z5 + b3*z1*z5^2 + b0*z4*z5^2
```

```
>>> from sage.all import *
>>> o = lattice_polytope.cross_polytope(Integer(3))
>>> np = o.nef_partitions()[Integer(0)]; np
Nef-partition {0, 1, 3} ⊔ {2, 4, 5}
>>> X = CPRFanoToricVariety(Delta_polar=o)
>>> X.nef_complete_intersection(np)
Closed subscheme of 3-d CPR-Fano toric variety
 covered by 8 affine patches defined by:
  a2*z0^2*z1 + a5*z0*z1*z3 + a1*z1*z3^2 + a3*z0^2*z4 + a4*z0*z3*z4 + a0*z3^2*z4,
  b1*z1*z2^2 + b2*z2^2*z4 + b5*z1*z2*z5 + b4*z2*z4*z5 + b3*z1*z5^2 + b0*z4*z5^2
```

See *CPRFanoToricVariety_field.nef_complete_intersection()* for a more elaborate example.

cohomology_class()

Return the class of `self` in the ambient space cohomology ring.

OUTPUT: a `cohomology class`

EXAMPLES:

```
sage: o = lattice_polytope.cross_polytope(3)
sage: np = o.nef_partitions()[0]; np
Nef-partition {0, 1, 3} ⊔ {2, 4, 5}
sage: X = CPRFanoToricVariety(Delta_polar=o)
sage: CI = X.nef_complete_intersection(np); CI
Closed subscheme of 3-d CPR-Fano toric variety
 covered by 8 affine patches defined by:
  a2*z0^2*z1 + a5*z0*z1*z3 + a1*z1*z3^2 + a3*z0^2*z4 + a4*z0*z3*z4 + a0*z3^
↪2*z4,
  b1*z1*z2^2 + b2*z2^2*z4 + b5*z1*z2*z5 + b4*z2*z4*z5 + b3*z1*z5^2 + b0*z4*z5^
↪2
sage: CI.cohomology_class()                                                  #␣
↪needs sage.libs.singular
[2*z3*z4 + 4*z3*z5 + 2*z4*z5]
```

```
>>> from sage.all import *
>>> o = lattice_polytope.cross_polytope(Integer(3))
>>> np = o.nef_partitions()[Integer(0)]; np
Nef-partition {0, 1, 3} ⊔ {2, 4, 5}
>>> X = CPRFanoToricVariety(Delta_polar=o)
>>> CI = X.nef_complete_intersection(np); CI
Closed subscheme of 3-d CPR-Fano toric variety
 covered by 8 affine patches defined by:
  a2*z0^2*z1 + a5*z0*z1*z3 + a1*z1*z3^2 + a3*z0^2*z4 + a4*z0*z3*z4 + a0*z3^
↪2*z4,
  b1*z1*z2^2 + b2*z2^2*z4 + b5*z1*z2*z5 + b4*z2*z4*z5 + b3*z1*z5^2 + b0*z4*z5^
↪2
>>> CI.cohomology_class()                                                    #␣
↪needs sage.libs.singular
[2*z3*z4 + 4*z3*z5 + 2*z4*z5]
```

nef_partition()

Return the nef-partition associated to `self`.

OUTPUT: a nef-partition

EXAMPLES:

```
sage: o = lattice_polytope.cross_polytope(3)
sage: np = o.nef_partitions()[0]; np
Nef-partition {0, 1, 3} ⊔ {2, 4, 5}
sage: X = CPRFanoToricVariety(Delta_polar=o)
sage: CI = X.nef_complete_intersection(np); CI
Closed subscheme of 3-d CPR-Fano toric variety
 covered by 8 affine patches defined by:
  a2*z0^2*z1 + a5*z0*z1*z3 + a1*z1*z3^2 + a3*z0^2*z4 + a4*z0*z3*z4 + a0*z3^
↪2*z4,
  b1*z1*z2^2 + b2*z2^2*z4 + b5*z1*z2*z5 + b4*z2*z4*z5 + b3*z1*z5^2 + b0*z4*z5^
↪2
sage: CI.nef_partition()
Nef-partition {0, 1, 3} ⊔ {2, 4, 5}
sage: CI.nef_partition() is np
True
```

```
>>> from sage.all import *
>>> o = lattice_polytope.cross_polytope(Integer(3))
>>> np = o.nef_partitions()[Integer(0)]; np
Nef-partition {0, 1, 3} ⊔ {2, 4, 5}
>>> X = CPRFanoToricVariety(Delta_polar=o)
>>> CI = X.nef_complete_intersection(np); CI
Closed subscheme of 3-d CPR-Fano toric variety
 covered by 8 affine patches defined by:
  a2*z0^2*z1 + a5*z0*z1*z3 + a1*z1*z3^2 + a3*z0^2*z4 + a4*z0*z3*z4 + a0*z3^
↪2*z4,
  b1*z1*z2^2 + b2*z2^2*z4 + b5*z1*z2*z5 + b4*z2*z4*z5 + b3*z1*z5^2 + b0*z4*z5^
↪2
>>> CI.nef_partition()
Nef-partition {0, 1, 3} ⊔ {2, 4, 5}
>>> CI.nef_partition() is np
True
```

sage.schemes.toric.fano_variety.**add_variables**(*field*, *variables*)

Extend `field` to include all `variables`.

INPUT:

- `field` – a field
- `variables` – list of strings

OUTPUT:

- a fraction field extending the original `field`, which has all `variables` among its generators.

EXAMPLES:

We start with the rational field and slowly add more variables:

```
sage: from sage.schemes.toric.fano_variety import *
sage: F = add_variables(QQ, []); F      # No extension
Rational Field
sage: F = add_variables(QQ, ["a"]); F
Fraction Field of Univariate Polynomial Ring in a over Rational Field
sage: F = add_variables(F, ["a"]); F
Fraction Field of Univariate Polynomial Ring in a over Rational Field
sage: F = add_variables(F, ["b", "c"]); F
Fraction Field of Multivariate Polynomial Ring in a, b, c over Rational Field
sage: F = add_variables(F, ["c", "d", "b", "c", "d"]); F
Fraction Field of Multivariate Polynomial Ring in a, b, c, d over Rational Field
```

```
>>> from sage.all import *
>>> from sage.schemes.toric.fano_variety import *
>>> F = add_variables(QQ, []); F      # No extension
Rational Field
>>> F = add_variables(QQ, ["a"]); F
Fraction Field of Univariate Polynomial Ring in a over Rational Field
>>> F = add_variables(F, ["a"]); F
Fraction Field of Univariate Polynomial Ring in a over Rational Field
>>> F = add_variables(F, ["b", "c"]); F
Fraction Field of Multivariate Polynomial Ring in a, b, c over Rational Field
```

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```
>>> F = add_variables(F, ["c", "d", "b", "c", "d"]); F
Fraction Field of Multivariate Polynomial Ring in a, b, c, d over Rational Field
```

sage.schemes.toric.fano_variety.**is_CPRFanoToricVariety**(*x*)

Check if `x` is a CPR-Fano toric variety.

INPUT:

- `x` – anything

OUTPUT:

- `True` if `x` is a *CPR-Fano toric variety* and `False` otherwise.

Note

While projective spaces are Fano toric varieties mathematically, they are not toric varieties in Sage due to efficiency considerations, so this function will return `False`.

EXAMPLES:

```
sage: from sage.schemes.toric.fano_variety import is_CPRFanoToricVariety
sage: is_CPRFanoToricVariety(1)
doctest:warning...
DeprecationWarning: The function is_CPRFanoToricVariety is deprecated; use
↪'isinstance(..., CPRFanoToricVariety_field)' instead.
See https://github.com/sagemath/sage/issues/38022 for details.
False
sage: FTV = toric_varieties.P2()
sage: FTV
2-d CPR-Fano toric variety covered by 3 affine patches
sage: is_CPRFanoToricVariety(FTV)
True
sage: is_CPRFanoToricVariety(ProjectiveSpace(2))
False
```

```
>>> from sage.all import *
>>> from sage.schemes.toric.fano_variety import is_CPRFanoToricVariety
>>> is_CPRFanoToricVariety(Integer(1))
doctest:warning...
DeprecationWarning: The function is_CPRFanoToricVariety is deprecated; use
↪'isinstance(..., CPRFanoToricVariety_field)' instead.
See https://github.com/sagemath/sage/issues/38022 for details.
False
>>> FTV = toric_varieties.P2()
>>> FTV
2-d CPR-Fano toric variety covered by 3 affine patches
>>> is_CPRFanoToricVariety(FTV)
True
>>> is_CPRFanoToricVariety(ProjectiveSpace(Integer(2)))
False
```

16.3 Library of toric varieties

This module provides a simple way to construct often-used toric varieties. Please see the help for the individual methods of `toric_varieties` for a more detailed description of which varieties can be constructed.

AUTHORS:

- Volker Braun (2010-07-02): initial version

EXAMPLES:

```
sage: toric_varieties.dP6()
2-d CPR-Fano toric variety covered by 6 affine patches
```

```
>>> from sage.all import *
>>> toric_varieties.dP6()
2-d CPR-Fano toric variety covered by 6 affine patches
```

You can assign the homogeneous coordinates to Sage variables either with `inject_variables()` or immediately during assignment like this:

```
sage: P2.<x,y,z> = toric_varieties.P2()
sage: x^2 + y^2 + z^2
x^2 + y^2 + z^2
sage: P2.coordinate_ring()
Multivariate Polynomial Ring in x, y, z over Rational Field
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2(names=('x', 'y', 'z',)); (x, y, z,) = P2._first_ngens(3)
>>> x**Integer(2) + y**Integer(2) + z**Integer(2)
x^2 + y^2 + z^2
>>> P2.coordinate_ring()
Multivariate Polynomial Ring in x, y, z over Rational Field
```

class sage.schemes.toric.library.**ToricVarietyFactory**

Bases: `SageObject`

The methods of this class construct toric varieties.

Warning

You need not create instances of this class. Use the already-provided object `toric_varieties` instead.

A(*n*, *names='z+'*, *base_ring=Rational Field*)

Construct the `n`-dimensional affine space.

INPUT:

- `n` – positive integer; the dimension of the affine space
- `names` – string; names for the homogeneous coordinates. See *`normalize_names()`* for acceptable formats.
- `base_ring` – a ring (default: **Q**); the base ring for the toric variety

OUTPUT: a *`toric variety`*.

EXAMPLES:

```
sage: A3 = toric_varieties.A(3); A3
3-d affine toric variety
sage: A3.fan().rays()
N(1, 0, 0),
N(0, 1, 0),
N(0, 0, 1)
in 3-d lattice N
sage: A3.gens()
(z0, z1, z2)
```

```
>>> from sage.all import *
>>> A3 = toric_varieties.A(Integer(3)); A3
3-d affine toric variety
>>> A3.fan().rays()
N(1, 0, 0),
N(0, 1, 0),
N(0, 0, 1)
in 3-d lattice N
>>> A3.gens()
(z0, z1, z2)
```

A1 (*names='z'*, *base_ring=Rational Field*)

Construct the affine line $\mathbb{A}^1$ as a toric variety.

INPUT:

- `names` – string; names for the homogeneous coordinates. See *normalize_names()* for acceptable formats.
- `base_ring` – a ring (default: $\mathbf{Q}$); the base ring for the toric variety

OUTPUT: a *toric variety*.

EXAMPLES:

```
sage: A1 = toric_varieties.A1(); A1
1-d affine toric variety
sage: A1.fan().rays()
N(1)
in 1-d lattice N
sage: A1.gens()
(z,)
```

```
>>> from sage.all import *
>>> A1 = toric_varieties.A1(); A1
1-d affine toric variety
>>> A1.fan().rays()
N(1)
in 1-d lattice N
>>> A1.gens()
(z,)
```

A2 (*names='x y'*, *base_ring=Rational Field*)

Construct the affine plane $\mathbb{A}^2$ as a toric variety.

INPUT:

- `names` – string; names for the homogeneous coordinates. See *normalize_names()* for acceptable formats.
- `base_ring` – a ring (default: $\mathbf{Q}$); the base ring for the toric variety

OUTPUT: a *toric variety*.

EXAMPLES:

```
sage: A2 = toric_varieties.A2(); A2
2-d affine toric variety
sage: A2.fan().rays()
N(1, 0),
N(0, 1)
in 2-d lattice N
sage: A2.gens()
(x, y)
```

```
>>> from sage.all import *
>>> A2 = toric_varieties.A2(); A2
2-d affine toric variety
>>> A2.fan().rays()
N(1, 0),
N(0, 1)
in 2-d lattice N
>>> A2.gens()
(x, y)
```

A2_Z2 (*names='x y'*, *base_ring=Rational Field*)

Construct the orbifold $\mathbb{A}^2/\mathbf{Z}_2$ as a toric variety.

INPUT:

- `names` – string; names for the homogeneous coordinates. See *normalize_names()* for acceptable formats.
- `base_ring` – a ring (default: $\mathbf{Q}$); the base ring for the toric variety

OUTPUT: a *toric variety*.

EXAMPLES:

```
sage: A2_Z2 = toric_varieties.A2_Z2(); A2_Z2
2-d affine toric variety
sage: A2_Z2.fan().rays()
N(1, 0),
N(1, 2)
in 2-d lattice N
sage: A2_Z2.gens()
(x, y)
```

```
>>> from sage.all import *
>>> A2_Z2 = toric_varieties.A2_Z2(); A2_Z2
2-d affine toric variety
>>> A2_Z2.fan().rays()
```

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```
N(1, 0),
N(1, 2)
in 2-d lattice N
>>> A2_Z2.gens()
(x, y)
```

BCdlOG(*names='v1 v2 c1 c2 v4 v5 b e1 e2 e3 f g v6'*, *base_ring=Rational Field*)

Construct the 5-dimensional toric variety studied in [BCdlOG2000], [HLY2002]

INPUT:

- `names` – string; names for the homogeneous coordinates. See *normalize_names()* for acceptable formats.
- `base_ring` – a ring (default: $\mathbf{Q}$); the base ring for the toric variety

OUTPUT: a *CPR-Fano toric variety*.

EXAMPLES:

```
sage: X = toric_varieties.BCdlOG(); X
5-d CPR-Fano toric variety covered by 54 affine patches
sage: X.fan().rays()
N(-1,  0,  0,  2,  3),          N( 0, -1,  0,  2,  3),
N( 0,  0, -1,  2,  3),          N( 0,  0, -1,  1,  2),
N( 0,  0,  0, -1,  0),          N( 0,  0,  0,  0, -1),
N( 0,  0,  0,  2,  3),          N( 0,  0,  1,  2,  3),
N( 0,  0,  2,  2,  3),          N( 0,  0,  1,  1,  1),
N( 0,  1,  2,  2,  3),          N( 0,  1,  3,  2,  3),
N( 1,  0,  4,  2,  3)
in 5-d lattice N
sage: X.gens()
(v1, v2, c1, c2, v4, v5, b, e1, e2, e3, f, g, v6)
```

```
>>> from sage.all import *
>>> X = toric_varieties.BCdlOG(); X
5-d CPR-Fano toric variety covered by 54 affine patches
>>> X.fan().rays()
N(-1,  0,  0,  2,  3),          N( 0, -1,  0,  2,  3),
N( 0,  0, -1,  2,  3),          N( 0,  0, -1,  1,  2),
N( 0,  0,  0, -1,  0),          N( 0,  0,  0,  0, -1),
N( 0,  0,  0,  2,  3),          N( 0,  0,  1,  2,  3),
N( 0,  0,  2,  2,  3),          N( 0,  0,  1,  1,  1),
N( 0,  1,  2,  2,  3),          N( 0,  1,  3,  2,  3),
N( 1,  0,  4,  2,  3)
in 5-d lattice N
>>> X.gens()
(v1, v2, c1, c2, v4, v5, b, e1, e2, e3, f, g, v6)
```

BCdlOG_base(*names='d4 d3 r2 r1 d2 u d1'*, *base_ring=Rational Field*)

Construct the base of the $\mathbb{P}^2(1,2,3)$ fibration *BCdlOG()*.

INPUT:

- `names` – string; names for the homogeneous coordinates. See *normalize_names()* for acceptable formats.

- `base_ring` – a ring (default: **Q**); the base ring for the toric variety

OUTPUT: a *toric variety*.

EXAMPLES:

```
sage: base = toric_varieties.BCdlOG_base(); base
3-d toric variety covered by 10 affine patches
sage: base.fan().rays()
N(-1,  0,  0),    N( 0, -1,  0),    N( 0,  0, -1),    N( 0,  0,  1),
N( 0,  1,  2),    N( 0,  1,  3),    N( 1,  0,  4)
in 3-d lattice N
sage: base.gens()
(d4, d3, r2, r1, d2, u, d1)
```

```
>>> from sage.all import *
>>> base = toric_varieties.BCdlOG_base(); base
3-d toric variety covered by 10 affine patches
>>> base.fan().rays()
N(-1,  0,  0),    N( 0, -1,  0),    N( 0,  0, -1),    N( 0,  0,  1),
N( 0,  1,  2),    N( 0,  1,  3),    N( 1,  0,  4)
in 3-d lattice N
>>> base.gens()
(d4, d3, r2, r1, d2, u, d1)
```

Conifold(*names='u x y v'*, *base_ring=Rational Field*)

Construct the conifold as a toric variety.

INPUT:

- `names` – string; names for the homogeneous coordinates. See *normalize_names()* for acceptable formats.
- `base_ring` – a ring (default: **Q**); the base ring for the toric variety

OUTPUT: a *toric variety*.

EXAMPLES:

```
sage: Conifold = toric_varieties.Conifold(); Conifold
3-d affine toric variety
sage: Conifold.fan().rays()
N(0, 0, 1),       N(0, 1, 1),
N(1, 0, 1),       N(1, 1, 1)
in 3-d lattice N
sage: Conifold.gens()
(u, x, y, v)
```

```
>>> from sage.all import *
>>> Conifold = toric_varieties.Conifold(); Conifold
3-d affine toric variety
>>> Conifold.fan().rays()
N(0, 0, 1),       N(0, 1, 1),
N(1, 0, 1),       N(1, 1, 1)
in 3-d lattice N
>>> Conifold.gens()
(u, x, y, v)
```

Cube_deformation(*k*, *names=None*, *base_ring=Rational Field*)

Construct, for each $k \in \mathbf{Z}_{\geq 0}$, a toric variety with $\mathbf{Z}_k$-torsion in the Chow group.

The fans of this sequence of toric varieties all equal the face fan of a unit cube topologically, but the `(1,1,1)`-vertex is moved to `(1,1,2k+1)`. This example was studied in [FS1994].

INPUT:

- `k` – integer; the case `k=0` is the same as *Cube_face_fan()*
- `names` – string; names for the homogeneous coordinates. See *normalize_names()* for acceptable formats.
- `base_ring` – a ring (default: $\mathbf{Q}$); the base ring for the toric variety

OUTPUT:

A *toric variety* X_k. Its Chow group is $A_1(X_k) = \mathbf{Z}_k$.

EXAMPLES:

```
sage: X_2 = toric_varieties.Cube_deformation(2); X_2
3-d toric variety covered by 6 affine patches
sage: X_2.fan().rays()
N( 1,  1,  5),    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: X_2.gens()
(z0, z1, z2, z3, z4, z5, z6, z7)
```

```
>>> from sage.all import *
>>> X_2 = toric_varieties.Cube_deformation(Integer(2)); X_2
3-d toric variety covered by 6 affine patches
>>> X_2.fan().rays()
N( 1,  1,  5),    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
>>> X_2.gens()
(z0, z1, z2, z3, z4, z5, z6, z7)
```

Cube_face_fan(*names='z+'*, *base_ring=Rational Field*)

Construct the toric variety given by the face fan of the 3-dimensional unit lattice cube.

This variety has 6 conifold singularities but the fan is still polyhedral.

INPUT:

- `names` – string; names for the homogeneous coordinates. See *normalize_names()* for acceptable formats.
- `base_ring` – a ring (default: $\mathbf{Q}$); the base ring for the toric variety

OUTPUT: a *CPR-Fano toric variety*.

EXAMPLES:

```
sage: Cube_face_fan = toric_varieties.Cube_face_fan(); Cube_face_fan
3-d CPR-Fano toric variety covered by 6 affine patches
sage: Cube_face_fan.fan().rays()
N( 1,  1,  1),    N( 1, -1,  1),    N(-1,  1,  1),    N(-1, -1,  1),
```

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```
N(-1, -1, -1),    N(-1,  1, -1),    N( 1, -1, -1),    N( 1,  1, -1)
in 3-d lattice N
sage: Cube_face_fan.gens()
(z0, z1, z2, z3, z4, z5, z6, z7)
```

```
>>> from sage.all import *
>>> Cube_face_fan = toric_varieties.Cube_face_fan(); Cube_face_fan
3-d CPR-Fano toric variety covered by 6 affine patches
>>> Cube_face_fan.fan().rays()
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
>>> Cube_face_fan.gens()
(z0, z1, z2, z3, z4, z5, z6, z7)
```

Cube_nonpolyhedral(*names='z+'*, *base_ring=Rational Field*)

Construct the toric variety defined by a fan that is not the face fan of a polyhedron.

This toric variety is defined by a fan that is topologically like the face fan of a 3-dimensional cube, but with a different N-lattice structure.

INPUT:

- `names` – string; names for the homogeneous coordinates. See *`normalize_names()`* for acceptable formats.
- `base_ring` – a ring (default: **Q**); the base ring for the toric variety

OUTPUT: a *`toric variety`*.

Note

- This is an example of a non-polyhedral fan.
- Its Chow group has torsion: $A_2(X) = \mathbf{Z}^5 \oplus \mathbf{Z}_2$

EXAMPLES:

```
sage: Cube_nonpolyhedral = toric_varieties.Cube_nonpolyhedral()
sage: Cube_nonpolyhedral
3-d toric variety covered by 6 affine patches
sage: Cube_nonpolyhedral.fan().rays()
N( 1,  2,  3),    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: Cube_nonpolyhedral.gens()
(z0, z1, z2, z3, z4, z5, z6, z7)
```

```
>>> from sage.all import *
>>> Cube_nonpolyhedral = toric_varieties.Cube_nonpolyhedral()
>>> Cube_nonpolyhedral
3-d toric variety covered by 6 affine patches
>>> Cube_nonpolyhedral.fan().rays()
```

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```
N( 1,  2,  3),    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
>>> Cube_nonpolyhedral.gens()
(z0, z1, z2, z3, z4, z5, z6, z7)
```

Cube_sublattice(*names='z+'*, *base_ring=Rational Field*)

Construct the toric variety defined by a face fan over a 3-dimensional cube, but not the unit cube in the N-lattice. See p. 65 of [Ful1993].

Its Chow group is $A_2(X) = \mathbf{Z}^5$, which distinguishes it from the face fan of the unit cube.

INPUT:

- `names` – string; names for the homogeneous coordinates. See *normalize_names()* for acceptable formats.
- `base_ring` – a ring (default: **Q**); the base ring for the toric variety

OUTPUT: a *CPR-Fano toric variety*.

EXAMPLES:

```
sage: Cube_sublattice = toric_varieties.Cube_sublattice(); Cube_sublattice
3-d CPR-Fano toric variety covered by 6 affine patches
sage: Cube_sublattice.fan().rays()
N( 1,  0,  0),    N( 0,  1,  0),    N( 0,  0,  1),    N(-1,  1,  1),
N(-1,  0,  0),    N( 0, -1,  0),    N( 0,  0, -1),    N( 1, -1, -1)
in 3-d lattice N
sage: Cube_sublattice.gens()
(z0, z1, z2, z3, z4, z5, z6, z7)
```

```
>>> from sage.all import *
>>> Cube_sublattice = toric_varieties.Cube_sublattice(); Cube_sublattice
3-d CPR-Fano toric variety covered by 6 affine patches
>>> Cube_sublattice.fan().rays()
N( 1,  0,  0),    N( 0,  1,  0),    N( 0,  0,  1),    N(-1,  1,  1),
N(-1,  0,  0),    N( 0, -1,  0),    N( 0,  0, -1),    N( 1, -1, -1)
in 3-d lattice N
>>> Cube_sublattice.gens()
(z0, z1, z2, z3, z4, z5, z6, z7)
```

P(*n*, *names='z+'*, *base_ring=Rational Field*)

Construct the `n`-dimensional projective space $\mathbb{P}^n$.

INPUT:

- `n` – positive integer; the dimension of the projective space
- `names` – string; names for the homogeneous coordinates. See *normalize_names()* for acceptable formats.
- `base_ring` – a ring (default: **Q**); the base ring for the toric variety

OUTPUT: a *CPR-Fano toric variety*.

EXAMPLES:

```
sage: P3 = toric_varieties.P(3); P3
3-d CPR-Fano toric variety covered by 4 affine patches
sage: P3.fan().rays()
N( 1,  0,  0),
N( 0,  1,  0),
N( 0,  0,  1),
N(-1, -1, -1)
in 3-d lattice N
sage: P3.gens()
(z0, z1, z2, z3)
```

```
>>> from sage.all import *
>>> P3 = toric_varieties.P(Integer(3)); P3
3-d CPR-Fano toric variety covered by 4 affine patches
>>> P3.fan().rays()
N( 1,  0,  0),
N( 0,  1,  0),
N( 0,  0,  1),
N(-1, -1, -1)
in 3-d lattice N
>>> P3.gens()
(z0, z1, z2, z3)
```

P1 (*names='s t'*, *base_ring=Rational Field*)

Construct the projective line $\mathbb{P}^1$ as a toric variety.

INPUT:

- `names` – string; names for the homogeneous coordinates. See *normalize_names()* for acceptable formats.
- `base_ring` – a ring (default: $\mathbf{Q}$); the base ring for the toric variety

OUTPUT: a *CPR-Fano toric variety*.

EXAMPLES:

```
sage: P1 = toric_varieties.P1(); P1
1-d CPR-Fano toric variety covered by 2 affine patches
sage: P1.fan().rays()
N( 1),
N(-1)
in 1-d lattice N
sage: P1.gens()
(s, t)
```

```
>>> from sage.all import *
>>> P1 = toric_varieties.P1(); P1
1-d CPR-Fano toric variety covered by 2 affine patches
>>> P1.fan().rays()
N( 1),
N(-1)
in 1-d lattice N
>>> P1.gens()
(s, t)
```

P1xA1 (*names='s t z'*, *base_ring=Rational Field*)

Construct the Cartesian product $\mathbb{P}^1 \times \mathbb{A}^1$ as a toric variety.

INPUT:

- `names` – string; names for the homogeneous coordinates. See *normalize_names()* for acceptable formats.
- `base_ring` – a ring (default: **Q**); the base ring for the toric variety

OUTPUT: a *toric variety*.

EXAMPLES:

```
sage: P1xA1 = toric_varieties.P1xA1(); P1xA1
2-d toric variety covered by 2 affine patches
sage: P1xA1.fan().rays()
N( 1, 0),
N(-1, 0),
N( 0, 1)
in 2-d lattice N
sage: P1xA1.gens()
(s, t, z)
```

```
>>> from sage.all import *
>>> P1xA1 = toric_varieties.P1xA1(); P1xA1
2-d toric variety covered by 2 affine patches
>>> P1xA1.fan().rays()
N( 1, 0),
N(-1, 0),
N( 0, 1)
in 2-d lattice N
>>> P1xA1.gens()
(s, t, z)
```

P1xP1 (*names='s t x y'*, *base_ring=Rational Field*)

Construct the del Pezzo surface $\mathbb{P}^1 \times \mathbb{P}^1$ as a toric variety.

INPUT:

- `names` – string; names for the homogeneous coordinates. See *normalize_names()* for acceptable formats.
- `base_ring` – a ring (default: **Q**); the base ring for the toric variety

OUTPUT: a *CPR-Fano toric variety*.

EXAMPLES:

```
sage: P1xP1 = toric_varieties.P1xP1(); P1xP1
2-d CPR-Fano toric variety covered by 4 affine patches
sage: P1xP1.fan().rays()
N( 1,  0),        N(-1,  0),
N( 0,  1),        N( 0, -1)
in 2-d lattice N
sage: P1xP1.gens()
(s, t, x, y)
```

```
>>> from sage.all import *
>>> P1xP1 = toric_varieties.P1xP1(); P1xP1
2-d CPR-Fano toric variety covered by 4 affine patches
>>> P1xP1.fan().rays()
N( 1,  0),        N(-1,  0),
N( 0,  1),        N( 0, -1)
in 2-d lattice N
>>> P1xP1.gens()
(s, t, x, y)
```

P1xP1_Z2 (*names='s t x y'*, *base_ring=Rational Field*)

Construct the toric $\mathbf{Z}_2$-orbifold of the del Pezzo surface $\mathbb{P}^1 \times \mathbb{P}^1$ as a toric variety.

INPUT:

- `names` – string; names for the homogeneous coordinates. See *normalize_names()* for acceptable formats.
- `base_ring` – a ring (default: $\mathbf{Q}$); the base ring for the toric variety

OUTPUT: a *CPR-Fano toric variety*.

EXAMPLES:

```
sage: P1xP1_Z2 = toric_varieties.P1xP1_Z2(); P1xP1_Z2
2-d CPR-Fano toric variety covered by 4 affine patches
sage: P1xP1_Z2.fan().rays()
N( 1,  1),        N(-1, -1),
N(-1,  1),        N( 1, -1)
in 2-d lattice N
sage: P1xP1_Z2.gens()
(s, t, x, y)
sage: P1xP1_Z2.Chow_group().degree(1)
C2 x Z^2
```

```
>>> from sage.all import *
>>> P1xP1_Z2 = toric_varieties.P1xP1_Z2(); P1xP1_Z2
2-d CPR-Fano toric variety covered by 4 affine patches
>>> P1xP1_Z2.fan().rays()
N( 1,  1),        N(-1, -1),
N(-1,  1),        N( 1, -1)
in 2-d lattice N
>>> P1xP1_Z2.gens()
(s, t, x, y)
>>> P1xP1_Z2.Chow_group().degree(Integer(1))
C2 x Z^2
```

P2 (*names='x y z'*, *base_ring=Rational Field*)

Construct the projective plane $\mathbb{P}^2$ as a toric variety.

INPUT:

- `names` – string; names for the homogeneous coordinates. See *normalize_names()* for acceptable formats.
- `base_ring` – a ring (default: $\mathbf{Q}$); the base ring for the toric variety

OUTPUT: a *CPR-Fano toric variety*.

EXAMPLES:

```
sage: P2 = toric_varieties.P2(); P2
2-d CPR-Fano toric variety covered by 3 affine patches
sage: P2.fan().rays()
N( 1,  0),
N( 0,  1),
N(-1, -1)
in 2-d lattice N
sage: P2.gens()
(x, y, z)
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2(); P2
2-d CPR-Fano toric variety covered by 3 affine patches
>>> P2.fan().rays()
N( 1,  0),
N( 0,  1),
N(-1, -1)
in 2-d lattice N
>>> P2.gens()
(x, y, z)
```

P2_112(*names='z+'*, *base_ring=Rational Field*)

Construct the weighted projective space $\mathbb{P}^2(1,1,2)$.

INPUT:

- `names` – string; names for the homogeneous coordinates. See *normalize_names()* for acceptable formats.
- `base_ring` – a ring (default: $\mathbf{Q}$); the base ring for the toric variety

OUTPUT: a *CPR-Fano toric variety*.

EXAMPLES:

```
sage: P2_112 = toric_varieties.P2_112(); P2_112
2-d CPR-Fano toric variety covered by 3 affine patches
sage: P2_112.fan().rays()
N( 1,  0),
N( 0,  1),
N(-1, -2)
in 2-d lattice N
sage: P2_112.gens()
(z0, z1, z2)
```

```
>>> from sage.all import *
>>> P2_112 = toric_varieties.P2_112(); P2_112
2-d CPR-Fano toric variety covered by 3 affine patches
>>> P2_112.fan().rays()
N( 1,  0),
N( 0,  1),
N(-1, -2)
```

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```
in 2-d lattice N
>>> P2_112.gens()
(z0, z1, z2)
```

P2_123(*names='z+', base_ring=Rational Field*)

Construct the weighted projective space $\mathbb{P}^2(1, 2, 3)$.

INPUT:

- `names` – string; names for the homogeneous coordinates. See *normalize_names()* for acceptable formats.
- `base_ring` – a ring (default: **Q**); the base ring for the toric variety

OUTPUT: a *CPR-Fano toric variety*.

EXAMPLES:

```
sage: P2_123 = toric_varieties.P2_123(); P2_123
2-d CPR-Fano toric variety covered by 3 affine patches
sage: P2_123.fan().rays()
N( 1,  0),
N( 0,  1),
N(-2, -3)
in 2-d lattice N
sage: P2_123.gens()
(z0, z1, z2)
```

```
>>> from sage.all import *
>>> P2_123 = toric_varieties.P2_123(); P2_123
2-d CPR-Fano toric variety covered by 3 affine patches
>>> P2_123.fan().rays()
N( 1,  0),
N( 0,  1),
N(-2, -3)
in 2-d lattice N
>>> P2_123.gens()
(z0, z1, z2)
```

P4_11133(*names='z+', base_ring=Rational Field*)

Construct the weighted projective space $\mathbb{P}^4(1, 1, 1, 3, 3)$.

INPUT:

- `names` – string; names for the homogeneous coordinates. See *normalize_names()* for acceptable formats.
- `base_ring` – a ring (default: **Q**); the base ring for the toric variety

OUTPUT: a *CPR-Fano toric variety*.

EXAMPLES:

```
sage: P4_11133 = toric_varieties.P4_11133(); P4_11133
4-d CPR-Fano toric variety covered by 5 affine patches
sage: P4_11133.fan().rays()
N( 1,  0,  0,  0),      N( 0,  1,  0,  0),      N( 0,  0,  1,  0),
```

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```
N( 0,  0,  0,  1),      N(-3, -3, -1, -1)
in 4-d lattice N
sage: P4_11133.gens()
(z0, z1, z2, z3, z4)
```

```
>>> from sage.all import *
>>> P4_11133 = toric_varieties.P4_11133(); P4_11133
4-d CPR-Fano toric variety covered by 5 affine patches
>>> P4_11133.fan().rays()
N( 1,  0,  0,  0),      N( 0,  1,  0,  0),      N( 0,  0,  1,  0),
N( 0,  0,  0,  1),      N(-3, -3, -1, -1)
in 4-d lattice N
>>> P4_11133.gens()
(z0, z1, z2, z3, z4)
```

P4_11133_resolved(*names='z+'*, *base_ring=Rational Field*)

Construct the weighted projective space $\mathbb{P}^4(1, 1, 1, 3, 3)$.

INPUT:

- `names` – string; names for the homogeneous coordinates. See *normalize_names()* for acceptable formats.
- `base_ring` – a ring (default: $\mathbf{Q}$); the base ring for the toric variety

OUTPUT: a *CPR-Fano toric variety*.

EXAMPLES:

```
sage: P4_11133_resolved = toric_varieties.P4_11133_resolved()
sage: P4_11133_resolved
4-d CPR-Fano toric variety covered by 9 affine patches
sage: P4_11133_resolved.fan().rays()
N( 1,  0,  0,  0),      N( 0,  1,  0,  0),      N( 0,  0,  1,  0),
N( 0,  0,  0,  1),      N(-3, -3, -1, -1),      N(-1, -1,  0,  0)
in 4-d lattice N
sage: P4_11133_resolved.gens()
(z0, z1, z2, z3, z4, z5)
```

```
>>> from sage.all import *
>>> P4_11133_resolved = toric_varieties.P4_11133_resolved()
>>> P4_11133_resolved
4-d CPR-Fano toric variety covered by 9 affine patches
>>> P4_11133_resolved.fan().rays()
N( 1,  0,  0,  0),      N( 0,  1,  0,  0),      N( 0,  0,  1,  0),
N( 0,  0,  0,  1),      N(-3, -3, -1, -1),      N(-1, -1,  0,  0)
in 4-d lattice N
>>> P4_11133_resolved.gens()
(z0, z1, z2, z3, z4, z5)
```

P4_11169(*names='z+'*, *base_ring=Rational Field*)

Construct the weighted projective space $\mathbb{P}^4(1, 1, 1, 6, 9)$.

INPUT:

- `names` – string; names for the homogeneous coordinates. See *`normalize_names()`* for acceptable formats.
- `base_ring` – a ring (default: **Q**); the base ring for the toric variety

OUTPUT: a *`CPR-Fano toric variety`*.

EXAMPLES:

```
sage: P4_11169 = toric_varieties.P4_11169(); P4_11169
4-d CPR-Fano toric variety covered by 5 affine patches
sage: P4_11169.fan().rays()
N( 1,  0,  0,  0),      N( 0,  1,  0,  0),      N( 0,  0,  1,  0),
N( 0,  0,  0,  1),      N(-9, -6, -1, -1)
in 4-d lattice N
sage: P4_11169.gens()
(z0, z1, z2, z3, z4)
```

```
>>> from sage.all import *
>>> P4_11169 = toric_varieties.P4_11169(); P4_11169
4-d CPR-Fano toric variety covered by 5 affine patches
>>> P4_11169.fan().rays()
N( 1,  0,  0,  0),      N( 0,  1,  0,  0),      N( 0,  0,  1,  0),
N( 0,  0,  0,  1),      N(-9, -6, -1, -1)
in 4-d lattice N
>>> P4_11169.gens()
(z0, z1, z2, z3, z4)
```

`P4_11169_resolved`(*names='z+'*, *base_ring=Rational Field*)

Construct the blow-up of the weighted projective space $\mathbb{P}^4(1,1,1,6,9)$ at its curve of $\mathbf{Z}_3$ orbifold fixed points.

INPUT:

- `names` – string; names for the homogeneous coordinates. See *`normalize_names()`* for acceptable formats.
- `base_ring` – a ring (default: **Q**); the base ring for the toric variety

OUTPUT: a *`CPR-Fano toric variety`*.

EXAMPLES:

```
sage: P4_11169_resolved = toric_varieties.P4_11169_resolved()
sage: P4_11169_resolved
4-d CPR-Fano toric variety covered by 9 affine patches
sage: P4_11169_resolved.fan().rays()
N( 1,  0,  0,  0),      N( 0,  1,  0,  0),      N( 0,  0,  1,  0),
N( 0,  0,  0,  1),      N(-9, -6, -1, -1),      N(-3, -2,  0,  0)
in 4-d lattice N
sage: P4_11169_resolved.gens()
(z0, z1, z2, z3, z4, z5)
```

```
>>> from sage.all import *
>>> P4_11169_resolved = toric_varieties.P4_11169_resolved()
>>> P4_11169_resolved
4-d CPR-Fano toric variety covered by 9 affine patches
>>> P4_11169_resolved.fan().rays()
```

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```
N( 1,  0,  0,  0),      N( 0,  1,  0,  0),      N( 0,  0,  1,  0),
N( 0,  0,  0,  1),      N(-9, -6, -1, -1),      N(-3, -2,  0,  0)
in 4-d lattice N
>>> P4_11169_resolved.gens()
(z0, z1, z2, z3, z4, z5)
```

WP(**q*, ***kw*)

Construct weighted projective n-space over a field.

INPUT:

- `q` – a sequence of positive integers relatively prime to one another. The weights `q` can be given either as a list or tuple, or as positional arguments.

Two keyword arguments:

- `base_ring` – a field (default: $\mathbf{Q}$)
- `names` – string or list (tuple) of strings (default: `'z+'`); see *normalize_names()* for acceptable formats.

OUTPUT:

- A *toric variety*. If $q = (q_0, \ldots, q_n)$, then the output is the weighted projective space $\mathbb{P}(q_0, \ldots, q_n)$ over `base_ring`. `names` are the names of the generators of the homogeneous coordinate ring.

EXAMPLES:

A hyperelliptic curve C of genus 2 as a subscheme of the weighted projective plane $\mathbb{P}(1, 3, 1)$:

```
sage: X = toric_varieties.WP([1,3,1], names='x y z')
sage: X.inject_variables()
Defining x, y, z
sage: g = y^2 - (x^6-z^6)
sage: C = X.subscheme([g]); C
Closed subscheme of 2-d toric variety covered by 3 affine patches defined by:
  -x^6 + z^6 + y^2
```

```
>>> from sage.all import *
>>> X = toric_varieties.WP([Integer(1),Integer(3),Integer(1)], names='x y z')
>>> X.inject_variables()
Defining x, y, z
>>> g = y**Integer(2) - (x**Integer(6)-z**Integer(6))
>>> C = X.subscheme([g]); C
Closed subscheme of 2-d toric variety covered by 3 affine patches defined by:
  -x^6 + z^6 + y^2
```

dP6(*names='x u y v z w'*, *base_ring=Rational Field*)

Construct the del Pezzo surface of degree 6 ($\mathbb{P}^2$ blown up at 3 points) as a toric variety.

INPUT:

- `names` – string; names for the homogeneous coordinates. See *normalize_names()* for acceptable formats.
- `base_ring` – a ring (default: $\mathbf{Q}$); the base ring for the toric variety

OUTPUT: a *CPR-Fano toric variety*.

EXAMPLES:

```
sage: dP6 = toric_varieties.dP6(); dP6
2-d CPR-Fano toric variety covered by 6 affine patches
sage: dP6.fan().rays()
N( 0,  1),        N(-1,  0),        N(-1, -1),
N( 0, -1),        N( 1,  0),        N( 1,  1)
in 2-d lattice N
sage: dP6.gens()
(x, u, y, v, z, w)
```

```
>>> from sage.all import *
>>> dP6 = toric_varieties.dP6(); dP6
2-d CPR-Fano toric variety covered by 6 affine patches
>>> dP6.fan().rays()
N( 0,  1),        N(-1,  0),        N(-1, -1),
N( 0, -1),        N( 1,  0),        N( 1,  1)
in 2-d lattice N
>>> dP6.gens()
(x, u, y, v, z, w)
```

dP6xdP6(*names='x0 x1 x2 x3 x4 x5 y0 y1 y2 y3 y4 y5'*, *base_ring=Rational Field*)

Construct the product of two del Pezzo surfaces of degree 6 ($\mathbb{P}^2$ blown up at 3 points) as a toric variety.

INPUT:

- `names` – string; names for the homogeneous coordinates. See *normalize_names()* for acceptable formats.
- `base_ring` – a ring (default: **Q**); the base ring for the toric variety

OUTPUT: a *CPR-Fano toric variety*.

EXAMPLES:

```
sage: dP6xdP6 = toric_varieties.dP6xdP6(); dP6xdP6
4-d CPR-Fano toric variety covered by 36 affine patches
sage: dP6xdP6.fan().rays()
N( 0,  1,  0,  0),      N(-1,  0,  0,  0),      N(-1, -1,  0,  0),
N( 0, -1,  0,  0),      N( 1,  0,  0,  0),      N( 1,  1,  0,  0),
N( 0,  0,  0,  1),      N( 0,  0, -1,  0),      N( 0,  0, -1, -1),
N( 0,  0,  0, -1),      N( 0,  0,  1,  0),      N( 0,  0,  1,  1)
in 4-d lattice N
sage: dP6xdP6.gens()
(x0, x1, x2, x3, x4, x5, y0, y1, y2, y3, y4, y5)
```

```
>>> from sage.all import *
>>> dP6xdP6 = toric_varieties.dP6xdP6(); dP6xdP6
4-d CPR-Fano toric variety covered by 36 affine patches
>>> dP6xdP6.fan().rays()
N( 0,  1,  0,  0),      N(-1,  0,  0,  0),      N(-1, -1,  0,  0),
N( 0, -1,  0,  0),      N( 1,  0,  0,  0),      N( 1,  1,  0,  0),
N( 0,  0,  0,  1),      N( 0,  0, -1,  0),      N( 0,  0, -1, -1),
N( 0,  0,  0, -1),      N( 0,  0,  1,  0),      N( 0,  0,  1,  1)
in 4-d lattice N
```

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```
>>> dP6xdP6.gens()
(x0, x1, x2, x3, x4, x5, y0, y1, y2, y3, y4, y5)
```

dP7(*names='x u y v z'*, *base_ring=Rational Field*)

Construct the del Pezzo surface of degree 7 ($\mathbb{P}^2$ blown up at 2 points) as a toric variety.

INPUT:

- `names` – string; names for the homogeneous coordinates. See *normalize_names()* for acceptable formats.
- `base_ring` – a ring (default: **Q**); the base ring for the toric variety

OUTPUT: a *CPR-Fano toric variety*.

EXAMPLES:

```
sage: dP7 = toric_varieties.dP7(); dP7
2-d CPR-Fano toric variety covered by 5 affine patches
sage: dP7.fan().rays()
N( 0,  1),        N(-1,  0),        N(-1, -1),
N( 0, -1),        N( 1,  0)
in 2-d lattice N
sage: dP7.gens()
(x, u, y, v, z)
```

```
>>> from sage.all import *
>>> dP7 = toric_varieties.dP7(); dP7
2-d CPR-Fano toric variety covered by 5 affine patches
>>> dP7.fan().rays()
N( 0,  1),        N(-1,  0),        N(-1, -1),
N( 0, -1),        N( 1,  0)
in 2-d lattice N
>>> dP7.gens()
(x, u, y, v, z)
```

dP8(*names='t x y z'*, *base_ring=Rational Field*)

Construct the del Pezzo surface of degree 8 ($\mathbb{P}^2$ blown up at 1 point) as a toric variety.

INPUT:

- `names` – string; names for the homogeneous coordinates. See *normalize_names()* for acceptable formats.
- `base_ring` – a ring (default: **Q**); the base ring for the toric variety

OUTPUT: a *CPR-Fano toric variety*.

EXAMPLES:

```
sage: dP8 = toric_varieties.dP8(); dP8
2-d CPR-Fano toric variety covered by 4 affine patches
sage: dP8.fan().rays()
N( 1,  1),        N( 0,  1),
N(-1, -1),        N( 1,  0)
in 2-d lattice N
```

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```
sage: dP8.gens()
(t, x, y, z)
```

```
>>> from sage.all import *
>>> dP8 = toric_varieties.dP8(); dP8
2-d CPR-Fano toric variety covered by 4 affine patches
>>> dP8.fan().rays()
N( 1,  1),        N( 0,  1),
N(-1, -1),        N( 1,  0)
in 2-d lattice N
>>> dP8.gens()
(t, x, y, z)
```

torus(*n*, *names='z+'*, *base_ring=Rational Field*)

Construct the `n`-dimensional algebraic torus $(\mathbb{F}^\times)^n$.

INPUT:

- `n` – nonnegative integer. The dimension of the algebraic torus
- `names` – string; names for the homogeneous coordinates. See *normalize_names()* for acceptable formats.
- `base_ring` – a ring (default: $\mathbf{Q}$); the base ring for the toric variety

OUTPUT: a *toric variety*.

EXAMPLES:

```
sage: T3 = toric_varieties.torus(3);  T3
3-d affine toric variety
sage: T3.fan().rays()
Empty collection
in 3-d lattice N
sage: T3.fan().virtual_rays()
N(1, 0, 0),
N(0, 1, 0),
N(0, 0, 1)
in 3-d lattice N
sage: T3.gens()
(z0, z1, z2)
sage: sorted(T3.change_ring(GF(3)).point_set().list())
[[1 : 1 : 1], [1 : 1 : 2], [1 : 2 : 1], [1 : 2 : 2],
 [2 : 1 : 1], [2 : 1 : 2], [2 : 2 : 1], [2 : 2 : 2]]
```

```
>>> from sage.all import *
>>> T3 = toric_varieties.torus(Integer(3));  T3
3-d affine toric variety
>>> T3.fan().rays()
Empty collection
in 3-d lattice N
>>> T3.fan().virtual_rays()
N(1, 0, 0),
N(0, 1, 0),
```

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```
N(0, 0, 1)
in 3-d lattice N
>>> T3.gens()
(z0, z1, z2)
>>> sorted(T3.change_ring(GF(Integer(3))).point_set().list())
[[1 : 1 : 1], [1 : 1 : 2], [1 : 2 : 1], [1 : 2 : 2],
 [2 : 1 : 1], [2 : 1 : 2], [2 : 2 : 1], [2 : 2 : 2]]
```

16.4 Toric divisors and divisor classes

Let X be a *toric variety* corresponding to a rational polyhedral fan Σ. A *toric divisor* D is a T-Weil divisor over a given coefficient ring (usually **Z** or **Q**), i.e. a formal linear combination of torus-invariant subvarieties of X of codimension one. In homogeneous coordinates $[z_0 : \cdots : z_k]$, these are the subvarieties $\{z_i = 0\}$. Note that there is a finite number of such subvarieties, one for each ray of Σ. We generally identify

- Toric divisor D,
- Sheaf $\mathcal{O}(D)$ (if D is Cartier, it is a line bundle),
- Support function ϕ_D (if D is **Q**-Cartier, it is a function linear on each cone of Σ).

EXAMPLES:

We start with an illustration of basic divisor arithmetic:

```
sage: dP6 = toric_varieties.dP6()
sage: Dx,Du,Dy,Dv,Dz,Dw = dP6.toric_divisor_group().gens()
sage: Dx
V(x)
sage: -Dx
-V(x)
sage: 2*Dx
2*V(x)
sage: Dx*2
2*V(x)
sage: (1/2)*Dx + Dy/3 - Dz
1/2*V(x) + 1/3*V(y) - V(z)
sage: Dx.parent()
Group of toric ZZ-Weil divisors
on 2-d CPR-Fano toric variety covered by 6 affine patches
sage: (Dx/2).parent()
Group of toric QQ-Weil divisors
on 2-d CPR-Fano toric variety covered by 6 affine patches
```

```
>>> from sage.all import *
>>> dP6 = toric_varieties.dP6()
>>> Dx,Du,Dy,Dv,Dz,Dw = dP6.toric_divisor_group().gens()
>>> Dx
V(x)
>>> -Dx
-V(x)
>>> Integer(2)*Dx
2*V(x)
```

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```
>>> Dx*Integer(2)
2*V(x)
>>> (Integer(1)/Integer(2))*Dx + Dy/Integer(3) - Dz
1/2*V(x) + 1/3*V(y) - V(z)
>>> Dx.parent()
Group of toric ZZ-Weil divisors
on 2-d CPR-Fano toric variety covered by 6 affine patches
>>> (Dx/Integer(2)).parent()
Group of toric QQ-Weil divisors
on 2-d CPR-Fano toric variety covered by 6 affine patches
```

Now we create a more complicated variety to demonstrate divisors of different types:

```
sage: F = Fan(cones=[(0,1,2,3), (0,1,4)],
....:         rays=[(1,1,1), (1,-1,1), (1,-1,-1), (1,1,-1), (0,0,1)])
sage: X = ToricVariety(F)
sage: QQ_Cartier = X.divisor([2,2,1,1,1])
sage: Cartier = 2 * QQ_Cartier
sage: Weil = X.divisor([1,1,1,0,0])
sage: QQ_Weil = 1/2 * Weil
sage: [QQ_Weil.is_QQ_Weil(),
....:  QQ_Weil.is_Weil(),
....:  QQ_Weil.is_QQ_Cartier(),
....:  QQ_Weil.is_Cartier()]
[True, False, False, False]
sage: [Weil.is_QQ_Weil(),
....:  Weil.is_Weil(),
....:  Weil.is_QQ_Cartier(),
....:  Weil.is_Cartier()]
[True, True, False, False]
sage: [QQ_Cartier.is_QQ_Weil(),
....:  QQ_Cartier.is_Weil(),
....:  QQ_Cartier.is_QQ_Cartier(),
....:  QQ_Cartier.is_Cartier()]
[True, True, True, False]
sage: [Cartier.is_QQ_Weil(),
....:  Cartier.is_Weil(),
....:  Cartier.is_QQ_Cartier(),
....:  Cartier.is_Cartier()]
[True, True, True, True]
```

```
>>> from sage.all import *
>>> F = Fan(cones=[(Integer(0),Integer(1),Integer(2),Integer(3)), (Integer(0),
↪Integer(1),Integer(4))],
...          rays=[(Integer(1),Integer(1),Integer(1)), (Integer(1),-Integer(1),
↪Integer(1)), (Integer(1),-Integer(1),-Integer(1)), (Integer(1),Integer(1),-
↪Integer(1)), (Integer(0),Integer(0),Integer(1))])
>>> X = ToricVariety(F)
>>> QQ_Cartier = X.divisor([Integer(2),Integer(2),Integer(1),Integer(1),Integer(1)])
>>> Cartier = Integer(2) * QQ_Cartier
>>> Weil = X.divisor([Integer(1),Integer(1),Integer(1),Integer(0),Integer(0)])
>>> QQ_Weil = Integer(1)/Integer(2) * Weil
```

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```
>>> [QQ_Weil.is_QQ_Weil(),
...  QQ_Weil.is_Weil(),
...  QQ_Weil.is_QQ_Cartier(),
...  QQ_Weil.is_Cartier()]
[True, False, False, False]
>>> [Weil.is_QQ_Weil(),
...  Weil.is_Weil(),
...  Weil.is_QQ_Cartier(),
...  Weil.is_Cartier()]
[True, True, False, False]
>>> [QQ_Cartier.is_QQ_Weil(),
...  QQ_Cartier.is_Weil(),
...  QQ_Cartier.is_QQ_Cartier(),
...  QQ_Cartier.is_Cartier()]
[True, True, True, False]
>>> [Cartier.is_QQ_Weil(),
...  Cartier.is_Weil(),
...  Cartier.is_QQ_Cartier(),
...  Cartier.is_Cartier()]
[True, True, True, True]
```

The toric (**Q**-Weil) divisors on a toric variety X modulo linear equivalence generate the divisor **class group** $\mathrm{Cl}(X)$, implemented by *ToricRationalDivisorClassGroup*. If X is smooth, this equals the **Picard group** $\mathrm{Pic}(X)$. We continue using del Pezzo surface of degree 6 introduced above:

```
sage: Cl = dP6.rational_class_group(); Cl
The toric rational divisor class group
of a 2-d CPR-Fano toric variety covered by 6 affine patches
sage: Cl.ngens()
4
sage: c0,c1,c2,c3 = Cl.gens()
sage: c = c0 + 2*c1 - c3; c
Divisor class [1, 2, 0, -1]
```

```
>>> from sage.all import *
>>> Cl = dP6.rational_class_group(); Cl
The toric rational divisor class group
of a 2-d CPR-Fano toric variety covered by 6 affine patches
>>> Cl.ngens()
4
>>> c0,c1,c2,c3 = Cl.gens()
>>> c = c0 + Integer(2)*c1 - c3; c
Divisor class [1, 2, 0, -1]
```

Divisors are mapped to their classes and lifted via:

```
sage: Dx.divisor_class()
Divisor class [1, 0, 0, 0]
sage: Dx.divisor_class() in Cl
True
sage: (-Dw + Dv + Dy).divisor_class()
Divisor class [1, 0, 0, 0]
```

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```
sage: c0
Divisor class [1, 0, 0, 0]
sage: c0.lift()
V(x)
```

```
>>> from sage.all import *
>>> Dx.divisor_class()
Divisor class [1, 0, 0, 0]
>>> Dx.divisor_class() in Cl
True
>>> (-Dw + Dv + Dy).divisor_class()
Divisor class [1, 0, 0, 0]
>>> c0
Divisor class [1, 0, 0, 0]
>>> c0.lift()
V(x)
```

The (rational) divisor class group is where the Kaehler cone lives:

```
sage: Kc = dP6.Kaehler_cone(); Kc
4-d cone in 4-d lattice
sage: Kc.rays()
Divisor class [0, 1, 1, 0],
Divisor class [0, 0, 1, 1],
Divisor class [1, 1, 0, 0],
Divisor class [1, 1, 1, 0],
Divisor class [0, 1, 1, 1]
in Basis lattice of The toric rational divisor class group
of a 2-d CPR-Fano toric variety covered by 6 affine patches
sage: Kc.ray(1).lift()
V(x) + V(w)
```

```
>>> from sage.all import *
>>> Kc = dP6.Kaehler_cone(); Kc
4-d cone in 4-d lattice
>>> Kc.rays()
Divisor class [0, 1, 1, 0],
Divisor class [0, 0, 1, 1],
Divisor class [1, 1, 0, 0],
Divisor class [1, 1, 1, 0],
Divisor class [0, 1, 1, 1]
in Basis lattice of The toric rational divisor class group
of a 2-d CPR-Fano toric variety covered by 6 affine patches
>>> Kc.ray(Integer(1)).lift()
V(x) + V(w)
```

Given a divisor D, we have an associated line bundle (or a reflexive sheaf, if D is not Cartier) $\mathcal{O}(D)$. Its sections are:

```
sage: P2 = toric_varieties.P2()
sage: H = P2.divisor(0); H
V(x)
sage: H.sections()
```

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```
(M(-1, 0), M(-1, 1), M(0, 0))
sage: H.sections_monomials()
(z, y, x)
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> H = P2.divisor(Integer(0)); H
V(x)
>>> H.sections()
(M(-1, 0), M(-1, 1), M(0, 0))
>>> H.sections_monomials()
(z, y, x)
```

Note that the space of sections is always spanned by monomials. Therefore, we can grade the sections (as homogeneous monomials) by their weight under rescaling individual coordinates. This weight data amounts to a point of the dual lattice.

In the same way, we can grade cohomology groups by their cohomological degree and a weight:

```
sage: M = P2.fan().lattice().dual()
sage: H.cohomology(deg=0, weight=M(-1,0))
Vector space of dimension 1 over Rational Field
sage: _.dimension()
1
```

```
>>> from sage.all import *
>>> M = P2.fan().lattice().dual()
>>> H.cohomology(deg=Integer(0), weight=M(-Integer(1),Integer(0)))
Vector space of dimension 1 over Rational Field
>>> _.dimension()
1
```

Here is a more complicated example with $h^1(dP_6, \mathcal{O}(D)) = 4$

```
sage: D = dP6.divisor([0, 0, -1, 0, 2, -1])
sage: D.cohomology()
{0: Vector space of dimension 0 over Rational Field,
 1: Vector space of dimension 4 over Rational Field,
 2: Vector space of dimension 0 over Rational Field}
sage: D.cohomology(dim=True)
(0, 4, 0)
```

```
>>> from sage.all import *
>>> D = dP6.divisor([Integer(0), Integer(0), -Integer(1), Integer(0), Integer(2), -
↪Integer(1)])
>>> D.cohomology()
{0: Vector space of dimension 0 over Rational Field,
 1: Vector space of dimension 4 over Rational Field,
 2: Vector space of dimension 0 over Rational Field}
>>> D.cohomology(dim=True)
(0, 4, 0)
```

AUTHORS:

- Volker Braun, Andrey Novoseltsev (2010-09-07): initial version.

sage.schemes.toric.divisor.**ToricDivisor**(*toric_variety*, *arg=None*, *ring=None*, *check=True*, *reduce=True*)

Construct a divisor of `toric_variety`.

INPUT:

- `toric_variety` – a *toric variety*
- `arg` – one of the following description of the toric divisor to be constructed:
  - `None` or 0 (the trivial divisor);
  - monomial in the homogeneous coordinates;
  - one-dimensional cone of the fan of `toric_variety` or a lattice point generating such a cone;
  - sequence of rational numbers, specifying multiplicities for each of the toric divisors.
- `ring` – usually either **Z** or **Q**. The base ring of the divisor group. If `ring` is not specified, a coefficient ring suitable for `arg` is derived.
- `check` – boolean (default: `True`); whether to coerce coefficients into base ring. Setting it to `False` can speed up construction.
- `reduce` – reduce (default: `True`); whether to combine common terms. Setting it to `False` can speed up construction.

Warning

The coefficients of the divisor must be in the base ring and the terms must be reduced. If you set `check=False` and/or `reduce=False` it is your responsibility to pass valid input data `arg`.

OUTPUT: a *sage.schemes.toric.divisor.ToricDivisor_generic*

EXAMPLES:

```
sage: from sage.schemes.toric.divisor import ToricDivisor
sage: dP6 = toric_varieties.dP6()
sage: ToricDivisor(dP6, [(1,dP6.gen(2)), (1,dP6.gen(1))])
V(u) + V(y)
sage: ToricDivisor(dP6, (0,1,1,0,0,0), ring=QQ)
V(u) + V(y)
sage: dP6.inject_variables()
Defining x, u, y, v, z, w
sage: ToricDivisor(dP6, u + y)
Traceback (most recent call last):
...
ValueError: u + y is not a monomial
sage: ToricDivisor(dP6, u*y)
V(u) + V(y)
sage: ToricDivisor(dP6, dP6.fan(dim=1)[2] )
V(y)
sage: cone = Cone(dP6.fan(dim=1)[2])
sage: ToricDivisor(dP6, cone)
V(y)
sage: N = dP6.fan().lattice()
```

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```
sage: ToricDivisor(dP6, N(1,1) )
V(w)
```

```
>>> from sage.all import *
>>> from sage.schemes.toric.divisor import ToricDivisor
>>> dP6 = toric_varieties.dP6()
>>> ToricDivisor(dP6, [(Integer(1),dP6.gen(Integer(2))), (Integer(1),dP6.
↪gen(Integer(1)))])
V(u) + V(y)
>>> ToricDivisor(dP6, (Integer(0),Integer(1),Integer(1),Integer(0),Integer(0),
↪Integer(0)), ring=QQ)
V(u) + V(y)
>>> dP6.inject_variables()
Defining x, u, y, v, z, w
>>> ToricDivisor(dP6, u + y)
Traceback (most recent call last):
...
ValueError: u + y is not a monomial
>>> ToricDivisor(dP6, u*y)
V(u) + V(y)
>>> ToricDivisor(dP6, dP6.fan(dim=Integer(1))[Integer(2)] )
V(y)
>>> cone = Cone(dP6.fan(dim=Integer(1))[Integer(2)])
>>> ToricDivisor(dP6, cone)
V(y)
>>> N = dP6.fan().lattice()
>>> ToricDivisor(dP6, N(Integer(1),Integer(1)) )
V(w)
```

We attempt to guess the correct base ring:

```
sage: ToricDivisor(dP6, [(1/2,u)])
1/2*V(u)
sage: _.parent()
Group of toric QQ-Weil divisors on
2-d CPR-Fano toric variety covered by 6 affine patches
sage: ToricDivisor(dP6, [(1/2,u), (1/2,u)])
V(u)
sage: _.parent()
Group of toric ZZ-Weil divisors on
2-d CPR-Fano toric variety covered by 6 affine patches
sage: ToricDivisor(dP6, [(u,u)])
Traceback (most recent call last):
...
TypeError: cannot deduce coefficient ring for [(u, u)]
```

```
>>> from sage.all import *
>>> ToricDivisor(dP6, [(Integer(1)/Integer(2),u)])
1/2*V(u)
>>> _.parent()
Group of toric QQ-Weil divisors on
2-d CPR-Fano toric variety covered by 6 affine patches
```

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```
>>> ToricDivisor(dP6, [(Integer(1)/Integer(2),u), (Integer(1)/Integer(2),u)])
V(u)
>>> _.parent()
Group of toric ZZ-Weil divisors on
2-d CPR-Fano toric variety covered by 6 affine patches
>>> ToricDivisor(dP6, [(u,u)])
Traceback (most recent call last):
...
TypeError: cannot deduce coefficient ring for [(u, u)]
```

class sage.schemes.toric.divisor.**ToricDivisorGroup**(*toric_variety*, *base_ring*)

Bases: *DivisorGroup_generic*

The group of (**Q**-T-Weil) divisors on a toric variety.

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: P2.toric_divisor_group()
Group of toric ZZ-Weil divisors
on 2-d CPR-Fano toric variety covered by 3 affine patches
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> P2.toric_divisor_group()
Group of toric ZZ-Weil divisors
on 2-d CPR-Fano toric variety covered by 3 affine patches
```

Element

alias of *ToricDivisor_generic*

base_extend(*R*)

Extend the scalars of `self` to `R`.

INPUT:

- `R` – ring

OUTPUT: toric divisor group

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: DivZZ = P2.toric_divisor_group()
sage: DivQQ = P2.toric_divisor_group(base_ring=QQ)
sage: DivZZ.base_extend(QQ) is DivQQ
True
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> DivZZ = P2.toric_divisor_group()
>>> DivQQ = P2.toric_divisor_group(base_ring=QQ)
>>> DivZZ.base_extend(QQ) is DivQQ
True
```

gen(*i*)

Return the `i`-th generator of the divisor group.

INPUT:

- `i` – integer

OUTPUT:

The divisor $z_i = 0$, where z_i is the i-th homogeneous coordinate.

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: TDiv = P2.toric_divisor_group()
sage: TDiv.gen(2)
V(z)
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> TDiv = P2.toric_divisor_group()
>>> TDiv.gen(Integer(2))
V(z)
```

gens()

Return the generators of the divisor group.

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: TDiv = P2.toric_divisor_group()
sage: TDiv.gens()
(V(x), V(y), V(z))
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> TDiv = P2.toric_divisor_group()
>>> TDiv.gens()
(V(x), V(y), V(z))
```

ngens()

Return the number of generators.

OUTPUT:

The number of generators of `self`, which equals the number of rays in the fan of the toric variety.

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: TDiv = P2.toric_divisor_group()
sage: TDiv.ngens()
3
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> TDiv = P2.toric_divisor_group()
```

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```
>>> TDiv.ngens()
3
```

class sage.schemes.toric.divisor.**ToricDivisor_generic**(*v*, *parent*, *check=True*, *reduce=True*)

Bases: *Divisor_generic*

Construct a *(toric Weil) divisor* on the given toric variety.

INPUT:

- `v` – list of tuples (multiplicity, coordinate)
- `parent` – *ToricDivisorGroup*; the parent divisor group
- `check` – boolean; type-check the entries of `v`, see *DivisorGroup_generic*
- `reduce` – boolean; combine coefficients in `v`, see *DivisorGroup_generic*

Warning

Do not construct *ToricDivisor_generic* objects manually. Instead, use either the function *ToricDivisor()* or the method *divisor()* of toric varieties.

EXAMPLES:

```
sage: dP6 = toric_varieties.dP6()
sage: ray = dP6.fan().ray(0)
sage: ray
N(0, 1)
sage: D = dP6.divisor(ray); D
V(x)
sage: D.parent()
Group of toric ZZ-Weil divisors
on 2-d CPR-Fano toric variety covered by 6 affine patches
```

```
>>> from sage.all import *
>>> dP6 = toric_varieties.dP6()
>>> ray = dP6.fan().ray(Integer(0))
>>> ray
N(0, 1)
>>> D = dP6.divisor(ray); D
V(x)
>>> D.parent()
Group of toric ZZ-Weil divisors
on 2-d CPR-Fano toric variety covered by 6 affine patches
```

Chern_character()

Return the Chern character of the sheaf $\mathcal{O}(D)$ defined by the divisor D.

You can also use a shortcut *ch()*.

EXAMPLES:

```
sage: dP6 = toric_varieties.dP6()
sage: N = dP6.fan().lattice()
```

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```
sage: D3 = dP6.divisor(dP6.fan().cone_containing( N(0,1)   ))
sage: D5 = dP6.divisor(dP6.fan().cone_containing( N(-1,-1) ))
sage: D6 = dP6.divisor(dP6.fan().cone_containing( N(0,-1)  ))
sage: D = -D3 + 2*D5 - D6
sage: D.Chern_character()                                                    #␣
↪needs sage.libs.singular
[5*w^2 + y - 2*v + w + 1]
sage: dP6.integrate(D.ch() * dP6.Td())                                       #␣
↪needs sage.libs.singular
-4
```

```
>>> from sage.all import *
>>> dP6 = toric_varieties.dP6()
>>> N = dP6.fan().lattice()
>>> D3 = dP6.divisor(dP6.fan().cone_containing( N(Integer(0),Integer(1))   ))
>>> D5 = dP6.divisor(dP6.fan().cone_containing( N(-Integer(1),-Integer(1)) ))
>>> D6 = dP6.divisor(dP6.fan().cone_containing( N(Integer(0),-Integer(1))  ))
>>> D = -D3 + Integer(2)*D5 - D6
>>> D.Chern_character()                                                      #␣
↪needs sage.libs.singular
[5*w^2 + y - 2*v + w + 1]
>>> dP6.integrate(D.ch() * dP6.Td())                                         #␣
↪needs sage.libs.singular
-4
```

Chow_cycle(*ring=Integer Ring*)

Return the Chow homology class of the divisor.

INPUT:

- `ring` – either `ZZ` (default) or `QQ`; the base ring of the Chow group

OUTPUT:

The *ChowCycle* represented by the divisor.

EXAMPLES:

```
sage: dP6 = toric_varieties.dP6()
sage: cone = dP6.fan(1)[5]
sage: D = dP6.divisor(cone); D
V(w)
sage: D.Chow_cycle()
( 0 | -1, 0, 1, 1 | 0 )
sage: dP6.Chow_group()(cone)
( 0 | -1, 0, 1, 1 | 0 )
```

```
>>> from sage.all import *
>>> dP6 = toric_varieties.dP6()
>>> cone = dP6.fan(Integer(1))[Integer(5)]
>>> D = dP6.divisor(cone); D
V(w)
>>> D.Chow_cycle()
( 0 | -1, 0, 1, 1 | 0 )
```

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```
>>> dP6.Chow_group()(cone)
( 0 | -1, 0, 1, 1 | 0 )
```

Kodaira_map(*names='z'*)

Return the Kodaira map.

The Kodaira map is the rational map $X_\Sigma \to \mathbb{P}^{n-1}$, where n equals the number of sections. It is defined by the monomial sections of the line bundle.

If the divisor is ample and the toric variety smooth or of dimension 2, then this is an embedding.

INPUT:

- `names` – string (default: `'z'`); the variable names for the destination projective space

EXAMPLES:

```
sage: P1.<u,v> = toric_varieties.P1()
sage: D = -P1.K()
sage: D.Kodaira_map()                                                    #␣
↪needs fpylll sage.libs.singular
Scheme morphism:
  From: 1-d CPR-Fano toric variety covered by 2 affine patches
  To:   Closed subscheme of Projective Space of dimension 2
        over Rational Field defined by: -z1^2 + z0*z2
  Defn: Defined on coordinates by sending [u : v] to (v^2 : u*v : u^2)

sage: dP6 = toric_varieties.dP6()
sage: D = -dP6.K()
sage: D.Kodaira_map(names='x')                                           #␣
↪needs fpylll sage.libs.singular
Scheme morphism:
  From: 2-d CPR-Fano toric variety covered by 6 affine patches
  To:   Closed subscheme of Projective Space of dimension 6
        over Rational Field defined by:
          -x1*x5 + x0*x6,       -x2*x3 + x0*x5,       -x1*x3 + x0*x4,
          x4*x5 - x3*x6,        -x1*x2 + x0*x3,       x3*x5 - x2*x6,
          x3*x4 - x1*x6,        x3^2 - x1*x5,         x2*x4 - x1*x5,
          -x1*x5^2 + x2*x3*x6, -x1*x5^3 + x2^2*x6^2
  Defn: Defined on coordinates by sending [x : u : y : v : z : w] to
        (x*u^2*y^2*v : x^2*u^2*y*w : u*y^2*v^2*z : x*u*y*v*z*w :
         x^2*u*z*w^2 : y*v^2*z^2*w : x*v*z^2*w^2)
```

```
>>> from sage.all import *
>>> P1 = toric_varieties.P1(names=('u', 'v',)); (u, v,) = P1._first_ngens(2)
>>> D = -P1.K()
>>> D.Kodaira_map()                                                      #␣
↪needs fpylll sage.libs.singular
Scheme morphism:
  From: 1-d CPR-Fano toric variety covered by 2 affine patches
  To:   Closed subscheme of Projective Space of dimension 2
        over Rational Field defined by: -z1^2 + z0*z2
  Defn: Defined on coordinates by sending [u : v] to (v^2 : u*v : u^2)
```

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```
>>> dP6 = toric_varieties.dP6()
>>> D = -dP6.K()
>>> D.Kodaira_map(names='x')                                                    #␣
↪needs fpylll sage.libs.singular
Scheme morphism:
  From: 2-d CPR-Fano toric variety covered by 6 affine patches
  To:   Closed subscheme of Projective Space of dimension 6
        over Rational Field defined by:
          -x1*x5 + x0*x6,       -x2*x3 + x0*x5,       -x1*x3 + x0*x4,
          x4*x5 - x3*x6,        -x1*x2 + x0*x3,       x3*x5 - x2*x6,
          x3*x4 - x1*x6,        x3^2 - x1*x5,         x2*x4 - x1*x5,
          -x1*x5^2 + x2*x3*x6, -x1*x5^3 + x2^2*x6^2
  Defn: Defined on coordinates by sending [x : u : y : v : z : w] to
        (x*u^2*y^2*v : x^2*u^2*y*w : u*y^2*v^2*z : x*u*y*v*z*w :
         x^2*u*z*w^2 : y*v^2*z^2*w : x*v*z^2*w^2)
```

ch()

Return the Chern character of the sheaf $\mathcal{O}(D)$ defined by the divisor D.

You can also use a shortcut *ch()*.

EXAMPLES:

```
sage: dP6 = toric_varieties.dP6()
sage: N = dP6.fan().lattice()
sage: D3 = dP6.divisor(dP6.fan().cone_containing( N(0,1)   ))
sage: D5 = dP6.divisor(dP6.fan().cone_containing( N(-1,-1) ))
sage: D6 = dP6.divisor(dP6.fan().cone_containing( N(0,-1)  ))
sage: D = -D3 + 2*D5 - D6
sage: D.Chern_character()                                                    #␣
↪needs sage.libs.singular
[5*w^2 + y - 2*v + w + 1]
sage: dP6.integrate(D.ch() * dP6.Td())                                       #␣
↪needs sage.libs.singular
-4
```

```
>>> from sage.all import *
>>> dP6 = toric_varieties.dP6()
>>> N = dP6.fan().lattice()
>>> D3 = dP6.divisor(dP6.fan().cone_containing( N(Integer(0),Integer(1))   ))
>>> D5 = dP6.divisor(dP6.fan().cone_containing( N(-Integer(1),-Integer(1)) ))
>>> D6 = dP6.divisor(dP6.fan().cone_containing( N(Integer(0),-Integer(1))  ))
>>> D = -D3 + Integer(2)*D5 - D6
>>> D.Chern_character()                                                       #␣
↪needs sage.libs.singular
[5*w^2 + y - 2*v + w + 1]
>>> dP6.integrate(D.ch() * dP6.Td())                                         #␣
↪needs sage.libs.singular
-4
```

coefficient(x)

Return the coefficient of `x`.

INPUT:

- `x` – one of the homogeneous coordinates, either given by the variable or its index

OUTPUT: the coefficient of `x`

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: D = P2.divisor((11,12,13)); D
11*V(x) + 12*V(y) + 13*V(z)
sage: D.coefficient(1)
12
sage: P2.inject_variables()
Defining x, y, z
sage: D.coefficient(y)
12
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> D = P2.divisor((Integer(11),Integer(12),Integer(13))); D
11*V(x) + 12*V(y) + 13*V(z)
>>> D.coefficient(Integer(1))
12
>>> P2.inject_variables()
Defining x, y, z
>>> D.coefficient(y)
12
```

cohomology(*weight=None*, *deg=None*, *dim=False*)

Return the cohomology of the line bundle associated to the Cartier divisor or reflexive sheaf associated to the Weil divisor.

Note

The cohomology of a toric line bundle/reflexive sheaf is graded by the usual degree as well as by the M-lattice.

INPUT:

- `weight` – (optional) a point of the M-lattice
- `deg` – (optional) the degree of the cohomology group
- `dim` – boolean; if `False` (default), the cohomology groups are returned as vector spaces. If `True`, only the dimension of the vector space(s) is returned.

OUTPUT:

The vector space $H^{\text{deg}}(X, \mathcal{O}(D))$ (if `deg` is specified) or a dictionary `{degree:cohomology(degree)}` of all degrees between 0 and the dimension of the variety.

If `weight` is specified, return only the subspace $H^{\text{deg}}(X, \mathcal{O}(D))_{\text{weight}}$ of the cohomology of the given weight.

If `dim==True`, the dimension of the cohomology vector space is returned instead of actual vector space. Moreover, if `deg` was not specified, a vector whose entries are the dimensions is returned instead of a dictionary.

ALGORITHM:

Roughly, Chech cohomology is used to compute the cohomology. For toric divisors, the local sections can be chosen to be monomials (instead of general homogeneous polynomials), this is the reason for the extra grading by $m \in M$. General references would be [Ful1993], [CLS2011]. Here are some salient features of our implementation:

- First, a finite set of M-lattice points is identified that supports the cohomology. The toric divisor determines a (polyhedral) chamber decomposition of $M_{\mathbf{R}}$, see Section 9.1 and Figure 4 of [CLS2011]. The cohomology vanishes on the non-compact chambers. Hence, the convex hull of the vertices of the chamber decomposition contains all non-vanishing cohomology groups. This is returned by the private method `_sheaf_cohomology_support()`.

  It would be more efficient, but more difficult to implement, to keep track of all of the individual chambers. We leave this for future work.

- For each point $m \in M$, the weight-m part of the cohomology can be rewritten as the cohomology of a simplicial complex, see Exercise 9.1.10 of [CLS2011], [Per2007]. This is returned by the private method `_sheaf_complex()`.

  The simplicial complex is the same for all points in a chamber, but we currently do not make use of this and compute each point $m \in M$ separately.

- Finally, the cohomology (over $\mathbf{Q}$) of this simplicial complex is computed in the private method `_sheaf_cohomology()`. Summing over the supporting points $m \in M$ yields the cohomology of the sheaf.

EXAMPLES:

Example 9.1.7 of Cox, Little, Schenck: "Toric Varieties" [CLS2011]:

```
sage: F = Fan(cones=[(0,1), (1,2), (2,3), (3,4), (4,5), (5,0)],
....:         rays=[(1,0), (1,1), (0,1), (-1,0), (-1,-1), (0,-1)])
sage: dP6 = ToricVariety(F)
sage: D3 = dP6.divisor(2)
sage: D5 = dP6.divisor(4)
sage: D6 = dP6.divisor(5)
sage: D = -D3 + 2*D5 - D6
sage: D.cohomology()
{0: Vector space of dimension 0 over Rational Field,
 1: Vector space of dimension 4 over Rational Field,
 2: Vector space of dimension 0 over Rational Field}
sage: D.cohomology(deg=1)
Vector space of dimension 4 over Rational Field
sage: M = F.dual_lattice()
sage: D.cohomology( M(0,0) )
{0: Vector space of dimension 0 over Rational Field,
 1: Vector space of dimension 1 over Rational Field,
 2: Vector space of dimension 0 over Rational Field}
sage: D.cohomology( weight=M(0,0), deg=1 )
Vector space of dimension 1 over Rational Field
sage: dP6.integrate(D.ch() * dP6.Td())                                    #␣
↪needs sage.libs.singular
-4
```

```
>>> from sage.all import *
>>> F = Fan(cones=[(Integer(0),Integer(1)), (Integer(1),Integer(2)),␣
↪(Integer(2),Integer(3)), (Integer(3),Integer(4)), (Integer(4),Integer(5)),␣
↪(Integer(5),Integer(0))],
```

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```
...         rays=[(Integer(1),Integer(0)), (Integer(1),Integer(1)),␣
↪(Integer(0),Integer(1)), (-Integer(1),Integer(0)), (-Integer(1),-
↪Integer(1)), (Integer(0),-Integer(1))])
>>> dP6 = ToricVariety(F)
>>> D3 = dP6.divisor(Integer(2))
>>> D5 = dP6.divisor(Integer(4))
>>> D6 = dP6.divisor(Integer(5))
>>> D = -D3 + Integer(2)*D5 - D6
>>> D.cohomology()
{0: Vector space of dimension 0 over Rational Field,
 1: Vector space of dimension 4 over Rational Field,
 2: Vector space of dimension 0 over Rational Field}
>>> D.cohomology(deg=Integer(1))
Vector space of dimension 4 over Rational Field
>>> M = F.dual_lattice()
>>> D.cohomology( M(Integer(0),Integer(0)) )
{0: Vector space of dimension 0 over Rational Field,
 1: Vector space of dimension 1 over Rational Field,
 2: Vector space of dimension 0 over Rational Field}
>>> D.cohomology( weight=M(Integer(0),Integer(0)), deg=Integer(1) )
Vector space of dimension 1 over Rational Field
>>> dP6.integrate(D.ch() * dP6.Td())                                    #␣
↪needs sage.libs.singular
-4
```

Note the different output options:

```
sage: D.cohomology()
{0: Vector space of dimension 0 over Rational Field,
 1: Vector space of dimension 4 over Rational Field,
 2: Vector space of dimension 0 over Rational Field}
sage: D.cohomology(dim=True)
(0, 4, 0)
sage: D.cohomology(weight=M(0,0))
{0: Vector space of dimension 0 over Rational Field,
 1: Vector space of dimension 1 over Rational Field,
 2: Vector space of dimension 0 over Rational Field}
sage: D.cohomology(weight=M(0,0), dim=True)
(0, 1, 0)
sage: D.cohomology(deg=1)
Vector space of dimension 4 over Rational Field
sage: D.cohomology(deg=1, dim=True)
4
sage: D.cohomology(weight=M(0,0), deg=1)
Vector space of dimension 1 over Rational Field
sage: D.cohomology(weight=M(0,0), deg=1, dim=True)
1
```

```
>>> from sage.all import *
>>> D.cohomology()
{0: Vector space of dimension 0 over Rational Field,
 1: Vector space of dimension 4 over Rational Field,
```

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```
 2: Vector space of dimension 0 over Rational Field}
>>> D.cohomology(dim=True)
(0, 4, 0)
>>> D.cohomology(weight=M(Integer(0),Integer(0)))
{0: Vector space of dimension 0 over Rational Field,
 1: Vector space of dimension 1 over Rational Field,
 2: Vector space of dimension 0 over Rational Field}
>>> D.cohomology(weight=M(Integer(0),Integer(0)), dim=True)
(0, 1, 0)
>>> D.cohomology(deg=Integer(1))
Vector space of dimension 4 over Rational Field
>>> D.cohomology(deg=Integer(1), dim=True)
4
>>> D.cohomology(weight=M(Integer(0),Integer(0)), deg=Integer(1))
Vector space of dimension 1 over Rational Field
>>> D.cohomology(weight=M(Integer(0),Integer(0)), deg=Integer(1), dim=True)
1
```

Here is a Weil (non-Cartier) divisor example:

```
sage: K = toric_varieties.Cube_nonpolyhedral().K()
sage: K.is_Weil()
True
sage: K.is_QQ_Cartier()
False
sage: K.cohomology(dim=True)
(0, 0, 0, 1)
```

```
>>> from sage.all import *
>>> K = toric_varieties.Cube_nonpolyhedral().K()
>>> K.is_Weil()
True
>>> K.is_QQ_Cartier()
False
>>> K.cohomology(dim=True)
(0, 0, 0, 1)
```

cohomology_class()

Return the degree-2 cohomology class associated to the divisor.

OUTPUT:

The corresponding cohomology class as an instance of *CohomologyClass*. The cohomology class is the first Chern class of the associated line bundle $\mathcal{O}(D)$.

EXAMPLES:

```
sage: dP6 = toric_varieties.dP6()
sage: D = dP6.divisor(dP6.fan().ray(0))
sage: D.cohomology_class()                                                  #␣
↪needs sage.libs.singular
[y + v - w]
```

```
>>> from sage.all import *
>>> dP6 = toric_varieties.dP6()
>>> D = dP6.divisor(dP6.fan().ray(Integer(0)))
>>> D.cohomology_class()                                                    #␣
↪needs sage.libs.singular
[y + v - w]
```

cohomology_support()

Return the weights for which the cohomology groups do not vanish.

OUTPUT:

A tuple of dual lattice points. `self.cohomology(weight=m)` does not vanish if and only if `m` is in the output.

Note

This method is provided for educational purposes and it is not an efficient way of computing the cohomology groups.

EXAMPLES:

```
sage: F = Fan(cones=[(0,1), (1,2), (2,3), (3,4), (4,5), (5,0)],
....:         rays=[(1,0), (1,1), (0,1), (-1,0), (-1,-1), (0,-1)])
sage: dP6 = ToricVariety(F)
sage: D3 = dP6.divisor(2)
sage: D5 = dP6.divisor(4)
sage: D6 = dP6.divisor(5)
sage: D = -D3 + 2*D5 - D6
sage: D.cohomology_support()
(M(0, 0), M(1, 0), M(2, 0), M(1, 1))
```

```
>>> from sage.all import *
>>> F = Fan(cones=[(Integer(0),Integer(1)), (Integer(1),Integer(2)),␣
↪(Integer(2),Integer(3)), (Integer(3),Integer(4)), (Integer(4),Integer(5)),␣
↪(Integer(5),Integer(0))],
...         rays=[(Integer(1),Integer(0)), (Integer(1),Integer(1)),␣
↪(Integer(0),Integer(1)), (-Integer(1),Integer(0)), (-Integer(1),-
↪Integer(1)), (Integer(0),-Integer(1))])
>>> dP6 = ToricVariety(F)
>>> D3 = dP6.divisor(Integer(2))
>>> D5 = dP6.divisor(Integer(4))
>>> D6 = dP6.divisor(Integer(5))
>>> D = -D3 + Integer(2)*D5 - D6
>>> D.cohomology_support()
(M(0, 0), M(1, 0), M(2, 0), M(1, 1))
```

divisor_class()

Return the linear equivalence class of the divisor.

OUTPUT:

The class of the divisor in $Cl(X) \otimes_{\mathbf{Z}} \mathbf{Q}$ as an instance of *ToricRationalDivisorClassGroup*.

EXAMPLES:

```
sage: dP6 = toric_varieties.dP6()
sage: D = dP6.divisor(0)
sage: D.divisor_class()
Divisor class [1, 0, 0, 0]
```

```
>>> from sage.all import *
>>> dP6 = toric_varieties.dP6()
>>> D = dP6.divisor(Integer(0))
>>> D.divisor_class()
Divisor class [1, 0, 0, 0]
```

function_value(*point*)

Return the value of the support function at `point`.

Let X be the ambient toric variety of `self`, Σ the fan associated to X, and N the ambient lattice of Σ.

INPUT:

- `point` – either an integer, interpreted as the index of a ray of Σ, or a point of the lattice N

OUTPUT: integer or a rational number

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: D = P2.divisor([11,22,44])    # total degree 77
sage: D.function_value(0)
11
sage: N = P2.fan().lattice()
sage: D.function_value( N(1,1) )
33
sage: D.function_value( P2.fan().ray(0) )
11
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> D = P2.divisor([Integer(11),Integer(22),Integer(44)])    # total degree 77
>>> D.function_value(Integer(0))
11
>>> N = P2.fan().lattice()
>>> D.function_value( N(Integer(1),Integer(1)) )
33
>>> D.function_value( P2.fan().ray(Integer(0)) )
11
```

is_Cartier()

Return whether the divisor is a Cartier-divisor.

Note

The sheaf $\mathcal{O}(D)$ associated to the given divisor D is a line bundle if and only if the divisor is Cartier.

EXAMPLES:

```
sage: X = toric_varieties.P4_11169()
sage: D = X.divisor(3)
sage: D.is_Cartier()
False
sage: D.is_QQ_Cartier()
True
```

```
>>> from sage.all import *
>>> X = toric_varieties.P4_11169()
>>> D = X.divisor(Integer(3))
>>> D.is_Cartier()
False
>>> D.is_QQ_Cartier()
True
```

is_QQ_Cartier()

Return whether the divisor is a **Q**-Cartier divisor.

A **Q**-Cartier divisor is a divisor such that some multiple of it is Cartier.

EXAMPLES:

```
sage: X = toric_varieties.P4_11169()
sage: D = X.divisor(3)
sage: D.is_QQ_Cartier()
True

sage: X = toric_varieties.Cube_face_fan()
sage: D = X.divisor(3)
sage: D.is_QQ_Cartier()
False
```

```
>>> from sage.all import *
>>> X = toric_varieties.P4_11169()
>>> D = X.divisor(Integer(3))
>>> D.is_QQ_Cartier()
True

>>> X = toric_varieties.Cube_face_fan()
>>> D = X.divisor(Integer(3))
>>> D.is_QQ_Cartier()
False
```

is_QQ_Weil()

Return whether the divisor is a **Q**-Weil-divisor.

Note

This function returns always `True` since *ToricDivisor* can only describe **Q**-Weil divisors.

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: D = P2.divisor([1,2,3])
sage: D.is_QQ_Weil()
True
sage: (D/2).is_QQ_Weil()
True
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> D = P2.divisor([Integer(1),Integer(2),Integer(3)])
>>> D.is_QQ_Weil()
True
>>> (D/Integer(2)).is_QQ_Weil()
True
```

is_Weil()

Return whether the divisor is a Weil-divisor.

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: D = P2.divisor([1,2,3])
sage: D.is_Weil()
True
sage: (D/2).is_Weil()
False
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> D = P2.divisor([Integer(1),Integer(2),Integer(3)])
>>> D.is_Weil()
True
>>> (D/Integer(2)).is_Weil()
False
```

is_ample()

Return whether a **Q**-Cartier divisor is ample.

OUTPUT: `True` if the divisor is in the ample cone, `False` otherwise

Note

- For a **Q**-Cartier divisor, some positive integral multiple is Cartier. We return whether this associated divisor is ample, i.e. corresponds to an ample line bundle.
- In the orbifold case, the ample cone is an open and full-dimensional cone in the rational divisor class group *ToricRationalDivisorClassGroup*.
- If the variety has worse than orbifold singularities, the ample cone is a full-dimensional cone within the (not full-dimensional) subspace spanned by the Cartier divisors inside the rational (Weil) divisor class group, that is, *ToricRationalDivisorClassGroup*. The ample cone is then relative open (open in this subspace).
- See also *is_nef()*.

- A toric divisor is ample if and only if its support function is strictly convex.

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: K = P2.K()
sage: (+K).is_ample()
False
sage: (0*K).is_ample()
False
sage: (-K).is_ample()
True
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> K = P2.K()
>>> (+K).is_ample()
False
>>> (Integer(0)*K).is_ample()
False
>>> (-K).is_ample()
True
```

Example 6.1.3, 6.1.11, 6.1.17 of [CLS2011]:

```
sage: from itertools import product
sage: fan = Fan(cones=[(0,1), (1,2), (2,3), (3,0)],
....:           rays=[(-1,2), (0,1), (1,0), (0,-1)])
sage: F2 = ToricVariety(fan,'u1, u2, u3, u4')
sage: def D(a, b): return a*F2.divisor(2) + b*F2.divisor(3)
sage: [ (a,b) for a,b in product(range(-3,3), repeat=2)
....:         if D(a,b).is_ample() ]
[(1, 1), (1, 2), (2, 1), (2, 2)]
sage: [ (a,b) for a,b in product(range(-3,3), repeat=2)
....:         if D(a,b).is_nef() ]
[(0, 0), (0, 1), (0, 2), (1, 0), (1, 1), (1, 2), (2, 0), (2, 1), (2, 2)]
```

```
>>> from sage.all import *
>>> from itertools import product
>>> fan = Fan(cones=[(Integer(0),Integer(1)), (Integer(1),Integer(2)),␣
↪(Integer(2),Integer(3)), (Integer(3),Integer(0))],
...           rays=[(-Integer(1),Integer(2)), (Integer(0),Integer(1)),␣
↪(Integer(1),Integer(0)), (Integer(0),-Integer(1))])
>>> F2 = ToricVariety(fan,'u1, u2, u3, u4')
>>> def D(a, b): return a*F2.divisor(Integer(2)) + b*F2.divisor(Integer(3))
>>> [ (a,b) for a,b in product(range(-Integer(3),Integer(3)),␣
↪repeat=Integer(2))
...         if D(a,b).is_ample() ]
[(1, 1), (1, 2), (2, 1), (2, 2)]
>>> [ (a,b) for a,b in product(range(-Integer(3),Integer(3)),␣
↪repeat=Integer(2))
...         if D(a,b).is_nef() ]
```

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```
[(0, 0), (0, 1), (0, 2), (1, 0), (1, 1), (1, 2), (2, 0), (2, 1), (2, 2)]
```

A (worse than orbifold) singular Fano threefold:

```
sage: points = [(1,0,0),(0,1,0),(0,0,1),(-2,0,-1),(-2,-1,0),(-3,-1,-1),(1,1,
↪1)]
sage: facets = [[0,1,3],[0,1,6],[0,2,4],[0,2,6],[0,3,5],[0,4,5],[1,2,3,4,5,6]]
sage: X = ToricVariety(Fan(cones=facets, rays=points))
sage: X.rational_class_group().dimension()
4
sage: X.Kaehler_cone().rays()
Divisor class [1, 0, 0, 0]
in Basis lattice of The toric rational divisor class group
of a 3-d toric variety covered by 7 affine patches
sage: antiK = -X.K()
sage: antiK.divisor_class()
Divisor class [2, 0, 0, 0]
sage: antiK.is_ample()
True
```

```
>>> from sage.all import *
>>> points = [(Integer(1),Integer(0),Integer(0)),(Integer(0),Integer(1),
↪Integer(0)),(Integer(0),Integer(0),Integer(1)),(-Integer(2),Integer(0),-
↪Integer(1)),(-Integer(2),-Integer(1),Integer(0)),(-Integer(3),-Integer(1),-
↪Integer(1)),(Integer(1),Integer(1),Integer(1))]
>>> facets = [[Integer(0),Integer(1),Integer(3)],[Integer(0),Integer(1),
↪Integer(6)],[Integer(0),Integer(2),Integer(4)],[Integer(0),Integer(2),
↪Integer(6)],[Integer(0),Integer(3),Integer(5)],[Integer(0),Integer(4),
↪Integer(5)],[Integer(1),Integer(2),Integer(3),Integer(4),Integer(5),
↪Integer(6)]]
>>> X = ToricVariety(Fan(cones=facets, rays=points))
>>> X.rational_class_group().dimension()
4
>>> X.Kaehler_cone().rays()
Divisor class [1, 0, 0, 0]
in Basis lattice of The toric rational divisor class group
of a 3-d toric variety covered by 7 affine patches
>>> antiK = -X.K()
>>> antiK.divisor_class()
Divisor class [2, 0, 0, 0]
>>> antiK.is_ample()
True
```

is_integral()

Return whether the coefficients of the divisor are all integral.

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: DZZ = P2.toric_divisor_group(base_ring=ZZ).gen(0); DZZ
V(x)
sage: DQQ = P2.toric_divisor_group(base_ring=QQ).gen(0); DQQ
```

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```
V(x)
sage: DZZ.is_integral()
True
sage: DQQ.is_integral()
True
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> DZZ = P2.toric_divisor_group(base_ring=ZZ).gen(Integer(0)); DZZ
V(x)
>>> DQQ = P2.toric_divisor_group(base_ring=QQ).gen(Integer(0)); DQQ
V(x)
>>> DZZ.is_integral()
True
>>> DQQ.is_integral()
True
```

is_nef()

Return whether a $\mathbf{Q}$-Cartier divisor is nef.

OUTPUT:

- `True` if the divisor is in the closure of the ample cone, `False` otherwise.

Note

- For a $\mathbf{Q}$-Cartier divisor, some positive integral multiple is Cartier. We return whether this associated divisor is nef.
- The nef cone is the closure of the ample cone.
- See also *is_ample()*.
- A toric divisor is nef if and only if its support function is convex (but not necessarily strictly convex).
- A toric Cartier divisor is nef if and only if its linear system is basepoint free.

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: K = P2.K()
sage: (+K).is_nef()
False
sage: (0*K).is_nef()
True
sage: (-K).is_nef()
True
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> K = P2.K()
>>> (+K).is_nef()
False
```

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```
>>> (Integer(0)*K).is_nef()
True
>>> (-K).is_nef()
True
```

Example 6.1.3, 6.1.11, 6.1.17 of [CLS2011]:

```
sage: from itertools import product
sage: fan = Fan(cones=[(0,1), (1,2), (2,3), (3,0)],
....:           rays=[(-1,2), (0,1), (1,0), (0,-1)])
sage: F2 = ToricVariety(fan,'u1, u2, u3, u4')
sage: def D(a, b): return a*F2.divisor(2) + b*F2.divisor(3)
sage: [ (a,b) for a,b in product(range(-3,3), repeat=2)
....:         if D(a,b).is_ample() ]
[(1, 1), (1, 2), (2, 1), (2, 2)]
sage: [ (a,b) for a,b in product(range(-3,3), repeat=2)
....:         if D(a,b).is_nef() ]
[(0, 0), (0, 1), (0, 2), (1, 0), (1, 1), (1, 2), (2, 0), (2, 1), (2, 2)]
```

```
>>> from sage.all import *
>>> from itertools import product
>>> fan = Fan(cones=[(Integer(0),Integer(1)), (Integer(1),Integer(2)),␣
↪(Integer(2),Integer(3)), (Integer(3),Integer(0))],
...           rays=[(-Integer(1),Integer(2)), (Integer(0),Integer(1)),␣
↪(Integer(1),Integer(0)), (Integer(0),-Integer(1))])
>>> F2 = ToricVariety(fan,'u1, u2, u3, u4')
>>> def D(a, b): return a*F2.divisor(Integer(2)) + b*F2.divisor(Integer(3))
>>> [ (a,b) for a,b in product(range(-Integer(3),Integer(3)),␣
↪repeat=Integer(2))
...         if D(a,b).is_ample() ]
[(1, 1), (1, 2), (2, 1), (2, 2)]
>>> [ (a,b) for a,b in product(range(-Integer(3),Integer(3)),␣
↪repeat=Integer(2))
...         if D(a,b).is_nef() ]
[(0, 0), (0, 1), (0, 2), (1, 0), (1, 1), (1, 2), (2, 0), (2, 1), (2, 2)]
```

m(*cone*)

Return m_σ representing ϕ_D on `cone`.

Let X be the ambient toric variety of this divisor D associated to the fan Σ in lattice N. Let M be the lattice dual to N. Given the cone $\sigma = \langle v_1, \ldots, v_k \rangle$ in Σ, this method searches for a vector $m_\sigma \in M_{\mathbf{Q}}$ such that $\phi_D(v_i) = \langle m_\sigma, v_i \rangle$ for all $i = 1, \ldots, k$, where ϕ_D is the support function of D.

INPUT:

- `cone` – a cone in the fan of the toric variety

OUTPUT: if possible, a point of lattice M

- If the dual vector cannot be chosen integral, a rational vector is returned.
- If there is no such vector (i.e. `self` is not even a $\mathbf{Q}$-Cartier divisor), a `ValueError` is raised.

EXAMPLES:

```
sage: F = Fan(cones=[(0,1,2,3), (0,1,4)],
....:         rays=[(1,1,1), (1,-1,1), (1,-1,-1), (1,1,-1), (0,0,1)])
sage: X = ToricVariety(F)
sage: square_cone = X.fan().cone_containing(0,1,2,3)
sage: triangle_cone = X.fan().cone_containing(0,1,4)
sage: ray = X.fan().cone_containing(0)
sage: QQ_Cartier = X.divisor([2,2,1,1,1])
sage: QQ_Cartier.m(ray)
M(0, 2, 0)
sage: QQ_Cartier.m(square_cone)
(3/2, 0, 1/2)
sage: QQ_Cartier.m(triangle_cone)
M(1, 0, 1)
sage: QQ_Cartier.m(Cone(triangle_cone))
M(1, 0, 1)
sage: Weil = X.divisor([1,1,1,0,0])
sage: Weil.m(square_cone)
Traceback (most recent call last):
...
ValueError: V(z0) + V(z1) + V(z2) is not QQ-Cartier,
cannot choose a dual vector on 3-d cone
of Rational polyhedral fan in 3-d lattice N
sage: Weil.m(triangle_cone)
M(1, 0, 0)
```

```
>>> from sage.all import *
>>> F = Fan(cones=[(Integer(0),Integer(1),Integer(2),Integer(3)), (Integer(0),
↪Integer(1),Integer(4))],
...         rays=[(Integer(1),Integer(1),Integer(1)), (Integer(1),-Integer(1),
↪Integer(1)), (Integer(1),-Integer(1),-Integer(1)), (Integer(1),Integer(1),-
↪Integer(1)), (Integer(0),Integer(0),Integer(1))])
>>> X = ToricVariety(F)
>>> square_cone = X.fan().cone_containing(Integer(0),Integer(1),Integer(2),
↪Integer(3))
>>> triangle_cone = X.fan().cone_containing(Integer(0),Integer(1),Integer(4))
>>> ray = X.fan().cone_containing(Integer(0))
>>> QQ_Cartier = X.divisor([Integer(2),Integer(2),Integer(1),Integer(1),
↪Integer(1)])
>>> QQ_Cartier.m(ray)
M(0, 2, 0)
>>> QQ_Cartier.m(square_cone)
(3/2, 0, 1/2)
>>> QQ_Cartier.m(triangle_cone)
M(1, 0, 1)
>>> QQ_Cartier.m(Cone(triangle_cone))
M(1, 0, 1)
>>> Weil = X.divisor([Integer(1),Integer(1),Integer(1),Integer(0),Integer(0)])
>>> Weil.m(square_cone)
Traceback (most recent call last):
...
ValueError: V(z0) + V(z1) + V(z2) is not QQ-Cartier,
cannot choose a dual vector on 3-d cone
```

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```
of Rational polyhedral fan in 3-d lattice N
>>> Weil.m(triangle_cone)
M(1, 0, 0)
```

monomial(*point*)

Return the monomial in the homogeneous coordinate ring associated to the `point` in the dual lattice.

INPUT:

- `point` – a point in `self.variety().fan().dual_lattice()`

OUTPUT:

For a fixed divisor `D`, the sections are generated by monomials in *ToricVariety.coordinate_ring*. Alternatively, the monomials can be described as M-lattice points in the polyhedron `D.polyhedron()`. This method converts the points $m \in M$ into homogeneous polynomials.

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: O3_P2 = -P2.K()
sage: M = P2.fan().dual_lattice()
sage: O3_P2.monomial( M(0,0) )
x*y*z
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> O3_P2 = -P2.K()
>>> M = P2.fan().dual_lattice()
>>> O3_P2.monomial( M(Integer(0),Integer(0)) )
x*y*z
```

move_away_from(*cone*)

Move the divisor away from the orbit closure of `cone`.

INPUT:

- A `cone` of the fan of the toric variety.

OUTPUT:

A (rationally equivalent) divisor that is moved off the orbit closure of the given cone.

Note

A divisor that is Weil but not Cartier might be impossible to move away. In this case, a `ValueError` is raised.

EXAMPLES:

```
sage: F = Fan(cones=[(0,1,2,3), (0,1,4)],
....:         rays=[(1,1,1), (1,-1,1), (1,-1,-1), (1,1,-1), (0,0,1)])
sage: X = ToricVariety(F)
sage: square_cone = X.fan().cone_containing(0,1,2,3)
sage: triangle_cone = X.fan().cone_containing(0,1,4)
```

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```
sage: line_cone = square_cone.intersection(triangle_cone)
sage: Cartier = X.divisor([2,2,1,1,1])
sage: Cartier
2*V(z0) + 2*V(z1) + V(z2) + V(z3) + V(z4)
sage: Cartier.move_away_from(line_cone)
3*V(z2) + 3*V(z3) - V(z4)
sage: QQ_Weil = X.divisor([1,0,1,1,0])
sage: QQ_Weil.move_away_from(line_cone)
2*V(z2) + V(z3) - 1/2*V(z4)
```

```
>>> from sage.all import *
>>> F = Fan(cones=[(Integer(0),Integer(1),Integer(2),Integer(3)), (Integer(0),
↪Integer(1),Integer(4))],
...         rays=[(Integer(1),Integer(1),Integer(1)), (Integer(1),-Integer(1),
↪Integer(1)), (Integer(1),-Integer(1),-Integer(1)), (Integer(1),Integer(1),-
↪Integer(1)), (Integer(0),Integer(0),Integer(1))])
>>> X = ToricVariety(F)
>>> square_cone = X.fan().cone_containing(Integer(0),Integer(1),Integer(2),
↪Integer(3))
>>> triangle_cone = X.fan().cone_containing(Integer(0),Integer(1),Integer(4))
>>> line_cone = square_cone.intersection(triangle_cone)
>>> Cartier = X.divisor([Integer(2),Integer(2),Integer(1),Integer(1),
↪Integer(1)])
>>> Cartier
2*V(z0) + 2*V(z1) + V(z2) + V(z3) + V(z4)
>>> Cartier.move_away_from(line_cone)
3*V(z2) + 3*V(z3) - V(z4)
>>> QQ_Weil = X.divisor([Integer(1),Integer(0),Integer(1),Integer(1),
↪Integer(0)])
>>> QQ_Weil.move_away_from(line_cone)
2*V(z2) + V(z3) - 1/2*V(z4)
```

polyhedron()

Return the polyhedron $P_D \subset M$ associated to a toric divisor D.

OUTPUT: P_D as an instance of `Polyhedron_base`

EXAMPLES:

```
sage: dP7 = toric_varieties.dP7()
sage: D = dP7.divisor(2)
sage: P_D = D.polyhedron(); P_D
A 0-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex
sage: P_D.Vrepresentation()
(A vertex at (0, 0),)
sage: D.is_nef()
False
sage: dP7.integrate(D.ch() * dP7.Td())                                    #␣
↪needs sage.libs.singular
1
sage: P_antiK = (-dP7.K()).polyhedron(); P_antiK
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 5 vertices
sage: P_antiK.Vrepresentation()
```

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```
(A vertex at (1, -1), A vertex at (0, 1), A vertex at (1, 0),
 A vertex at (-1, 1), A vertex at (-1, -1))
sage: P_antiK.integral_points()
((-1, -1), (-1, 0), (-1, 1), (0, -1), (0, 0), (0, 1), (1, -1), (1, 0))
```

```
>>> from sage.all import *
>>> dP7 = toric_varieties.dP7()
>>> D = dP7.divisor(Integer(2))
>>> P_D = D.polyhedron(); P_D
A 0-dimensional polyhedron in QQ^2 defined as the convex hull of 1 vertex
>>> P_D.Vrepresentation()
(A vertex at (0, 0),)
>>> D.is_nef()
False
>>> dP7.integrate(D.ch() * dP7.Td())                                    #␣
↪needs sage.libs.singular
1
>>> P_antiK = (-dP7.K()).polyhedron(); P_antiK
A 2-dimensional polyhedron in QQ^2 defined as the convex hull of 5 vertices
>>> P_antiK.Vrepresentation()
(A vertex at (1, -1), A vertex at (0, 1), A vertex at (1, 0),
 A vertex at (-1, 1), A vertex at (-1, -1))
>>> P_antiK.integral_points()
((-1, -1), (-1, 0), (-1, 1), (0, -1), (0, 0), (0, 1), (1, -1), (1, 0))
```

Example 6.1.3, 6.1.11, 6.1.17 of [CLS2011]:

```
sage: fan = Fan(cones=[(0,1), (1,2), (2,3), (3,0)],
....:           rays=[(-1,2), (0,1), (1,0), (0,-1)])
sage: F2 = ToricVariety(fan,'u1, u2, u3, u4')
sage: D = F2.divisor(3)
sage: D.polyhedron().Vrepresentation()
(A vertex at (0, 0), A vertex at (2, 1), A vertex at (0, 1))
sage: Dprime = F2.divisor(1) + D
sage: Dprime.polyhedron().Vrepresentation()
(A vertex at (2, 1), A vertex at (0, 1), A vertex at (0, 0))
sage: D.is_ample()
False
sage: D.is_nef()
True
sage: Dprime.is_nef()
False
```

```
>>> from sage.all import *
>>> fan = Fan(cones=[(Integer(0),Integer(1)), (Integer(1),Integer(2)),␣
↪(Integer(2),Integer(3)), (Integer(3),Integer(0))],
...           rays=[(-Integer(1),Integer(2)), (Integer(0),Integer(1)),␣
↪(Integer(1),Integer(0)), (Integer(0),-Integer(1))])
>>> F2 = ToricVariety(fan,'u1, u2, u3, u4')
>>> D = F2.divisor(Integer(3))
>>> D.polyhedron().Vrepresentation()
(A vertex at (0, 0), A vertex at (2, 1), A vertex at (0, 1))
```

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```
>>> Dprime = F2.divisor(Integer(1)) + D
>>> Dprime.polyhedron().Vrepresentation()
(A vertex at (2, 1), A vertex at (0, 1), A vertex at (0, 0))
>>> D.is_ample()
False
>>> D.is_nef()
True
>>> Dprime.is_nef()
False
```

A more complicated example where P_D is not a lattice polytope:

```
sage: X = toric_varieties.BCdlOG_base()
sage: antiK = -X.K()
sage: P_D = antiK.polyhedron()
sage: P_D
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 8 vertices
sage: P_D.Vrepresentation()
(A vertex at (1, -1, 0), A vertex at (1, -3, 1),
 A vertex at (1, 1, 1), A vertex at (-5, 1, 1),
 A vertex at (1, 1, -1/2), A vertex at (1, 1/2, -1/2),
 A vertex at (-1, -1, 0), A vertex at (-5, -3, 1))
sage: P_D.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, 4) x + 1 >= 0,
 An inequality (0, 1, 3) x + 1 >= 0, An inequality (0, 1, 2) x + 1 >= 0)
sage: P_D.integral_points()
((-1, -1, 0), (0, -1, 0), (1, -1, 0), (-1, 0, 0), (0, 0, 0),
 (1, 0, 0), (-1, 1, 0), (0, 1, 0), (1, 1, 0), (-5, -3, 1),
 (-4, -3, 1), (-3, -3, 1), (-2, -3, 1), (-1, -3, 1), (0, -3, 1),
 (1, -3, 1), (-5, -2, 1), (-4, -2, 1), (-3, -2, 1), (-2, -2, 1),
 (-1, -2, 1), (0, -2, 1), (1, -2, 1), (-5, -1, 1), (-4, -1, 1),
 (-3, -1, 1), (-2, -1, 1), (-1, -1, 1), (0, -1, 1), (1, -1, 1),
 (-5, 0, 1), (-4, 0, 1), (-3, 0, 1), (-2, 0, 1), (-1, 0, 1),
 (0, 0, 1), (1, 0, 1), (-5, 1, 1), (-4, 1, 1), (-3, 1, 1),
 (-2, 1, 1), (-1, 1, 1), (0, 1, 1), (1, 1, 1))
```

```
>>> from sage.all import *
>>> X = toric_varieties.BCdlOG_base()
>>> antiK = -X.K()
>>> P_D = antiK.polyhedron()
>>> P_D
A 3-dimensional polyhedron in QQ^3 defined as the convex hull of 8 vertices
>>> P_D.Vrepresentation()
(A vertex at (1, -1, 0), A vertex at (1, -3, 1),
 A vertex at (1, 1, 1), A vertex at (-5, 1, 1),
 A vertex at (1, 1, -1/2), A vertex at (1, 1/2, -1/2),
 A vertex at (-1, -1, 0), A vertex at (-5, -3, 1))
>>> P_D.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, 4) x + 1 >= 0,
 An inequality (0, 1, 3) x + 1 >= 0, An inequality (0, 1, 2) x + 1 >= 0)
```

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```
>>> P_D.integral_points()
((-1, -1, 0), (0, -1, 0), (1, -1, 0), (-1, 0, 0), (0, 0, 0),
 (1, 0, 0), (-1, 1, 0), (0, 1, 0), (1, 1, 0), (-5, -3, 1),
 (-4, -3, 1), (-3, -3, 1), (-2, -3, 1), (-1, -3, 1), (0, -3, 1),
 (1, -3, 1), (-5, -2, 1), (-4, -2, 1), (-3, -2, 1), (-2, -2, 1),
 (-1, -2, 1), (0, -2, 1), (1, -2, 1), (-5, -1, 1), (-4, -1, 1),
 (-3, -1, 1), (-2, -1, 1), (-1, -1, 1), (0, -1, 1), (1, -1, 1),
 (-5, 0, 1), (-4, 0, 1), (-3, 0, 1), (-2, 0, 1), (-1, 0, 1),
 (0, 0, 1), (1, 0, 1), (-5, 1, 1), (-4, 1, 1), (-3, 1, 1),
 (-2, 1, 1), (-1, 1, 1), (0, 1, 1), (1, 1, 1))
```

sections()

Return the global sections (as points of the M-lattice) of the line bundle (or reflexive sheaf) associated to the divisor.

OUTPUT: a `tuple` of points of lattice M

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: P2.fan().nrays()
3
sage: P2.divisor(0).sections()
(M(-1, 0), M(-1, 1), M(0, 0))
sage: P2.divisor(1).sections()
(M(0, -1), M(0, 0), M(1, -1))
sage: P2.divisor(2).sections()
(M(0, 0), M(0, 1), M(1, 0))
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> P2.fan().nrays()
3
>>> P2.divisor(Integer(0)).sections()
(M(-1, 0), M(-1, 1), M(0, 0))
>>> P2.divisor(Integer(1)).sections()
(M(0, -1), M(0, 0), M(1, -1))
>>> P2.divisor(Integer(2)).sections()
(M(0, 0), M(0, 1), M(1, 0))
```

The divisor can be non-nef yet still have sections:

```
sage: rays = [(1,0,0),(0,1,0),(0,0,1),(-2,0,-1),(-2,-1,0),(-3,-1,-1),(1,1,1),
 ↪(-1,0,0)]
sage: cones = [[0,1,3],[0,1,6],[0,2,4],[0,2,6],[0,3,5],[0,4,5],[1,3,7],[1,6,
 ↪7],[2,4,7],[2,6,7],[3,5,7],[4,5,7]]
sage: X = ToricVariety(Fan(rays=rays, cones=cones))
sage: D = X.divisor(2); D
V(z2)
sage: D.is_nef()
False
sage: D.sections()
(M(0, 0, 0),)
```

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```
sage: D.cohomology(dim=True)
(1, 0, 0, 0)
```

```
>>> from sage.all import *
>>> rays = [(Integer(1),Integer(0),Integer(0)),(Integer(0),Integer(1),
↪Integer(0)),(Integer(0),Integer(0),Integer(1)),(-Integer(2),Integer(0),-
↪Integer(1)),(-Integer(2),-Integer(1),Integer(0)),(-Integer(3),-Integer(1),-
↪Integer(1)),(Integer(1),Integer(1),Integer(1)),(-Integer(1),Integer(0),
↪Integer(0))]
>>> cones = [[Integer(0),Integer(1),Integer(3)],[Integer(0),Integer(1),
↪Integer(6)],[Integer(0),Integer(2),Integer(4)],[Integer(0),Integer(2),
↪Integer(6)],[Integer(0),Integer(3),Integer(5)],[Integer(0),Integer(4),
↪Integer(5)],[Integer(1),Integer(3),Integer(7)],[Integer(1),Integer(6),
↪Integer(7)],[Integer(2),Integer(4),Integer(7)],[Integer(2),Integer(6),
↪Integer(7)],[Integer(3),Integer(5),Integer(7)],[Integer(4),Integer(5),
↪Integer(7)]]
>>> X = ToricVariety(Fan(rays=rays, cones=cones))
>>> D = X.divisor(Integer(2)); D
V(z2)
>>> D.is_nef()
False
>>> D.sections()
(M(0, 0, 0),)
>>> D.cohomology(dim=True)
(1, 0, 0, 0)
```

sections_monomials()

Return the global sections of the line bundle associated to the Cartier divisor.

The sections are described as monomials in the generalized homogeneous coordinates.

OUTPUT: tuple of monomials in the coordinate ring of `self`

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: P2.fan().nrays()
3
sage: P2.divisor(0).sections_monomials()
(z, y, x)
sage: P2.divisor(1).sections_monomials()
(z, y, x)
sage: P2.divisor(2).sections_monomials()
(z, y, x)
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> P2.fan().nrays()
3
>>> P2.divisor(Integer(0)).sections_monomials()
(z, y, x)
>>> P2.divisor(Integer(1)).sections_monomials()
(z, y, x)
```

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```
>>> P2.divisor(Integer(2)).sections_monomials()
(z, y, x)
```

From [Cox] page 38:

```
sage: lp = LatticePolytope([(1,0), (1,1), (0,1), (-1,0), (0,-1)])
sage: lp
2-d reflexive polytope #5 in 2-d lattice M
sage: dP7 = ToricVariety(FaceFan(lp), 'x1, x2, x3, x4, x5')
sage: AK = -dP7.K()
sage: AK.sections()
(N(-1, 0), N(-1, 1), N(0, -1), N(0, 0),
 N(0, 1), N(1, -1), N(1, 0), N(1, 1))
sage: AK.sections_monomials()
(x3*x4^2*x5, x2*x3^2*x4^2, x1*x4*x5^2, x1*x2*x3*x4*x5,
 x1*x2^2*x3^2*x4, x1^2*x2*x5^2, x1^2*x2^2*x3*x5, x1^2*x2^3*x3^2)
```

```
>>> from sage.all import *
>>> lp = LatticePolytope([(Integer(1),Integer(0)), (Integer(1),Integer(1)),␣
↪(Integer(0),Integer(1)), (-Integer(1),Integer(0)), (Integer(0),-
↪Integer(1))])
>>> lp
2-d reflexive polytope #5 in 2-d lattice M
>>> dP7 = ToricVariety(FaceFan(lp), 'x1, x2, x3, x4, x5')
>>> AK = -dP7.K()
>>> AK.sections()
(N(-1, 0), N(-1, 1), N(0, -1), N(0, 0),
 N(0, 1), N(1, -1), N(1, 0), N(1, 1))
>>> AK.sections_monomials()
(x3*x4^2*x5, x2*x3^2*x4^2, x1*x4*x5^2, x1*x2*x3*x4*x5,
 x1*x2^2*x3^2*x4, x1^2*x2*x5^2, x1^2*x2^2*x3*x5, x1^2*x2^3*x3^2)
```

class sage.schemes.toric.divisor.**ToricRationalDivisorClassGroup**(*toric_variety*)

Bases: FreeModule_ambient_field, UniqueRepresentation

The rational divisor class group of a toric variety.

The **T-Weil divisor class group** $Cl(X)$ of a toric variety X is a finitely generated abelian group and can contain torsion. Its rank equals the number of rays in the fan of X minus the dimension of X.

The **rational divisor class group** is $Cl(X) \otimes_{\mathbf{Z}} \mathbf{Q}$ and never includes torsion. If X is *smooth*, this equals the **Picard group** $\mathrm{Pic}(X)$, whose elements are the isomorphism classes of line bundles on X. The group law (which we write as addition) is the tensor product of the line bundles. The Picard group of a toric variety is always torsion-free.

Warning

Do not instantiate this class yourself. Use *rational_class_group()* method of *toric varieties* if you need the divisor class group. Or you can obtain it as the parent of any divisor class constructed, for example, via *ToricDivisor_generic.divisor_class()*.

INPUT:

- toric_variety – toric variety <sage.schemes.toric.variety.ToricVariety_field

OUTPUT: rational divisor class group of a toric variety

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: P2.rational_class_group()
The toric rational divisor class group of a 2-d CPR-Fano
toric variety covered by 3 affine patches
sage: D = P2.divisor(0); D
V(x)
sage: Dclass = D.divisor_class(); Dclass
Divisor class [1]
sage: Dclass.lift()
V(y)
sage: Dclass.parent()
The toric rational divisor class group of a 2-d CPR-Fano
toric variety covered by 3 affine patches
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> P2.rational_class_group()
The toric rational divisor class group of a 2-d CPR-Fano
toric variety covered by 3 affine patches
>>> D = P2.divisor(Integer(0)); D
V(x)
>>> Dclass = D.divisor_class(); Dclass
Divisor class [1]
>>> Dclass.lift()
V(y)
>>> Dclass.parent()
The toric rational divisor class group of a 2-d CPR-Fano
toric variety covered by 3 affine patches
```

Element

alias of *ToricRationalDivisorClass*

class sage.schemes.toric.divisor.**ToricRationalDivisorClassGroup_basis_lattice**(*group*)

Bases: FreeModule_ambient_pid

Construct the basis lattice of the `group`.

INPUT:

- `group` – *toric rational divisor class group*

OUTPUT: the basis lattice of `group`

EXAMPLES:

```
sage: P1xP1 = toric_varieties.P1xP1()
sage: L = P1xP1.Kaehler_cone().lattice()
sage: L
Basis lattice of The toric rational divisor class group of a
2-d CPR-Fano toric variety covered by 4 affine patches
sage: L.basis()
[Divisor class [1, 0], Divisor class [0, 1]]
```

```
>>> from sage.all import *
>>> P1xP1 = toric_varieties.P1xP1()
>>> L = P1xP1.Kaehler_cone().lattice()
>>> L
Basis lattice of The toric rational divisor class group of a
2-d CPR-Fano toric variety covered by 4 affine patches
>>> L.basis()
[Divisor class [1, 0], Divisor class [0, 1]]
```

Element

alias of *ToricRationalDivisorClass*

sage.schemes.toric.divisor.**is_ToricDivisor**(*x*)

Test whether `x` is a toric divisor.

INPUT:

- `x` – anything

OUTPUT:

- `True` if `x` is an instance of *ToricDivisor_generic* and `False` otherwise.

EXAMPLES:

```
sage: from sage.schemes.toric.divisor import is_ToricDivisor
sage: is_ToricDivisor(1)
doctest:warning...
DeprecationWarning: The function is_ToricDivisor is deprecated;
use 'isinstance(..., ToricDivisor_generic)' instead.
See https://github.com/sagemath/sage/issues/38277 for details.
False
sage: P2 = toric_varieties.P2()
sage: D = P2.divisor(0); D
V(x)
sage: is_ToricDivisor(D)
True
```

```
>>> from sage.all import *
>>> from sage.schemes.toric.divisor import is_ToricDivisor
>>> is_ToricDivisor(Integer(1))
doctest:warning...
DeprecationWarning: The function is_ToricDivisor is deprecated;
use 'isinstance(..., ToricDivisor_generic)' instead.
See https://github.com/sagemath/sage/issues/38277 for details.
False
>>> P2 = toric_varieties.P2()
>>> D = P2.divisor(Integer(0)); D
V(x)
>>> is_ToricDivisor(D)
True
```

16.5 Toric rational divisor classes

This module is a part of the framework for *toric varieties*.

AUTHORS:

- Volker Braun and Andrey Novoseltsev (2010-09-05): initial version.

class sage.schemes.toric.divisor_class.**ToricRationalDivisorClass**

Bases: Vector_rational_dense

Create a toric rational divisor class.

Warning

You probably should not construct divisor classes explicitly.

INPUT:

- same as for Vector_rational_dense.

OUTPUT: toric rational divisor class

lift()

Return a divisor representing this divisor class.

OUTPUT: an instance of ToricDivisor representing self

EXAMPLES:

```
sage: X = toric_varieties.Cube_nonpolyhedral()
sage: D = X.divisor([0,1,2,3,4,5,6,7]); D
V(z1) + 2*V(z2) + 3*V(z3) + 4*V(z4) + 5*V(z5) + 6*V(z6) + 7*V(z7)
sage: D.divisor_class()
Divisor class [29, 6, 8, 10, 0]
sage: Dequiv = D.divisor_class().lift(); Dequiv
15*V(z1) - 11*V(z2) - 9*V(z5) + 19*V(z6) + 10*V(z7)
sage: Dequiv == D
False
sage: Dequiv.divisor_class() == D.divisor_class()
True
```

```
>>> from sage.all import *
>>> X = toric_varieties.Cube_nonpolyhedral()
>>> D = X.divisor([Integer(0),Integer(1),Integer(2),Integer(3),Integer(4),
...Integer(5),Integer(6),Integer(7)]); D
V(z1) + 2*V(z2) + 3*V(z3) + 4*V(z4) + 5*V(z5) + 6*V(z6) + 7*V(z7)
>>> D.divisor_class()
Divisor class [29, 6, 8, 10, 0]
>>> Dequiv = D.divisor_class().lift(); Dequiv
15*V(z1) - 11*V(z2) - 9*V(z5) + 19*V(z6) + 10*V(z7)
>>> Dequiv == D
False
>>> Dequiv.divisor_class() == D.divisor_class()
True
```

sage.schemes.toric.divisor_class.**is_ToricRationalDivisorClass**(*x*)

Check if `x` is a toric rational divisor class.

INPUT:

- `x` – anything

OUTPUT: `True` if `x` is a toric rational divisor class, `False` otherwise

EXAMPLES:

```
sage: from sage.schemes.toric.divisor_class import is_ToricRationalDivisorClass
sage: is_ToricRationalDivisorClass(1)
False
sage: dP6 = toric_varieties.dP6()
sage: D = dP6.rational_class_group().gen(0); D
Divisor class [1, 0, 0, 0]
sage: is_ToricRationalDivisorClass(D)
True
```

```
>>> from sage.all import *
>>> from sage.schemes.toric.divisor_class import is_ToricRationalDivisorClass
>>> is_ToricRationalDivisorClass(Integer(1))
False
>>> dP6 = toric_varieties.dP6()
>>> D = dP6.rational_class_group().gen(Integer(0)); D
Divisor class [1, 0, 0, 0]
>>> is_ToricRationalDivisorClass(D)
True
```

16.6 The Chow group of a toric variety

In general, the Chow group is an algebraic version of a homology theory. That is, the objects are formal linear combinations of submanifolds modulo relations. In particular, the objects of the Chow group are formal linear combinations of algebraic subvarieties and the equivalence relation is rational equivalence. There is no relative version of the Chow group, so it is not a generalized homology theory.

The Chow groups of smooth or mildly singular toric varieties are almost the same as the homology groups:

- For smooth toric varieties, $A_k(X) = H_{2k}(X, \mathbf{Z})$. While they are the same, using the cohomology ring instead of the Chow group will be much faster! The cohomology ring does not try to keep track of torsion and uses Groebner bases to encode the cup product.
- For simplicial toric varieties, $A_k(X) \otimes \mathbf{Q} = H_{2k}(X, \mathbf{Q})$.

Note that in these cases the odd-dimensional (co)homology groups vanish. But for sufficiently singular toric varieties the Chow group differs from the homology groups (and the odd-dimensional homology groups no longer vanish). For singular varieties the Chow group is much easier to compute than the (co)homology groups.

The toric Chow group of a toric variety is the Chow group generated by the toric subvarieties, that is, closures of orbits under the torus action. These are in one-to-one correspondence with the cones of the fan and, therefore, the toric Chow group is a quotient of the free Abelian group generated by the cones. In particular, the toric Chow group has finite rank. One can show [FMSS1995] that the toric Chow groups equal the "full" Chow group of a toric variety, so there is no need to distinguish these in the following.

AUTHORS:

- Volker Braun (2010-08-09): Initial version

REFERENCES:

- Wikipedia article Chow_ring
- [FMSS1995]
- [Ful1993], Chapter 5.1, "Chow Groups"

EXAMPLES:

```
sage: X = toric_varieties.Cube_deformation(7)
sage: X.is_smooth()
False
sage: X.is_orbifold()
False
sage: A = X.Chow_group()
sage: A.degree()
(Z, C7, C2 x C2 x Z^5, Z)
sage: A.degree(2).ngens()
7
sage: a = sum( A.gen(i) * (i+1) for i in range(A.ngens()) )    # an element of A
sage: a  # long time (2s on sage.math, 2011)
( 9 | 1 mod 7 | 1 mod 2, 0 mod 2, 4, 5, 6, 7, 8 | 3 )
```

```
>>> from sage.all import *
>>> X = toric_varieties.Cube_deformation(Integer(7))
>>> X.is_smooth()
False
>>> X.is_orbifold()
False
>>> A = X.Chow_group()
>>> A.degree()
(Z, C7, C2 x C2 x Z^5, Z)
>>> A.degree(Integer(2)).ngens()
7
>>> a = sum( A.gen(i) * (i+Integer(1)) for i in range(A.ngens()) )    # an element of A
>>> a  # long time (2s on sage.math, 2011)
( 9 | 1 mod 7 | 1 mod 2, 0 mod 2, 4, 5, 6, 7, 8 | 3 )
```

The Chow group elements are printed as `( a0 | a1 mod 7 | a2 mod 2, a3 mod 2, a4, a5, a6, a7, a8 | a9 )`, which denotes the element of the Chow group in the same basis as `A.degree()`. The `|` separates individual degrees, so the example means:

- The degree-0 part is $3 \in \mathbf{Z}$.
- The degree-1 part is $1 \in \mathbf{Z}_7$.
- The torsion of the degree-2 Chow group is $(0,1) \in \mathbf{Z}_2 \oplus \mathbf{Z}_2$.
- The free part of the degree-2 Chow group is $(4,5,6,7,8) \in \mathbf{Z}^5$.
- The degree-3 part is $9 \in \mathbf{Z}$.

Note that the generators `A.gens()` are not sorted in any way. In fact, they may be of mixed degree. Use `A.gens(degree=d)` to obtain the generators in a fixed degree `d`. See *ChowGroup_class.gens()* for more details.

Cones of toric varieties can determine their own Chow cycle:

```
sage: A = X.Chow_group(); A
Chow group of 3-d toric variety covered by 6 affine patches
sage: cone = X.fan(dim=2)[3]; cone
2-d cone of Rational polyhedral fan in 3-d lattice N
sage: A_cone = A(cone); A_cone
( 0 | 6 mod 7 | 0 mod 2, 0 mod 2, 0, 0, 0, 0, 0 | 0 )
sage: A_cone.degree()
1
sage: 2 * A_cone
( 0 | 5 mod 7 | 0 mod 2, 0 mod 2, 0, 0, 0, 0, 0 | 0 )
sage: A_cone + A.gen(0)
( 0 | 6 mod 7 | 1 mod 2, 0 mod 2, 0, 0, 0, 0, 0 | 0 )
```

```
>>> from sage.all import *
>>> A = X.Chow_group(); A
Chow group of 3-d toric variety covered by 6 affine patches
>>> cone = X.fan(dim=Integer(2))[Integer(3)]; cone
2-d cone of Rational polyhedral fan in 3-d lattice N
>>> A_cone = A(cone); A_cone
( 0 | 6 mod 7 | 0 mod 2, 0 mod 2, 0, 0, 0, 0, 0 | 0 )
>>> A_cone.degree()
1
>>> Integer(2) * A_cone
( 0 | 5 mod 7 | 0 mod 2, 0 mod 2, 0, 0, 0, 0, 0 | 0 )
>>> A_cone + A.gen(Integer(0))
( 0 | 6 mod 7 | 1 mod 2, 0 mod 2, 0, 0, 0, 0, 0 | 0 )
```

Chow cycles can be of mixed degrees:

```
sage: mixed = sum(A.gens()); mixed
( 1 | 4 mod 7 | 1 mod 2, 1 mod 2, 1, 1, 1, 1, 1 | 1 )
sage: mixed.project_to_degree(1)
( 0 | 4 mod 7 | 0 mod 2, 0 mod 2, 0, 0, 0, 0, 0 | 0 )
sage: sum( mixed.project_to_degree(i) for i in range(X.dimension()+1) ) == mixed
True
```

```
>>> from sage.all import *
>>> mixed = sum(A.gens()); mixed
( 1 | 4 mod 7 | 1 mod 2, 1 mod 2, 1, 1, 1, 1, 1 | 1 )
>>> mixed.project_to_degree(Integer(1))
( 0 | 4 mod 7 | 0 mod 2, 0 mod 2, 0, 0, 0, 0, 0 | 0 )
>>> sum( mixed.project_to_degree(i) for i in range(X.dimension()+Integer(1)) ) ==␣
↪mixed
True
```

class sage.schemes.toric.chow_group.**ChowCycle**(*parent*, *v*, *check=True*)

Bases: FGP_Element

The elements of the Chow group.

Warning

Do not construct *ChowCycle* objects manually. Instead, use the parent *ChowGroup* to obtain generators or Chow cycles corresponding to cones of the fan.

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: A = P2.Chow_group()
sage: A.gens()
(( 0 | 0 | 1 ), ( 0 | 1 | 0 ), ( 1 | 0 | 0 ))
sage: cone = P2.fan(1)[0]
sage: A(cone)
( 0 | 1 | 0 )
sage: A( Cone([(1,0)]) )
( 0 | 1 | 0 )
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> A = P2.Chow_group()
>>> A.gens()
(( 0 | 0 | 1 ), ( 0 | 1 | 0 ), ( 1 | 0 | 0 ))
>>> cone = P2.fan(Integer(1))[Integer(0)]
>>> A(cone)
( 0 | 1 | 0 )
>>> A( Cone([(Integer(1),Integer(0))]) )
( 0 | 1 | 0 )
```

cohomology_class()

Return the (Poincaré-dual) cohomology class.

Consider a simplicial cone of the fan, that is, a d-dimensional cone spanned by d rays. Take the product of the corresponding d homogeneous coordinates. This monomial represents a cohomology classes of the toric variety X, see *cohomology_ring()*. Its cohomological degree is $2d$, which is the same degree as the Poincaré-dual of the (real) $\dim(X) - 2d$-dimensional torus orbit associated to the simplicial cone. By linearity, we can associate a cohomology class to each Chow cycle of a simplicial toric variety.

If the toric variety is compact and smooth, the associated cohomology class actually is the Poincaré dual (over the integers) of the Chow cycle. In particular, integrals of dual cohomology classes perform intersection computations.

If the toric variety is compact and has at most orbifold singularities, the torsion parts in cohomology and the Chow group can differ. But they are still isomorphic as rings over the rationals. Moreover, the normalization of integration (*volume_class*) and *count_points()* are chosen to agree.

OUTPUT:

The *CohomologyClass* which is associated to the Chow cycle.

If the toric variety is not simplicial, that is, has worse than orbifold singularities, there is no way to associate a cohomology class of the correct degree. In this case, *cohomology_class()* raises a ValueError.

EXAMPLES:

```
sage: # needs sage.libs.singular
sage: dP6 = toric_varieties.dP6()
sage: cone = dP6.fan().cone_containing(2,3)
```

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```
sage: HH = dP6.cohomology_ring()
sage: A = dP6.Chow_group()
sage: HH(cone)
[-w^2]
sage: A(cone)
( 1 | 0, 0, 0, 0 | 0 )
sage: A(cone).cohomology_class()
[-w^2]
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> dP6 = toric_varieties.dP6()
>>> cone = dP6.fan().cone_containing(Integer(2),Integer(3))
>>> HH = dP6.cohomology_ring()
>>> A = dP6.Chow_group()
>>> HH(cone)
[-w^2]
>>> A(cone)
( 1 | 0, 0, 0, 0 | 0 )
>>> A(cone).cohomology_class()
[-w^2]
```

Here is an example of a toric variety with orbifold singularities, where we can also use the isomorphism with the rational cohomology ring:

```
sage: # needs sage.libs.singular
sage: WP4 = toric_varieties.P4_11169()
sage: A = WP4.Chow_group()
sage: HH = WP4.cohomology_ring()
sage: cone3d = Cone([(0,0,1,0), (0,0,0,1), (-9,-6,-1,-1)])
sage: A(cone3d)
( 0 | -1 | 0 | 0 | 0 )
sage: HH(cone3d)
[3*z4^3]
sage: D = -WP4.K()  # the anticanonical divisor
sage: A(D)
( 0 | 0 | 0 | -18 | 0 )
sage: HH(D)
[18*z4]
sage: WP4.integrate( A(cone3d).cohomology_class() * D.cohomology_class() )
1
sage: WP4.integrate( HH(cone3d) * D.cohomology_class() )
1
sage: A(cone3d).intersection_with_divisor(D).count_points()
1
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> WP4 = toric_varieties.P4_11169()
>>> A = WP4.Chow_group()
>>> HH = WP4.cohomology_ring()
>>> cone3d = Cone([(Integer(0),Integer(0),Integer(1),Integer(0)), (Integer(0),
```

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```
↪Integer(0),Integer(0),Integer(1)), (-Integer(9),-Integer(6),-Integer(1),-
↪Integer(1))])
>>> A(cone3d)
( 0 | -1 | 0 | 0 | 0 )
>>> HH(cone3d)
[3*z4^3]
>>> D = -WP4.K()  # the anticanonical divisor
>>> A(D)
( 0 | 0 | 0 | -18 | 0 )
>>> HH(D)
[18*z4]
>>> WP4.integrate( A(cone3d).cohomology_class() * D.cohomology_class() )
1
>>> WP4.integrate( HH(cone3d) * D.cohomology_class() )
1
>>> A(cone3d).intersection_with_divisor(D).count_points()
1
```

count_points()

Return the number of points in the Chow cycle.

OUTPUT:

An element of `self.base_ring()`, which is usually **Z**. The number of points in the Chow cycle.

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: A = P2.Chow_group()
sage: a = 5*A.gen(2) + 7*A.gen(1); a
( 5 | 7 | 0 )
sage: a.count_points()
5
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> A = P2.Chow_group()
>>> a = Integer(5)*A.gen(Integer(2)) + Integer(7)*A.gen(Integer(1)); a
( 5 | 7 | 0 )
>>> a.count_points()
5
```

In the case of a smooth complete toric variety, the Chow (homology) groups are Poincaré dual to the integral cohomology groups. Here is such a smooth example:

```
sage: D = P2.divisor(1)
sage: a = D.Chow_cycle()
sage: aD = a.intersection_with_divisor(D)
sage: aD.count_points()
1
sage: P2.integrate(aD.cohomology_class())                                    #␣
↪needs sage.libs.singular
1
```

```
>>> from sage.all import *
>>> D = P2.divisor(Integer(1))
>>> a = D.Chow_cycle()
>>> aD = a.intersection_with_divisor(D)
>>> aD.count_points()
1
>>> P2.integrate(aD.cohomology_class())                                    #␣
↪needs sage.libs.singular
1
```

For toric varieties with at most orbifold singularities, the isomorphism only holds over $\mathbf{Q}$. But the normalization of the integral is still chosen such that the intersection numbers (which are potentially rational) computed both ways agree:

```
sage: P1xP1_Z2 = toric_varieties.P1xP1_Z2()
sage: Dt = P1xP1_Z2.divisor(1);  Dt
V(t)
sage: Dy = P1xP1_Z2.divisor(3);  Dy
V(y)
sage: Dt.Chow_cycle(QQ).intersection_with_divisor(Dy).count_points()
1/2
sage: P1xP1_Z2.integrate(Dt.cohomology_class() * Dy.cohomology_class())     #␣
↪needs sage.libs.singular
1/2
```

```
>>> from sage.all import *
>>> P1xP1_Z2 = toric_varieties.P1xP1_Z2()
>>> Dt = P1xP1_Z2.divisor(Integer(1));  Dt
V(t)
>>> Dy = P1xP1_Z2.divisor(Integer(3));  Dy
V(y)
>>> Dt.Chow_cycle(QQ).intersection_with_divisor(Dy).count_points()
1/2
>>> P1xP1_Z2.integrate(Dt.cohomology_class() * Dy.cohomology_class())     #␣
↪needs sage.libs.singular
1/2
```

degree()

Return the degree of the Chow cycle.

OUTPUT:

Integer. The complex dimension of the subvariety representing the Chow cycle.

This raises a `ValueError` if the Chow cycle is a sum of mixed degree cycles.

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: A = P2.Chow_group()
sage: [ a.degree() for a in A.gens() ]
[2, 1, 0]
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> A = P2.Chow_group()
>>> [ a.degree() for a in A.gens() ]
[2, 1, 0]
```

intersection_with_divisor(*divisor*)

Intersect the Chow cycle with `divisor`.

See Chapter 5.1 of [Ful1993] for a description of the toric algorithm.

INPUT:

- `divisor` – a *ToricDivisor* that can be moved away from the Chow cycle. For example, any Cartier divisor. See also *ToricDivisor.move_away_from*.

OUTPUT:

A new *ChowCycle*. If the divisor is not Cartier then this method potentially raises a `ValueError`, indicating that the divisor cannot be made transversal to the Chow cycle.

EXAMPLES:

```
sage: dP6 = toric_varieties.dP6()
sage: cone = dP6.fan().cone_containing(2); cone
1-d cone of Rational polyhedral fan in 2-d lattice N
sage: D = dP6.divisor(cone); D
V(y)
sage: A = dP6.Chow_group()
sage: A(cone)
( 0 | 0, 0, 1, 0 | 0 )
sage: intersection = A(cone).intersection_with_divisor(D); intersection
( -1 | 0, 0, 0, 0 | 0 )
sage: intersection.count_points()
-1
```

```
>>> from sage.all import *
>>> dP6 = toric_varieties.dP6()
>>> cone = dP6.fan().cone_containing(Integer(2)); cone
1-d cone of Rational polyhedral fan in 2-d lattice N
>>> D = dP6.divisor(cone); D
V(y)
>>> A = dP6.Chow_group()
>>> A(cone)
( 0 | 0, 0, 1, 0 | 0 )
>>> intersection = A(cone).intersection_with_divisor(D); intersection
( -1 | 0, 0, 0, 0 | 0 )
>>> intersection.count_points()
-1
```

You can do the same computation over the rational Chow group since there is no torsion in this case:

```
sage: A_QQ = dP6.Chow_group(base_ring=QQ)
sage: A_QQ(cone)
( 0 | 0, 0, 0, 1 | 0 )
```

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```
sage: intersection_QQ = A_QQ(cone).intersection_with_divisor(D); intersection
( -1 | 0, 0, 0, 0 | 0 )
sage: intersection_QQ.count_points()
-1
sage: type(intersection_QQ.count_points())
<... 'sage.rings.rational.Rational'>
sage: type(intersection.count_points())
<... 'sage.rings.integer.Integer'>
```

```
>>> from sage.all import *
>>> A_QQ = dP6.Chow_group(base_ring=QQ)
>>> A_QQ(cone)
( 0 | 0, 0, 0, 1 | 0 )
>>> intersection_QQ = A_QQ(cone).intersection_with_divisor(D); intersection
( -1 | 0, 0, 0, 0 | 0 )
>>> intersection_QQ.count_points()
-1
>>> type(intersection_QQ.count_points())
<... 'sage.rings.rational.Rational'>
>>> type(intersection.count_points())
<... 'sage.rings.integer.Integer'>
```

project_to_degree(*degree*)

Project a (mixed-degree) Chow cycle to the given `degree`.

INPUT:

- `degree` – integer; the degree to project to

OUTPUT:

The projection of the Chow class to the given degree as a new *ChowCycle* of the same Chow group.

EXAMPLES:

```
sage: A = toric_varieties.P2().Chow_group()
sage: cycle = 10*A.gen(0) + 11*A.gen(1) + 12*A.gen(2); cycle
( 12 | 11 | 10 )
sage: cycle.project_to_degree(2)
( 0 | 0 | 10 )
```

```
>>> from sage.all import *
>>> A = toric_varieties.P2().Chow_group()
>>> cycle = Integer(10)*A.gen(Integer(0)) + Integer(11)*A.gen(Integer(1)) +␣
↪Integer(12)*A.gen(Integer(2)); cycle
( 12 | 11 | 10 )
>>> cycle.project_to_degree(Integer(2))
( 0 | 0 | 10 )
```

class sage.schemes.toric.chow_group.**ChowGroupFactory**

Bases: `UniqueFactory`

Factory for *ChowGroup_class*.

create_key_and_extra_args(*toric_variety*, *base_ring=Integer Ring*, *check=True*)

Create a key that uniquely determines the *ChowGroup_class*.

INPUT:

- `toric_variety` – a toric variety
- `base_ring` – either **Z** (default) or **Q**; the coefficient ring of the Chow group
- `check` – boolean (default: `True`)

EXAMPLES:

```
sage: from sage.schemes.toric.chow_group import *
sage: P2 = toric_varieties.P2()
sage: ChowGroup(P2, ZZ, check=True) == ChowGroup(P2, ZZ, check=False)    #␣
↪indirect doctest
True
```

```
>>> from sage.all import *
>>> from sage.schemes.toric.chow_group import *
>>> P2 = toric_varieties.P2()
>>> ChowGroup(P2, ZZ, check=True) == ChowGroup(P2, ZZ, check=False)    #␣
↪indirect doctest
True
```

create_object(*version*, *key*, ***extra_args*)

Create a *ChowGroup_class*.

INPUT:

- `version` – object version; currently not used
- `key` – a key created by *create_key_and_extra_args()*
- `**extra_args` – currently not used

EXAMPLES:

```
sage: from sage.schemes.toric.chow_group import *
sage: P2 = toric_varieties.P2()
sage: ChowGroup(P2)     # indirect doctest
Chow group of 2-d CPR-Fano toric variety covered by 3 affine patches
```

```
>>> from sage.all import *
>>> from sage.schemes.toric.chow_group import *
>>> P2 = toric_varieties.P2()
>>> ChowGroup(P2)     # indirect doctest
Chow group of 2-d CPR-Fano toric variety covered by 3 affine patches
```

class sage.schemes.toric.chow_group.**ChowGroup_class**(*toric_variety*, *base_ring*, *check*)

Bases: `FGP_Module_class`, `WithEqualityById`

The Chow group of a toric variety.

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: from sage.schemes.toric.chow_group import ChowGroup_class
sage: A = ChowGroup_class(P2,ZZ,True);  A
Chow group of 2-d CPR-Fano toric variety covered by 3 affine patches
sage: A.an_element()
( 0 | 0 | 1 )
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> from sage.schemes.toric.chow_group import ChowGroup_class
>>> A = ChowGroup_class(P2,ZZ,True);  A
Chow group of 2-d CPR-Fano toric variety covered by 3 affine patches
>>> A.an_element()
( 0 | 0 | 1 )
```

Element

alias of *ChowCycle*

coordinate_vector(*chow_cycle*, *degree=None*, *reduce=True*)

Return the coordinate vector of the `chow_cycle`.

INPUT:

- `chow_cycle` – a *ChowCycle*
- `degree` – `None` (default) or integer
- `reduce` – boolean (default: `True`); whether to reduce modulo the invariants

OUTPUT:

- If `degree is None` (default), the coordinate vector relative to the basis `self.gens()` is returned.
- If some integer `degree=d` is specified, the chow cycle is projected to the given degree and the coordinate vector relative to the basis `self.gens(degree=d)` is returned.

EXAMPLES:

```
sage: A = toric_varieties.P2().Chow_group()
sage: a = A.gen(0) + 2*A.gen(1) + 3*A.gen(2)
sage: A.coordinate_vector(a)
(1, 2, 3)
sage: A.coordinate_vector(a, degree=1)
(2)
```

```
>>> from sage.all import *
>>> A = toric_varieties.P2().Chow_group()
>>> a = A.gen(Integer(0)) + Integer(2)*A.gen(Integer(1)) + Integer(3)*A.
↪gen(Integer(2))
>>> A.coordinate_vector(a)
(1, 2, 3)
>>> A.coordinate_vector(a, degree=Integer(1))
(2)
```

degree(*k=None*)

Return the degree-k Chow group.

INPUT:

- `k` – integer or `None` (default); the degree of the Chow group

OUTPUT:

- if k was specified, the Chow group A_k as an Abelian group.
- if k was not specified, a tuple containing the Chow groups in all degrees.

Note

- For a smooth toric variety, this is the same as the Poincaré-dual cohomology group $H^{d-2k}(X, \mathbf{Z})$.
- For a simplicial toric variety ("orbifold"), $A_k(X) \otimes \mathbf{Q} = H^{d-2k}(X, \mathbf{Q})$.

EXAMPLES:

Four exercises from page 65 of [Ful1993]. First, an example with $A_1(X) = \mathbf{Z} \oplus \mathbf{Z}/3\mathbf{Z}$:

```
sage: X = ToricVariety(Fan(cones=[[0,1], [1,2], [2,0]],
....:                      rays=[[2,-1], [-1,2], [-1,-1]]))
sage: A = X.Chow_group()
sage: A.degree(1)
C3 x Z
```

```
>>> from sage.all import *
>>> X = ToricVariety(Fan(cones=[[Integer(0),Integer(1)], [Integer(1),
↪Integer(2)], [Integer(2),Integer(0)]],
...                      rays=[[Integer(2),-Integer(1)], [-Integer(1),
↪Integer(2)], [-Integer(1),-Integer(1)]]))
>>> A = X.Chow_group()
>>> A.degree(Integer(1))
C3 x Z
```

Second, an example with $A_2(X) = \mathbf{Z}^2$:

```
sage: points = [[1,0,0], [0,1,0], [0,0,1], [1,-1,1], [-1,0,-1]]
sage: l = LatticePolytope(points)
sage: l.show3d()                                                    #␣
↪needs sage.plot
sage: X = ToricVariety(FaceFan(l))
sage: A = X.Chow_group()
sage: A.degree(2)
Z^2
```

```
>>> from sage.all import *
>>> points = [[Integer(1),Integer(0),Integer(0)], [Integer(0),Integer(1),
↪Integer(0)], [Integer(0),Integer(0),Integer(1)], [Integer(1),-Integer(1),
↪Integer(1)], [-Integer(1),Integer(0),-Integer(1)]]
>>> l = LatticePolytope(points)
>>> l.show3d()                                                      #␣
↪needs sage.plot
>>> X = ToricVariety(FaceFan(l))
>>> A = X.Chow_group()
```

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```
>>> A.degree(Integer(2))
Z^2
```

Third, an example with $A_2(X) = \mathbf{Z}^5$:

```
sage: cube = [[ 1,0,0], [0, 1,0], [0,0, 1], [-1, 1, 1],
....:         [-1,0,0], [0,-1,0], [0,0,-1], [ 1,-1,-1]]
sage: lat_cube = LatticePolytope(cube)
sage: X = ToricVariety(FaceFan((LatticePolytope(lat_cube))))
sage: X.Chow_group().degree(2)
Z^5
```

```
>>> from sage.all import *
>>> cube = [[ Integer(1),Integer(0),Integer(0)], [Integer(0), Integer(1),
↪Integer(0)], [Integer(0),Integer(0), Integer(1)], [-Integer(1), Integer(1),␣
↪Integer(1)],
...          [-Integer(1),Integer(0),Integer(0)], [Integer(0),-Integer(1),
↪Integer(0)], [Integer(0),Integer(0),-Integer(1)], [ Integer(1),-Integer(1),-
↪Integer(1)]]
>>> lat_cube = LatticePolytope(cube)
>>> X = ToricVariety(FaceFan((LatticePolytope(lat_cube))))
>>> X.Chow_group().degree(Integer(2))
Z^5
```

Fourth, a fan that is not the fan over a polytope. Combinatorially, the fan is the same in the third example, only the coordinates of the first point are different. But the resulting fan is not the face fan of a cube, so the variety is "more singular". Its Chow group has torsion, $A_2(X) = \mathbf{Z}^5 \oplus \mathbf{Z}/2$:

```
sage: rays = [[ 1, 2, 3], [ 1,-1, 1], [-1, 1, 1], [-1,-1, 1],
....:         [-1,-1,-1], [-1, 1,-1], [ 1,-1,-1], [ 1, 1,-1]]
sage: cones = [[0,1,2,3], [4,5,6,7], [0,1,7,6],
....:          [4,5,3,2], [0,2,5,7], [4,6,1,3]]
sage: X = ToricVariety(Fan(cones, rays))
sage: X.Chow_group().degree(2)  # long time (2s on sage.math, 2011)
C2 x Z^5
```

```
>>> from sage.all import *
>>> rays = [[ Integer(1), Integer(2), Integer(3)], [ Integer(1),-Integer(1),␣
↪Integer(1)], [-Integer(1), Integer(1), Integer(1)], [-Integer(1),-
↪Integer(1), Integer(1)],
...          [-Integer(1),-Integer(1),-Integer(1)], [-Integer(1), Integer(1),-
↪Integer(1)], [ Integer(1),-Integer(1),-Integer(1)], [ Integer(1),␣
↪Integer(1),-Integer(1)]]
>>> cones = [[Integer(0),Integer(1),Integer(2),Integer(3)], [Integer(4),
↪Integer(5),Integer(6),Integer(7)], [Integer(0),Integer(1),Integer(7),
↪Integer(6)],
...           [Integer(4),Integer(5),Integer(3),Integer(2)], [Integer(0),
↪Integer(2),Integer(5),Integer(7)], [Integer(4),Integer(6),Integer(1),
↪Integer(3)]]
>>> X = ToricVariety(Fan(cones, rays))
>>> X.Chow_group().degree(Integer(2))  # long time (2s on sage.math, 2011)
C2 x Z^5
```

Finally, Example 1.3 of [FS1994]:

```
sage: def points_mod(k):
....:     return matrix([[ 1,  1,  2*k+1], [ 1,-1,  1],
....:                    [-1,  1,  1], [-1,-1,  1], [-1,-1,-1],
....:                    [-1,  1,-1], [ 1,-1,-1], [ 1,  1,-1]])
sage: def rays(k):
....:     return matrix([[ 1,   1,   1],
....:                    [ 1,  -1,   1],
....:                    [-1,   1,   1]]).solve_left(points_mod(k)).rows()
sage: cones = [[0,1,2,3], [4,5,6,7], [0,1,7,6], [4,5,3,2], [0,2,5,7], [4,6,1,
↪3]]
sage: X_Delta = lambda k: ToricVariety(Fan(cones=cones, rays=rays(k)))
sage: X_Delta(0).Chow_group().degree()  # long time (3s on sage.math, 2011)
(Z, Z, Z^5, Z)
sage: X_Delta(1).Chow_group().degree()  # long time (3s on sage.math, 2011)
(Z, 0, Z^5, Z)
sage: X_Delta(2).Chow_group().degree()  # long time (3s on sage.math, 2011)
(Z, C2, Z^5, Z)
sage: X_Delta(2).Chow_group(base_ring=QQ).degree()  # long time (4s on sage.
↪math, 2011)
(Q, 0, Q^5, Q)
```

```
>>> from sage.all import *
>>> def points_mod(k):
...     return matrix([[ Integer(1), Integer(1), Integer(2)*k+Integer(1)], [␣
↪Integer(1),-Integer(1), Integer(1)],
...                    [-Integer(1), Integer(1), Integer(1)], [-Integer(1),-
↪Integer(1), Integer(1)], [-Integer(1),-Integer(1),-Integer(1)],
...                    [-Integer(1), Integer(1),-Integer(1)], [ Integer(1),-
↪Integer(1),-Integer(1)], [ Integer(1), Integer(1),-Integer(1)]])
>>> def rays(k):
...     return matrix([[ Integer(1),  Integer(1),  Integer(1)],
...                    [ Integer(1), -Integer(1),  Integer(1)],
...                    [-Integer(1),  Integer(1),  Integer(1)]]).solve_
↪left(points_mod(k)).rows()
>>> cones = [[Integer(0),Integer(1),Integer(2),Integer(3)], [Integer(4),
↪Integer(5),Integer(6),Integer(7)], [Integer(0),Integer(1),Integer(7),
↪Integer(6)], [Integer(4),Integer(5),Integer(3),Integer(2)], [Integer(0),
↪Integer(2),Integer(5),Integer(7)], [Integer(4),Integer(6),Integer(1),
↪Integer(3)]]
>>> X_Delta = lambda k: ToricVariety(Fan(cones=cones, rays=rays(k)))
>>> X_Delta(Integer(0)).Chow_group().degree()  # long time (3s on sage.math,␣
↪2011)
(Z, Z, Z^5, Z)
>>> X_Delta(Integer(1)).Chow_group().degree()  # long time (3s on sage.math,␣
↪2011)
(Z, 0, Z^5, Z)
>>> X_Delta(Integer(2)).Chow_group().degree()  # long time (3s on sage.math,␣
↪2011)
(Z, C2, Z^5, Z)
>>> X_Delta(Integer(2)).Chow_group(base_ring=QQ).degree()  # long time (4s on␣
↪sage.math, 2011)
```

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```
(Q, 0, Q^5, Q)
```

gens(*degree=None*)

Return the generators of the Chow group.

INPUT:

- `degree` – integer (optional); the degree of the Chow group

OUTPUT:

- if no degree is specified, the generators of the whole Chow group. The chosen generators may be of mixed degree.
- if `degree=` k was specified, the generators of the degree-k part A_k of the Chow group.

EXAMPLES:

```
sage: A = toric_varieties.P2().Chow_group()
sage: A.gens()
(( 0 | 0 | 1 ), ( 0 | 1 | 0 ), ( 1 | 0 | 0 ))
sage: A.gens(degree=1)
(( 0 | 1 | 0 ),)
```

```
>>> from sage.all import *
>>> A = toric_varieties.P2().Chow_group()
>>> A.gens()
(( 0 | 0 | 1 ), ( 0 | 1 | 0 ), ( 1 | 0 | 0 ))
>>> A.gens(degree=Integer(1))
(( 0 | 1 | 0 ),)
```

relation_gens()

Return the Chow cycles equivalent to zero.

For each $d-k-1$-dimensional cone $\rho \in \Sigma^{(d-k-1)}$, the relations in $A_k(X)$, that is the cycles equivalent to zero, are generated by

$$0 \stackrel{!}{=} \mathrm{div}(u) = \sum_{\rho<\sigma\in\Sigma^{(n-p)}} \langle u, n_{\rho,\sigma}\rangle V(\sigma), \qquad u \in M(\rho)$$

where $n_{\rho,\sigma}$ is a (randomly chosen) lift of the generator of $N_\sigma/N_\rho \simeq \mathbf{Z}$. See also Exercise 12.5.7 of [CLS2011].

See also `relations()` to obtain the relations as submodule of the free module generated by the cones. Or use `self.relations().gens()` to list the relations in the free module.

OUTPUT:

A tuple of Chow cycles, each rationally equivalent to zero, that generates the rational equivalence.

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: A = P2.Chow_group()
sage: first = A.relation_gens()[0]; first
( 0 | 0 | 0 )
sage: first.is_zero()
```

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```
True
sage: first.lift()
(0, 1, 0, -1, 0, 0, 0)
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> A = P2.Chow_group()
>>> first = A.relation_gens()[Integer(0)]; first
( 0 | 0 | 0 )
>>> first.is_zero()
True
>>> first.lift()
(0, 1, 0, -1, 0, 0, 0)
```

scheme()

Return the underlying toric variety.

OUTPUT: a *ToricVariety*.

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: A = P2.Chow_group()
sage: A.scheme()
2-d CPR-Fano toric variety covered by 3 affine patches
sage: A.scheme() is P2
True
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> A = P2.Chow_group()
>>> A.scheme()
2-d CPR-Fano toric variety covered by 3 affine patches
>>> A.scheme() is P2
True
```

class sage.schemes.toric.chow_group.**ChowGroup_degree_class**(A, d)

Bases: SageObject

A fixed-degree subgroup of the Chow group of a toric variety.

Warning

Use *degree()* to construct *ChowGroup_degree_class* instances.

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: A = P2.Chow_group(); A
Chow group of 2-d CPR-Fano toric variety covered by 3 affine patches
sage: A.degree()
(Z, Z, Z)
```

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```
sage: A.degree(2)
Z
sage: type(_)
<class 'sage.schemes.toric.chow_group.ChowGroup_degree_class'>
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> A = P2.Chow_group(); A
Chow group of 2-d CPR-Fano toric variety covered by 3 affine patches
>>> A.degree()
(Z, Z, Z)
>>> A.degree(Integer(2))
Z
>>> type(_)
<class 'sage.schemes.toric.chow_group.ChowGroup_degree_class'>
```

gen(*i*)

Return the `i`-th generator of the Chow group of fixed degree.

INPUT:

- `i` – integer; the index of the generator to be returned

OUTPUT: a Chow cycle

EXAMPLES:

```
sage: projective_plane = toric_varieties.P2()
sage: A2 = projective_plane.Chow_group().degree(2)
sage: A2.gen(0)
( 0 | 0 | 1 )
```

```
>>> from sage.all import *
>>> projective_plane = toric_varieties.P2()
>>> A2 = projective_plane.Chow_group().degree(Integer(2))
>>> A2.gen(Integer(0))
( 0 | 0 | 1 )
```

gens()

Return the generators of the Chow group of fixed degree.

OUTPUT: a tuple of Chow cycles of fixed degree generating *module()*.

EXAMPLES:

```
sage: projective_plane = toric_varieties.P2()
sage: A2 = projective_plane.Chow_group().degree(2)
sage: A2.gens()
(( 0 | 0 | 1 ),)
```

```
>>> from sage.all import *
>>> projective_plane = toric_varieties.P2()
>>> A2 = projective_plane.Chow_group().degree(Integer(2))
>>> A2.gens()
(( 0 | 0 | 1 ),)
```

module()

Return the submodule of the toric Chow group generated.

OUTPUT: a sage.modules.fg_pid.fgp_module.FGP_Module_class

EXAMPLES:

```
sage: projective_plane = toric_varieties.P2()
sage: A2 = projective_plane.Chow_group().degree(2)
sage: A2.module()
Finitely generated module V/W over Integer Ring with invariants (0)
```

```
>>> from sage.all import *
>>> projective_plane = toric_varieties.P2()
>>> A2 = projective_plane.Chow_group().degree(Integer(2))
>>> A2.module()
Finitely generated module V/W over Integer Ring with invariants (0)
```

ngens()

Return the number of generators.

OUTPUT: integer

EXAMPLES:

```
sage: projective_plane = toric_varieties.P2()
sage: A2 = projective_plane.Chow_group().degree(2)
sage: A2.ngens()
1
```

```
>>> from sage.all import *
>>> projective_plane = toric_varieties.P2()
>>> A2 = projective_plane.Chow_group().degree(Integer(2))
>>> A2.ngens()
1
```

sage.schemes.toric.chow_group.**is_ChowCycle**(*x*)

Return whether x is a *ChowCycle*.

INPUT:

- x – anything

OUTPUT: boolean

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: A = P2.Chow_group()
sage: from sage.schemes.toric.chow_group import *
sage: is_ChowCycle(A)
doctest:warning...
DeprecationWarning: The function is_ChowCycle is deprecated;
use 'isinstance(..., ChowCycle)' instead.
See https://github.com/sagemath/sage/issues/38277 for details.
False
```

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```
sage: is_ChowCycle(A.an_element())
True
sage: is_ChowCycle('Victoria')
False
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> A = P2.Chow_group()
>>> from sage.schemes.toric.chow_group import *
>>> is_ChowCycle(A)
doctest:warning...
DeprecationWarning: The function is_ChowCycle is deprecated;
use 'isinstance(..., ChowCycle)' instead.
See https://github.com/sagemath/sage/issues/38277 for details.
False
>>> is_ChowCycle(A.an_element())
True
>>> is_ChowCycle('Victoria')
False
```

sage.schemes.toric.chow_group.**is_ChowGroup**(*x*)

Return whether `x` is a *ChowGroup_class*.

INPUT:

- `x` – anything

OUTPUT: boolean

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: A = P2.Chow_group()
sage: from sage.schemes.toric.chow_group import is_ChowGroup
sage: is_ChowGroup(A)
doctest:warning...
DeprecationWarning: The function is_ChowGroup is deprecated; use 'isinstance(...,␣
↪ChowGroup_class)' instead.
See https://github.com/sagemath/sage/issues/38022 for details.
True
sage: is_ChowGroup('Victoria')
False
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> A = P2.Chow_group()
>>> from sage.schemes.toric.chow_group import is_ChowGroup
>>> is_ChowGroup(A)
doctest:warning...
DeprecationWarning: The function is_ChowGroup is deprecated; use 'isinstance(...,␣
↪ChowGroup_class)' instead.
See https://github.com/sagemath/sage/issues/38022 for details.
True
```

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```
>>> is_ChowGroup('Victoria')
False
```

16.7 Toric ideals

A toric ideal (associated to an integer matrix A) is an ideal of the form

$$I_A = \left\langle x^u - x^v : u, v \in \mathbf{Z}^n_{\geq}, u - v \in \ker(A) \right\rangle$$

In other words, it is an ideal generated by irreducible "binomials", that is, differences of monomials without a common factor. Since the Buchberger algorithm preserves this property, any Groebner basis is then also generated by binomials.

EXAMPLES:

```
sage: A = matrix([[1,1,1], [0,1,2]])
sage: IA = ToricIdeal(A)
sage: IA.ker()
Free module of degree 3 and rank 1 over Integer Ring
User basis matrix:
[-1  2 -1]
sage: IA
Ideal (-z1^2 + z0*z2) of Multivariate Polynomial
Ring in z0, z1, z2 over Rational Field
```

```
>>> from sage.all import *
>>> A = matrix([[Integer(1),Integer(1),Integer(1)], [Integer(0),Integer(1),
↪Integer(2)]])
>>> IA = ToricIdeal(A)
>>> IA.ker()
Free module of degree 3 and rank 1 over Integer Ring
User basis matrix:
[-1  2 -1]
>>> IA
Ideal (-z1^2 + z0*z2) of Multivariate Polynomial
Ring in z0, z1, z2 over Rational Field
```

Here, the "naive" ideal generated by $z_0 z_2 - z_1^2$ does already equal the toric ideal. But that is not true in general! For example, this toric ideal ([Stu1997], Example 1.2) is the twisted cubic and cannot be generated by $2 = \dim \ker(A)$ polynomials:

```
sage: A = matrix([[3,2,1,0], [0,1,2,3]])
sage: IA = ToricIdeal(A)
sage: IA.ker()
Free module of degree 4 and rank 2 over Integer Ring
User basis matrix:
[-1  1  1 -1]
[-1  2 -1  0]
sage: IA
Ideal (-z1*z2 + z0*z3, -z1^2 + z0*z2, z2^2 - z1*z3) of
Multivariate Polynomial Ring in z0, z1, z2, z3 over Rational Field
```

```
>>> from sage.all import *
>>> A = matrix([[Integer(3),Integer(2),Integer(1),Integer(0)], [Integer(0),Integer(1),
↪Integer(2),Integer(3)]])
>>> IA = ToricIdeal(A)
>>> IA.ker()
Free module of degree 4 and rank 2 over Integer Ring
User basis matrix:
[-1  1  1 -1]
[-1  2 -1  0]
>>> IA
Ideal (-z1*z2 + z0*z3, -z1^2 + z0*z2, z2^2 - z1*z3) of
Multivariate Polynomial Ring in z0, z1, z2, z3 over Rational Field
```

The following family of toric ideals is from Example 4.4 of [Stu1997]. One can show that I_d is generated by one quadric and d binomials of degree d:

```
sage: def I(d):
....:     return ToricIdeal(matrix([[1,1,1,1,1], [0,1,1,0,0], [0,0,1,1,d]]))
sage: I(2)
Ideal (-z3^2 + z0*z4,
       z0*z2 - z1*z3,
       z2*z3 - z1*z4) of
Multivariate Polynomial Ring in z0, z1, z2, z3, z4 over Rational Field
sage: I(3)
Ideal (-z3^3 + z0^2*z4,
       z0*z2 - z1*z3,
       z2*z3^2 - z0*z1*z4,
       z2^2*z3 - z1^2*z4) of
Multivariate Polynomial Ring in z0, z1, z2, z3, z4 over Rational Field
sage: I(4)
Ideal (-z3^4 + z0^3*z4,
       z0*z2 - z1*z3,
       z2*z3^3 - z0^2*z1*z4,
       z2^2*z3^2 - z0*z1^2*z4,
       z2^3*z3 - z1^3*z4) of
Multivariate Polynomial Ring in z0, z1, z2, z3, z4 over Rational Field
```

```
>>> from sage.all import *
>>> def I(d):
...     return ToricIdeal(matrix([[Integer(1),Integer(1),Integer(1),Integer(1),
↪Integer(1)], [Integer(0),Integer(1),Integer(1),Integer(0),Integer(0)], [Integer(0),
↪Integer(0),Integer(1),Integer(1),d]]))
>>> I(Integer(2))
Ideal (-z3^2 + z0*z4,
       z0*z2 - z1*z3,
       z2*z3 - z1*z4) of
Multivariate Polynomial Ring in z0, z1, z2, z3, z4 over Rational Field
>>> I(Integer(3))
Ideal (-z3^3 + z0^2*z4,
       z0*z2 - z1*z3,
       z2*z3^2 - z0*z1*z4,
       z2^2*z3 - z1^2*z4) of
Multivariate Polynomial Ring in z0, z1, z2, z3, z4 over Rational Field
```

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```
>>> I(Integer(4))
Ideal (-z3^4 + z0^3*z4,
       z0*z2 - z1*z3,
       z2*z3^3 - z0^2*z1*z4,
       z2^2*z3^2 - z0*z1^2*z4,
       z2^3*z3 - z1^3*z4) of
Multivariate Polynomial Ring in z0, z1, z2, z3, z4 over Rational Field
```

Finally, the example in [SH1995b]

```
sage: A = matrix(ZZ, [ [15,  4, 14, 19,  2,  1, 10, 17],
....:                  [18, 11, 13,  5, 16, 16,  8, 19],
....:                  [11,  7,  8, 19, 15, 18, 14,  6],
....:                  [17, 10, 13, 17, 16, 14, 15, 18] ])
sage: IA = ToricIdeal(A)      # long time
sage: IA.ngens()              # long time
213
```

```
>>> from sage.all import *
>>> A = matrix(ZZ, [ [Integer(15),  Integer(4), Integer(14), Integer(19),  Integer(2),
↪  Integer(1), Integer(10), Integer(17)],
...                  [Integer(18), Integer(11), Integer(13),  Integer(5), Integer(16),
↪ Integer(16),  Integer(8), Integer(19)],
...                  [Integer(11),  Integer(7),  Integer(8), Integer(19), Integer(15),
↪ Integer(18), Integer(14),  Integer(6)],
...                  [Integer(17), Integer(10), Integer(13), Integer(17), Integer(16),
↪ Integer(14), Integer(15), Integer(18)] ])
>>> IA = ToricIdeal(A)      # long time
>>> IA.ngens()              # long time
213
```

AUTHORS:

- Volker Braun (2011-01-03): Initial version

class sage.schemes.toric.ideal.**ToricIdeal**(*A*, *names='z'*, *base_ring=Rational Field*, *polynomial_ring=None*, *algorithm='HostenSturmfels'*)

Bases: `MPolynomialIdeal`

This class represents a toric ideal defined by an integral matrix.

INPUT:

- `A` – integer matrix; the defining matrix of the toric ideal
- `names` – string (optional); names for the variables. By default, this is `'z'` and the variables will be named `z0`, `z1`, ...
- `base_ring` – a ring (default: $\mathbf{Q}$); the base ring of the ideal. A toric ideal uses only coefficients ± 1.
- `polynomial_ring` – a polynomial ring (optional); the polynomial ring to construct the ideal in

  You may specify the ambient polynomial ring via the `polynomial_ring` parameter or via the `names` and `base_ring` parameter. A `ValueError` is raised if you specify both.
- `algorithm` – string (optional); the algorithm to use. For now, must be `'HostenSturmfels'` which is the algorithm proposed by Hosten and Sturmfels in [SH1995b].

EXAMPLES:

```
sage: A = matrix([[1,1,1], [0,1,2]])
sage: ToricIdeal(A)
Ideal (-z1^2 + z0*z2) of Multivariate Polynomial Ring
in z0, z1, z2 over Rational Field
```

```
>>> from sage.all import *
>>> A = matrix([[Integer(1),Integer(1),Integer(1)], [Integer(0),Integer(1),
↪Integer(2)]])
>>> ToricIdeal(A)
Ideal (-z1^2 + z0*z2) of Multivariate Polynomial Ring
in z0, z1, z2 over Rational Field
```

First way of specifying the polynomial ring:

```
sage: ToricIdeal(A, names='x,y,z', base_ring=ZZ)
Ideal (-y^2 + x*z) of Multivariate Polynomial Ring
in x, y, z over Integer Ring
```

```
>>> from sage.all import *
>>> ToricIdeal(A, names='x,y,z', base_ring=ZZ)
Ideal (-y^2 + x*z) of Multivariate Polynomial Ring
in x, y, z over Integer Ring
```

Second way of specifying the polynomial ring:

```
sage: R.<x,y,z> = ZZ[]
sage: ToricIdeal(A, polynomial_ring=R)
Ideal (-y^2 + x*z) of Multivariate Polynomial Ring
in x, y, z over Integer Ring
```

```
>>> from sage.all import *
>>> R = ZZ['x, y, z']; (x, y, z,) = R._first_ngens(3)
>>> ToricIdeal(A, polynomial_ring=R)
Ideal (-y^2 + x*z) of Multivariate Polynomial Ring
in x, y, z over Integer Ring
```

It is an error to specify both:

```
sage: ToricIdeal(A, names='x,y,z', polynomial_ring=R)
Traceback (most recent call last):
...
ValueError: you must not specify both variable names and a polynomial ring
```

```
>>> from sage.all import *
>>> ToricIdeal(A, names='x,y,z', polynomial_ring=R)
Traceback (most recent call last):
...
ValueError: you must not specify both variable names and a polynomial ring
```

A()

Return the defining matrix.

OUTPUT: integer matrix

EXAMPLES:

```
sage: A = matrix([[1,1,1], [0,1,2]])
sage: IA = ToricIdeal(A)
sage: IA.A()
[1 1 1]
[0 1 2]
```

```
>>> from sage.all import *
>>> A = matrix([[Integer(1),Integer(1),Integer(1)], [Integer(0),Integer(1),
↪Integer(2)]])
>>> IA = ToricIdeal(A)
>>> IA.A()
[1 1 1]
[0 1 2]
```

ker()

Return the kernel of the defining matrix.

OUTPUT: the kernel of `self.A()`.

EXAMPLES:

```
sage: A = matrix([[1,1,1], [0,1,2]])
sage: IA = ToricIdeal(A)
sage: IA.ker()
Free module of degree 3 and rank 1 over Integer Ring
 User basis matrix: [-1  2 -1]
```

```
>>> from sage.all import *
>>> A = matrix([[Integer(1),Integer(1),Integer(1)], [Integer(0),Integer(1),
↪Integer(2)]])
>>> IA = ToricIdeal(A)
>>> IA.ker()
Free module of degree 3 and rank 1 over Integer Ring
 User basis matrix: [-1  2 -1]
```

nvariables()

Return the number of variables of the ambient polynomial ring.

OUTPUT: integer; the number of columns of the defining matrix *A()*

EXAMPLES:

```
sage: A = matrix([[1,1,1], [0,1,2]])
sage: IA = ToricIdeal(A)
sage: IA.nvariables()
3
```

```
>>> from sage.all import *
>>> A = matrix([[Integer(1),Integer(1),Integer(1)], [Integer(0),Integer(1),
↪Integer(2)]])
>>> IA = ToricIdeal(A)
```

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```
>>> IA.nvariables()
3
```

16.8 Morphisms of toric varieties

There are three "obvious" ways to map toric varieties to toric varieties:

1. Polynomial maps in local coordinates, the usual morphisms in algebraic geometry.
2. Polynomial maps in the (global) homogeneous coordinates.
3. Toric morphisms, that is, algebraic morphisms equivariant with respect to the torus action on the toric variety.

Both 2 and 3 are special cases of 1, which is just to say that we always remain within the realm of algebraic geometry. But apart from that, none is included in one of the other cases. In the examples below, we will explore some algebraic maps that can or can not be written as a toric morphism. Often a toric morphism can be written with polynomial maps in homogeneous coordinates, but sometimes it cannot.

The toric morphisms are perhaps the most mysterious at the beginning. Let us quickly review their definition (See Definition 3.3.3 of [CLS2011]). Let Σ_1 be a fan in $N_{1,\mathbf{R}}$ and Σ_2 be a fan in $N_{2,\mathbf{R}}$. A morphism $\phi : X_{\Sigma_1} \to X_{\Sigma_2}$ of the associated toric varieties is toric if ϕ maps the maximal torus $T_{N_1} \subseteq X_{\Sigma_1}$ into $T_{N_2} \subseteq X_{\Sigma_2}$ and $\phi|_{T_N}$ is a group homomorphism.

The data defining a toric morphism is precisely what defines a fan morphism (see `fan_morphism`), extending the more familiar dictionary between toric varieties and fans. Toric geometry is a functor from the category of fans and fan morphisms to the category of toric varieties and toric morphisms.

Note

Do not create the toric morphisms (or any morphism of schemes) directly from the `SchemeMorphism...` classes. Instead, use the `hom()` method common to all algebraic schemes to create new homomorphisms.

EXAMPLES:

First, consider the following embedding of $\mathbb{P}^1$ into $\mathbb{P}^2$

```
sage: P2.<x,y,z> = toric_varieties.P2()
sage: P1.<u,v> = toric_varieties.P1()
sage: P1.hom([0, u^2 + v^2, u*v], P2)
Scheme morphism:
  From: 1-d CPR-Fano toric variety covered by 2 affine patches
  To:   2-d CPR-Fano toric variety covered by 3 affine patches
  Defn: Defined on coordinates by sending [u : v] to [0 : u^2 + v^2 : u*v]
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2(names=('x', 'y', 'z',)); (x, y, z,) = P2._first_ngens(3)
>>> P1 = toric_varieties.P1(names=('u', 'v',)); (u, v,) = P1._first_ngens(2)
>>> P1.hom([Integer(0), u**Integer(2) + v**Integer(2), u*v], P2)
Scheme morphism:
  From: 1-d CPR-Fano toric variety covered by 2 affine patches
  To:   2-d CPR-Fano toric variety covered by 3 affine patches
  Defn: Defined on coordinates by sending [u : v] to [0 : u^2 + v^2 : u*v]
```

This is a well-defined morphism of algebraic varieties because homogeneously rescaled coordinates of a point of $\mathbb{P}^1$ map to the same point in $\mathbb{P}^2$ up to its homogeneous rescalings. It is not equivariant with respect to the torus actions

$$\mathbf{C}^\times \times \mathbb{P}^1, (\mu, [u:v]) \mapsto [u:\mu v] \quad \text{and} \quad \left(\mathbf{C}^\times\right)^2 \times \mathbb{P}^2, ((\alpha,\beta),[x:y:z]) \mapsto [x:\alpha y:\beta z],$$

hence it is not a toric morphism. Clearly, the problem is that the map in homogeneous coordinates contains summands that transform differently under the torus action. However, this is not the only difficulty. For example, consider

```
sage: phi = P1.hom([0,u,v], P2);  phi
Scheme morphism:
  From: 1-d CPR-Fano toric variety covered by 2 affine patches
  To:   2-d CPR-Fano toric variety covered by 3 affine patches
  Defn: Defined on coordinates by sending [u : v] to [0 : u : v]
```

```
>>> from sage.all import *
>>> phi = P1.hom([Integer(0),u,v], P2);  phi
Scheme morphism:
  From: 1-d CPR-Fano toric variety covered by 2 affine patches
  To:   2-d CPR-Fano toric variety covered by 3 affine patches
  Defn: Defined on coordinates by sending [u : v] to [0 : u : v]
```

This map is actually the embedding of the *orbit_closure()* associated to one of the rays of the fan of $\mathbb{P}^2$. Now the morphism is equivariant with respect to **some** map $\mathbf{C}^\times \to (\mathbf{C}^\times)^2$ of the maximal tori of $\mathbb{P}^1$ and $\mathbb{P}^2$. But this map of the maximal tori cannot be the same as `phi` defined above. Indeed, the image of `phi` completely misses the maximal torus $T_{\mathbb{P}^2} = \{[x:y:z] | x \neq 0, y \neq 0, z \neq 0\}$ of $\mathbb{P}^2$.

Consider instead the following morphism of fans:

```
sage: fm = FanMorphism(matrix(ZZ, [[1,0]]), P1.fan(), P2.fan());  fm
Fan morphism defined by the matrix
[1 0]
Domain fan: Rational polyhedral fan in 1-d lattice N
Codomain fan: Rational polyhedral fan in 2-d lattice N
```

```
>>> from sage.all import *
>>> fm = FanMorphism(matrix(ZZ, [[Integer(1),Integer(0)]]), P1.fan(), P2.fan());  fm
Fan morphism defined by the matrix
[1 0]
Domain fan: Rational polyhedral fan in 1-d lattice N
Codomain fan: Rational polyhedral fan in 2-d lattice N
```

which also defines a morphism of toric varieties:

```
sage: P1.hom(fm, P2)
Scheme morphism:
  From: 1-d CPR-Fano toric variety covered by 2 affine patches
  To:   2-d CPR-Fano toric variety covered by 3 affine patches
  Defn: Defined by sending Rational polyhedral fan in 1-d lattice N
        to Rational polyhedral fan in 2-d lattice N.
```

```
>>> from sage.all import *
>>> P1.hom(fm, P2)
Scheme morphism:
  From: 1-d CPR-Fano toric variety covered by 2 affine patches
```

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```
  To:   2-d CPR-Fano toric variety covered by 3 affine patches
  Defn: Defined by sending Rational polyhedral fan in 1-d lattice N
        to Rational polyhedral fan in 2-d lattice N.
```

The fan morphism map is equivalent to the following polynomial map:

```
sage: _.as_polynomial_map()
Scheme morphism:
  From: 1-d CPR-Fano toric variety covered by 2 affine patches
  To:   2-d CPR-Fano toric variety covered by 3 affine patches
  Defn: Defined on coordinates by sending [u : v] to [u : v : v]
```

```
>>> from sage.all import *
>>> _.as_polynomial_map()
Scheme morphism:
  From: 1-d CPR-Fano toric variety covered by 2 affine patches
  To:   2-d CPR-Fano toric variety covered by 3 affine patches
  Defn: Defined on coordinates by sending [u : v] to [u : v : v]
```

Finally, here is an example of a fan morphism that cannot be written using homogeneous polynomials. Consider the blowup $O_{\mathbb{P}^1}(2) \to \mathbf{C}^2/\mathbf{Z}_2$. In terms of toric data, this blowup is:

```
sage: A2_Z2 = toric_varieties.A2_Z2()
sage: A2_Z2.fan().rays()
N(1, 0),
N(1, 2)
in 2-d lattice N
sage: O2_P1 = A2_Z2.resolve(new_rays=[(1,1)])
sage: blowup = O2_P1.hom(identity_matrix(2), A2_Z2)
sage: blowup.as_polynomial_map()
Traceback (most recent call last):
...
TypeError: the fan morphism cannot be written in homogeneous polynomials
```

```
>>> from sage.all import *
>>> A2_Z2 = toric_varieties.A2_Z2()
>>> A2_Z2.fan().rays()
N(1, 0),
N(1, 2)
in 2-d lattice N
>>> O2_P1 = A2_Z2.resolve(new_rays=[(Integer(1),Integer(1))])
>>> blowup = O2_P1.hom(identity_matrix(Integer(2)), A2_Z2)
>>> blowup.as_polynomial_map()
Traceback (most recent call last):
...
TypeError: the fan morphism cannot be written in homogeneous polynomials
```

If we denote the homogeneous coordinates of $O_{\mathbb{P}^1}(2)$ by x, t, y corresponding to the rays $(1,2)$, $(1,1)$, and $(1,0)$ then the blow-up map is [BB2013]:

$$f : O_{\mathbb{P}^1}(2) \to \mathbf{C}^2/\mathbf{Z}_2, \quad (x,t,y) \mapsto \left(x\sqrt{t}, y\sqrt{t}\right)$$

which requires square roots.

16.8.1 Fibrations

If a toric morphism is *dominant*, then all fibers over a fixed torus orbit in the base are isomorphic. Hence, studying the fibers is again a combinatorial question and Sage implements additional methods to study such fibrations that are not available otherwise (however, note that you can always *factor()* to pick out the part that is dominant over the image or its closure).

For example, consider the blow-up restricted to one of the two coordinate charts of $O_{\mathbb{P}^1}(2)$

```
sage: O2_P1_chart = ToricVariety(Fan([O2_P1.fan().generating_cones()[0]]))
sage: single_chart = O2_P1_chart.hom(identity_matrix(2), A2_Z2)
sage: single_chart.is_dominant()
True
sage: single_chart.is_surjective()
False

sage: fiber = single_chart.fiber_generic();  fiber
(0-d affine toric variety, 1)
sage: fiber[0].embedding_morphism().as_polynomial_map()
Scheme morphism:
  From: 0-d affine toric variety
  To:   2-d affine toric variety
  Defn: Defined on coordinates by sending [] to [1 : 1]
```

```
>>> from sage.all import *
>>> O2_P1_chart = ToricVariety(Fan([O2_P1.fan().generating_cones()[Integer(0)]]))
>>> single_chart = O2_P1_chart.hom(identity_matrix(Integer(2)), A2_Z2)
>>> single_chart.is_dominant()
True
>>> single_chart.is_surjective()
False

>>> fiber = single_chart.fiber_generic();  fiber
(0-d affine toric variety, 1)
>>> fiber[Integer(0)].embedding_morphism().as_polynomial_map()
Scheme morphism:
  From: 0-d affine toric variety
  To:   2-d affine toric variety
  Defn: Defined on coordinates by sending [] to [1 : 1]
```

The fibers are labeled by torus orbits in the base, that is, cones of the codomain fan. In this case, the fibers over lower-dimensional torus orbits are:

```
sage: A2_Z2_cones = flatten(A2_Z2.fan().cones())
sage: table([('cone', 'dim')] +
....:       [(cone.ambient_ray_indices(), single_chart.fiber_dimension(cone))
....:        for cone in A2_Z2_cones], header_row=True)
    cone     dim
  ├──────────┼─────┤
    ()       0
    (0,)     0
    (1,)     -1
    (0, 1)   1
```

```
>>> from sage.all import *
>>> A2_Z2_cones = flatten(A2_Z2.fan().cones())
>>> table([('cone', 'dim')] +
...       [(cone.ambient_ray_indices(), single_chart.fiber_dimension(cone))
...        for cone in A2_Z2_cones], header_row=True)
    cone     dim
  ├────────┼─────┤
    ()       0
    (0,)     0
    (1,)     -1
    (0, 1)   1
```

Lets look closer at the one-dimensional fiber. Although not the case in this example, connected components of fibers over higher-dimensional cones (corresponding to lower-dimensional torus orbits) of the base are often not irreducible. The irreducible components are labeled by the `primitive_preimage_cones()`, which are certain cones of the domain fan that map to the cone in the base that defines the torus orbit:

```
sage: table([('base cone', 'primitive preimage cones')] +
....:       [(cone.ambient_ray_indices(),
....:         single_chart.fan_morphism().primitive_preimage_cones(cone))
....:        for cone in A2_Z2_cones], header_row=True)
    base cone   primitive preimage cones
  ├──────────┼──────────────────────────────────────────────────────────┤
    ()         (0-d cone of Rational polyhedral fan in 2-d lattice N,)
    (0,)       (1-d cone of Rational polyhedral fan in 2-d lattice N,)
    (1,)       ()
    (0, 1)     (1-d cone of Rational polyhedral fan in 2-d lattice N,)
```

```
>>> from sage.all import *
>>> table([('base cone', 'primitive preimage cones')] +
...       [(cone.ambient_ray_indices(),
...         single_chart.fan_morphism().primitive_preimage_cones(cone))
...        for cone in A2_Z2_cones], header_row=True)
    base cone   primitive preimage cones
  ├──────────┼──────────────────────────────────────────────────────────┤
    ()         (0-d cone of Rational polyhedral fan in 2-d lattice N,)
    (0,)       (1-d cone of Rational polyhedral fan in 2-d lattice N,)
    (1,)       ()
    (0, 1)     (1-d cone of Rational polyhedral fan in 2-d lattice N,)
```

The fiber over the trivial cone is the generic fiber that we have already encountered. The interesting fiber is the one over the 2-dimensional cone, which represents the exceptional set of the blow-up in this single coordinate chart. Lets investigate further:

```
sage: fm = single_chart.fan_morphism()
sage: exceptional_cones = fm.primitive_preimage_cones(A2_Z2.fan(2)[0])
sage: exceptional_set = single_chart.fiber_component(exceptional_cones[0])
sage: exceptional_set
1-d affine toric variety
sage: exceptional_set.embedding_morphism().as_polynomial_map()
Scheme morphism:
  From: 1-d affine toric variety
  To:   2-d affine toric variety
```

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```
  Defn: Defined on coordinates by sending [z0] to [z0 : 0]
```

```
>>> from sage.all import *
>>> fm = single_chart.fan_morphism()
>>> exceptional_cones = fm.primitive_preimage_cones(A2_Z2.fan(Integer(2))[Integer(0)])
>>> exceptional_set = single_chart.fiber_component(exceptional_cones[Integer(0)])
>>> exceptional_set
1-d affine toric variety
>>> exceptional_set.embedding_morphism().as_polynomial_map()
Scheme morphism:
  From: 1-d affine toric variety
  To:   2-d affine toric variety
  Defn: Defined on coordinates by sending [z0] to [z0 : 0]
```

So we see that the fiber over this point is an affine line. Together with another affine line in the other coordinate patch, this covers the exceptional $\mathbb{P}^1$ of the blowup $O_{\mathbb{P}^1}(2) \to \mathbf{C}^2/\mathbf{Z}_2$.

Here is an example with higher dimensional varieties involved:

```
sage: A3 = toric_varieties.A(3)
sage: P3 = toric_varieties.P(3)
sage: m = matrix([(2,0,0), (1,1,0), (3,1,0)])
sage: phi = A3.hom(m, P3)
sage: phi.as_polynomial_map()
Scheme morphism:
  From: 3-d affine toric variety
  To:   3-d CPR-Fano toric variety covered by 4 affine patches
  Defn: Defined on coordinates by sending [z0 : z1 : z2] to
        [z0^2*z1*z2^3 : z1*z2 : 1 : 1]
sage: phi.fiber_generic()
Traceback (most recent call last):
...
AttributeError: 'SchemeMorphism_fan_toric_variety' object
has no attribute 'fiber_generic'...
```

```
>>> from sage.all import *
>>> A3 = toric_varieties.A(Integer(3))
>>> P3 = toric_varieties.P(Integer(3))
>>> m = matrix([(Integer(2),Integer(0),Integer(0)), (Integer(1),Integer(1),
↪Integer(0)), (Integer(3),Integer(1),Integer(0))])
>>> phi = A3.hom(m, P3)
>>> phi.as_polynomial_map()
Scheme morphism:
  From: 3-d affine toric variety
  To:   3-d CPR-Fano toric variety covered by 4 affine patches
  Defn: Defined on coordinates by sending [z0 : z1 : z2] to
        [z0^2*z1*z2^3 : z1*z2 : 1 : 1]
>>> phi.fiber_generic()
Traceback (most recent call last):
...
AttributeError: 'SchemeMorphism_fan_toric_variety' object
has no attribute 'fiber_generic'...
```

Let's use factorization mentioned above:

```
sage: phi_i, phi_b, phi_s = phi.factor()
```

```
>>> from sage.all import *
>>> phi_i, phi_b, phi_s = phi.factor()
```

It is possible to study fibers of the last two morphisms or their composition:

```
sage: phi_d = phi_b * phi_s
sage: phi_d
Scheme morphism:
  From: 3-d affine toric variety
  To:   2-d toric variety covered by 3 affine patches
  Defn: Defined by sending Rational polyhedral fan in 3-d lattice N to
        Rational polyhedral fan in Sublattice <N(1, 0, 0), N(0, 1, 0)>.
sage: phi_d.as_polynomial_map()
Scheme morphism:
  From: 3-d affine toric variety
  To:   2-d toric variety covered by 3 affine patches
  Defn: Defined on coordinates by sending [z0 : z1 : z2] to
        [1 : z1*z2 : z0^2*z1*z2^3]
sage: phi_d.codomain().fan().rays()
N(-1, -1, 0),
N( 0,  1, 0),
N( 1,  0, 0)
in Sublattice <N(1, 0, 0), N(0, 1, 0)>
sage: for c in phi_d.codomain().fan():
....:     c.ambient_ray_indices()
(0, 1)
(0, 2)
(1, 2)
```

```
>>> from sage.all import *
>>> phi_d = phi_b * phi_s
>>> phi_d
Scheme morphism:
  From: 3-d affine toric variety
  To:   2-d toric variety covered by 3 affine patches
  Defn: Defined by sending Rational polyhedral fan in 3-d lattice N to
        Rational polyhedral fan in Sublattice <N(1, 0, 0), N(0, 1, 0)>.
>>> phi_d.as_polynomial_map()
Scheme morphism:
  From: 3-d affine toric variety
  To:   2-d toric variety covered by 3 affine patches
  Defn: Defined on coordinates by sending [z0 : z1 : z2] to
        [1 : z1*z2 : z0^2*z1*z2^3]
>>> phi_d.codomain().fan().rays()
N(-1, -1, 0),
N( 0,  1, 0),
N( 1,  0, 0)
in Sublattice <N(1, 0, 0), N(0, 1, 0)>
>>> for c in phi_d.codomain().fan():
```

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```
...       c.ambient_ray_indices()
(0, 1)
(0, 2)
(1, 2)
```

We see that codomain fan of this morphism is a projective plane, which can be verified by

```
sage: phi_d.codomain().fan().is_isomorphic(toric_varieties.P2().fan()) # known bug
True
```

```
>>> from sage.all import *
>>> phi_d.codomain().fan().is_isomorphic(toric_varieties.P2().fan()) # known bug
True
```

(Unfortunately it cannot be verified correctly until Issue #16012 is fixed.)

We now have access to fiber methods:

```
sage: fiber = phi_d.fiber_generic()
sage: fiber
(1-d affine toric variety, 2)
sage: fiber[0].embedding_morphism()
Scheme morphism:
  From: 1-d affine toric variety
  To:   3-d affine toric variety
  Defn: Defined by sending
        Rational polyhedral fan in Sublattice <N(1, 1, -1)> to
        Rational polyhedral fan in 3-d lattice N.
sage: fiber[0].embedding_morphism().as_polynomial_map()
Traceback (most recent call last):
...
NotImplementedError: polynomial representations for
fans with virtual rays are not implemented yet
sage: fiber[0].fan().rays()
Empty collection
in Sublattice <N(1, 1, -1)>
```

```
>>> from sage.all import *
>>> fiber = phi_d.fiber_generic()
>>> fiber
(1-d affine toric variety, 2)
>>> fiber[Integer(0)].embedding_morphism()
Scheme morphism:
  From: 1-d affine toric variety
  To:   3-d affine toric variety
  Defn: Defined by sending
        Rational polyhedral fan in Sublattice <N(1, 1, -1)> to
        Rational polyhedral fan in 3-d lattice N.
>>> fiber[Integer(0)].embedding_morphism().as_polynomial_map()
Traceback (most recent call last):
...
NotImplementedError: polynomial representations for
```

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```
fans with virtual rays are not implemented yet
>>> fiber[Integer(0)].fan().rays()
Empty collection
in Sublattice <N(1, 1, -1)>
```

We see that generic fibers of this morphism consist of 2 one-dimensional tori each. To see what happens over boundary points we can look at fiber components corresponding to the cones of the domain fan:

```
sage: fm = phi_d.fan_morphism()
sage: for c in flatten(phi_d.domain().fan().cones()):
....:     fc, m = phi_d.fiber_component(c, multiplicity=True)
....:     print("{} |-> {} ({} rays, multiplicity {}) over {}".format(
....:       c.ambient_ray_indices(), fc, fc.fan().nrays(),
....:       m, fm.image_cone(c).ambient_ray_indices()))
() |-> 1-d affine toric variety (0 rays, multiplicity 2) over ()
(0,) |-> 1-d affine toric variety (0 rays, multiplicity 1) over (2,)
(1,) |-> 2-d affine toric variety (2 rays, multiplicity 1) over (1, 2)
(2,) |-> 2-d affine toric variety (2 rays, multiplicity 1) over (1, 2)
(0, 1) |-> 1-d affine toric variety (1 rays, multiplicity 1) over (1, 2)
(1, 2) |-> 1-d affine toric variety (1 rays, multiplicity 1) over (1, 2)
(0, 2) |-> 1-d affine toric variety (1 rays, multiplicity 1) over (1, 2)
(0, 1, 2) |-> 0-d affine toric variety (0 rays, multiplicity 1) over (1, 2)
```

```
>>> from sage.all import *
>>> fm = phi_d.fan_morphism()
>>> for c in flatten(phi_d.domain().fan().cones()):
...     fc, m = phi_d.fiber_component(c, multiplicity=True)
...     print("{} |-> {} ({} rays, multiplicity {}) over {}".format(
...       c.ambient_ray_indices(), fc, fc.fan().nrays(),
...       m, fm.image_cone(c).ambient_ray_indices()))
() |-> 1-d affine toric variety (0 rays, multiplicity 2) over ()
(0,) |-> 1-d affine toric variety (0 rays, multiplicity 1) over (2,)
(1,) |-> 2-d affine toric variety (2 rays, multiplicity 1) over (1, 2)
(2,) |-> 2-d affine toric variety (2 rays, multiplicity 1) over (1, 2)
(0, 1) |-> 1-d affine toric variety (1 rays, multiplicity 1) over (1, 2)
(1, 2) |-> 1-d affine toric variety (1 rays, multiplicity 1) over (1, 2)
(0, 2) |-> 1-d affine toric variety (1 rays, multiplicity 1) over (1, 2)
(0, 1, 2) |-> 0-d affine toric variety (0 rays, multiplicity 1) over (1, 2)
```

Now we see that over one of the coordinate lines of the projective plane we also have one-dimensional tori (but only one in each fiber), while over one of the points fixed by torus action we have two affine planes intersecting along an affine line. An alternative perspective is provided by cones of the codomain fan:

```
sage: for c in flatten(phi_d.codomain().fan().cones()):
....:     print("{} connected components over {}, each with {} irreducible components.
↪".format(
....:       fm.index(c), c.ambient_ray_indices(),
....:       len(fm.primitive_preimage_cones(c))))
2 connected components over (), each with 1 irreducible components.
None connected components over (0,), each with 0 irreducible components.
None connected components over (1,), each with 0 irreducible components.
1 connected components over (2,), each with 1 irreducible components.
```

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```
None connected components over (0, 1), each with 0 irreducible components.
None connected components over (0, 2), each with 0 irreducible components.
1 connected components over (1, 2), each with 2 irreducible components.
```

```
>>> from sage.all import *
>>> for c in flatten(phi_d.codomain().fan().cones()):
...     print("{} connected components over {}, each with {} irreducible components.".
↪format(
...       fm.index(c), c.ambient_ray_indices(),
...       len(fm.primitive_preimage_cones(c))))
2 connected components over (), each with 1 irreducible components.
None connected components over (0,), each with 0 irreducible components.
None connected components over (1,), each with 0 irreducible components.
1 connected components over (2,), each with 1 irreducible components.
None connected components over (0, 1), each with 0 irreducible components.
None connected components over (0, 2), each with 0 irreducible components.
1 connected components over (1, 2), each with 2 irreducible components.
```

class sage.schemes.toric.morphism.**SchemeMorphism_fan_fiber_component_toric_variety**(*toric_morphism*, *defining_cone*)

Bases: *SchemeMorphism*

The embedding of a fiber component of a toric morphism.

Note that the embedding map of a fiber component of a toric morphism is itself not a toric morphism!

INPUT:

- `toric_morphism` – a toric morphism; the toric morphism whose fiber component we are describing
- `defining_cone` – a cone of the fan of the domain of `toric_morphism`; see *fiber_component()* for details

EXAMPLES:

```
sage: polytope = Polyhedron(
....:     [(-3,0,-1,-1),(-1,2,-1,-1),(0,-1,0,0),(0,0,0,1),(0,0,1,0),
....:      (0,1,0,0),(0,2,-1,-1),(1,0,0,0),(2,0,-1,-1)])
sage: coarse_fan = FaceFan(polytope, lattice=ToricLattice(4))
sage: P2 = toric_varieties.P2()
sage: proj24 = matrix([[0,0],[1,0],[0,0],[0,1]])
sage: fm = FanMorphism(proj24, coarse_fan, P2.fan(), subdivide=True)
sage: fibration = ToricVariety(fm.domain_fan()).hom(fm, P2)
sage: ffm = fibration.fan_morphism()
sage: primitive_cones = ffm.primitive_preimage_cones(P2.fan(1)[0])
sage: primitive_cone = primitive_cones[0]
sage: fiber_component = fibration.fiber_component(primitive_cone)
sage: fiber_component
2-d toric variety covered by 4 affine patches
sage: fiber_component.embedding_morphism()
Scheme morphism:
  From: 2-d toric variety covered by 4 affine patches
  To:   4-d toric variety covered by 23 affine patches
```

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```
  Defn: Defined by embedding a fiber component corresponding to
        1-d cone of Rational polyhedral fan in 4-d lattice N.
sage: fiber_component.embedding_morphism().as_polynomial_map()
Scheme morphism:
  From: 2-d toric variety covered by 4 affine patches
  To:   4-d toric variety covered by 23 affine patches
  Defn: Defined on coordinates by sending [z0 : z1 : z2 : z3] to
        [1 : 1 : 1 : 1 : z2 : 0 : 1 : z3 : 1 : 1 : 1 : z1 : z0 : 1 : 1]
sage: type(fiber_component.embedding_morphism())
<class 'sage.schemes.toric.morphism.SchemeMorphism_fan_fiber_component_toric_
↪variety'>
```

```
>>> from sage.all import *
>>> polytope = Polyhedron(
...     [(-Integer(3),Integer(0),-Integer(1),-Integer(1)),(-Integer(1),Integer(2),
↪-Integer(1),-Integer(1)),(Integer(0),-Integer(1),Integer(0),Integer(0)),
↪(Integer(0),Integer(0),Integer(0),Integer(1)),(Integer(0),Integer(0),Integer(1),
↪Integer(0)),
...      (Integer(0),Integer(1),Integer(0),Integer(0)),(Integer(0),Integer(2),-
↪Integer(1),-Integer(1)),(Integer(1),Integer(0),Integer(0),Integer(0)),
↪(Integer(2),Integer(0),-Integer(1),-Integer(1))])
>>> coarse_fan = FaceFan(polytope, lattice=ToricLattice(Integer(4)))
>>> P2 = toric_varieties.P2()
>>> proj24 = matrix([[Integer(0),Integer(0)],[Integer(1),Integer(0)],[Integer(0),
↪Integer(0)],[Integer(0),Integer(1)]])
>>> fm = FanMorphism(proj24, coarse_fan, P2.fan(), subdivide=True)
>>> fibration = ToricVariety(fm.domain_fan()).hom(fm, P2)
>>> ffm = fibration.fan_morphism()
>>> primitive_cones = ffm.primitive_preimage_cones(P2.fan(Integer(1))[Integer(0)])
>>> primitive_cone = primitive_cones[Integer(0)]
>>> fiber_component = fibration.fiber_component(primitive_cone)
>>> fiber_component
2-d toric variety covered by 4 affine patches
>>> fiber_component.embedding_morphism()
Scheme morphism:
  From: 2-d toric variety covered by 4 affine patches
  To:   4-d toric variety covered by 23 affine patches
  Defn: Defined by embedding a fiber component corresponding to
        1-d cone of Rational polyhedral fan in 4-d lattice N.
>>> fiber_component.embedding_morphism().as_polynomial_map()
Scheme morphism:
  From: 2-d toric variety covered by 4 affine patches
  To:   4-d toric variety covered by 23 affine patches
  Defn: Defined on coordinates by sending [z0 : z1 : z2 : z3] to
        [1 : 1 : 1 : 1 : z2 : 0 : 1 : z3 : 1 : 1 : 1 : z1 : z0 : 1 : 1]
>>> type(fiber_component.embedding_morphism())
<class 'sage.schemes.toric.morphism.SchemeMorphism_fan_fiber_component_toric_
↪variety'>
```

as_polynomial_map()

Express the embedding morphism via homogeneous polynomials.

OUTPUT: a *SchemeMorphism_polynomial_toric_variety*

This raises a `ValueError` if the morphism cannot be written in terms of homogeneous polynomials.

EXAMPLES:

```
sage: polytope = Polyhedron(
....:     [(-3,0,-1,-1),(-1,2,-1,-1),(0,-1,0,0),(0,0,0,1),(0,0,1,0),
....:      (0,1,0,0),(0,2,-1,-1),(1,0,0,0),(2,0,-1,-1)])
sage: coarse_fan = FaceFan(polytope, lattice=ToricLattice(4))
sage: P2 = toric_varieties.P2()
sage: proj24 = matrix([[0,0], [1,0], [0,0], [0,1]])
sage: fm = FanMorphism(proj24, coarse_fan, P2.fan(), subdivide=True)
sage: fibration = ToricVariety(fm.domain_fan()).hom(fm, P2)

sage: primitive_cone = Cone([(0, 1, 0, 0)])
sage: f = fibration.fiber_component(primitive_cone).embedding_morphism()
sage: f.as_polynomial_map()
Scheme morphism:
  From: 2-d toric variety covered by 4 affine patches
  To:   4-d toric variety covered by 23 affine patches
  Defn: Defined on coordinates by sending [z0 : z1 : z2 : z3] to
        [1 : 1 : 1 : 1 : z2 : 0 : 1 : z3 : 1 : 1 : 1 : z1 : z0 : 1 : 1]

sage: primitive_cone = Cone([(-1, 2, -1, 0)])
sage: f = fibration.fiber_component(primitive_cone).embedding_morphism()
sage: f.as_polynomial_map()
Traceback (most recent call last):
...
ValueError: the morphism cannot be written using homogeneous polynomials
```

```
>>> from sage.all import *
>>> polytope = Polyhedron(
...     [(-Integer(3),Integer(0),-Integer(1),-Integer(1)),(-Integer(1),
↪Integer(2),-Integer(1),-Integer(1)),(Integer(0),-Integer(1),Integer(0),
↪Integer(0)),(Integer(0),Integer(0),Integer(0),Integer(1)),(Integer(0),
↪Integer(0),Integer(1),Integer(0)),
...      (Integer(0),Integer(1),Integer(0),Integer(0)),(Integer(0),Integer(2),
↪-Integer(1),-Integer(1)),(Integer(1),Integer(0),Integer(0),Integer(0)),
↪(Integer(2),Integer(0),-Integer(1),-Integer(1))])
>>> coarse_fan = FaceFan(polytope, lattice=ToricLattice(Integer(4)))
>>> P2 = toric_varieties.P2()
>>> proj24 = matrix([[Integer(0),Integer(0)], [Integer(1),Integer(0)],␣
↪[Integer(0),Integer(0)], [Integer(0),Integer(1)]])
>>> fm = FanMorphism(proj24, coarse_fan, P2.fan(), subdivide=True)
>>> fibration = ToricVariety(fm.domain_fan()).hom(fm, P2)

>>> primitive_cone = Cone([(Integer(0), Integer(1), Integer(0), Integer(0))])
>>> f = fibration.fiber_component(primitive_cone).embedding_morphism()
>>> f.as_polynomial_map()
Scheme morphism:
  From: 2-d toric variety covered by 4 affine patches
  To:   4-d toric variety covered by 23 affine patches
  Defn: Defined on coordinates by sending [z0 : z1 : z2 : z3] to
        [1 : 1 : 1 : 1 : z2 : 0 : 1 : z3 : 1 : 1 : 1 : z1 : z0 : 1 : 1]
```

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```
>>> primitive_cone = Cone([(-Integer(1), Integer(2), -Integer(1),␣
↪Integer(0))])
>>> f = fibration.fiber_component(primitive_cone).embedding_morphism()
>>> f.as_polynomial_map()
Traceback (most recent call last):
...
ValueError: the morphism cannot be written using homogeneous polynomials
```

base_cone()

Return the base cone σ.

The fiber is constant over the base orbit closure $V(\sigma)$.

OUTPUT: a cone of the base of the toric fibration

EXAMPLES:

```
sage: P1xP1 = toric_varieties.P1xP1()
sage: P1 = toric_varieties.P1()
sage: fc = P1xP1.hom(matrix([[1],[0]]), P1).fiber_component(Cone([(1,0)]))
sage: f = fc.embedding_morphism()
sage: f.defining_cone().rays()
N(1, 0)
in 2-d lattice N
sage: f.base_cone().rays()
N(1)
in 1-d lattice N
```

```
>>> from sage.all import *
>>> P1xP1 = toric_varieties.P1xP1()
>>> P1 = toric_varieties.P1()
>>> fc = P1xP1.hom(matrix([[Integer(1)],[Integer(0)]]), P1).fiber_
↪component(Cone([(Integer(1),Integer(0))]))
>>> f = fc.embedding_morphism()
>>> f.defining_cone().rays()
N(1, 0)
in 2-d lattice N
>>> f.base_cone().rays()
N(1)
in 1-d lattice N
```

defining_cone()

Return the cone corresponding to the fiber torus orbit.

OUTPUT: a cone of the fan of the total space of the toric fibration

EXAMPLES:

```
sage: P1xP1 = toric_varieties.P1xP1()
sage: P1 = toric_varieties.P1()
sage: fc = P1xP1.hom(matrix([[1],[0]]), P1).fiber_component(Cone([(1,0)]))
sage: f = fc.embedding_morphism()
sage: f.defining_cone().rays()
N(1, 0)
```

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```
in 2-d lattice N
sage: f.base_cone().rays()
N(1)
in 1-d lattice N
```

```
>>> from sage.all import *
>>> P1xP1 = toric_varieties.P1xP1()
>>> P1 = toric_varieties.P1()
>>> fc = P1xP1.hom(matrix([[Integer(1)],[Integer(0)]]), P1).fiber_
↪component(Cone([(Integer(1),Integer(0))]))
>>> f = fc.embedding_morphism()
>>> f.defining_cone().rays()
N(1, 0)
in 2-d lattice N
>>> f.base_cone().rays()
N(1)
in 1-d lattice N
```

pullback_divisor(*divisor*)

Pull back a toric divisor.

INPUT:

- `divisor` – a torus-invariant $\mathbf{Q}$-Cartier divisor on the codomain of the embedding map

OUTPUT:

A divisor on the domain of the embedding map (irreducible component of a fiber of a toric morphism) that is isomorphic to the pull-back divisor $f^*(D)$ but with possibly different linearization.

EXAMPLES:

```
sage: A1 = toric_varieties.A1()
sage: fan = Fan([(0,1,2)], [(1,1,0),(1,0,1),(1,-1,-1)]).subdivide(new_
↪rays=[(1,0,0)])
sage: f = ToricVariety(fan).hom(matrix([[1],[0],[0]]), A1)
sage: D = f.domain().divisor([1,1,3,4]); D
V(z0) + V(z1) + 3*V(z2) + 4*V(z3)
sage: fc = f.fiber_component(Cone([(1,1,0)]))
sage: fc.embedding_morphism().pullback_divisor(D)
4*V(z0) + V(z1) + 4*V(z2)
sage: fc = f.fiber_component(Cone([(1,0,0)]))
sage: fc.embedding_morphism().pullback_divisor(D)
-V(z0) - 3*V(z1) - 3*V(z2)
```

```
>>> from sage.all import *
>>> A1 = toric_varieties.A1()
>>> fan = Fan([(Integer(0),Integer(1),Integer(2))], [(Integer(1),Integer(1),
↪Integer(0)),(Integer(1),Integer(0),Integer(1)),(Integer(1),-Integer(1),-
↪Integer(1))]).subdivide(new_rays=[(Integer(1),Integer(0),Integer(0))])
>>> f = ToricVariety(fan).hom(matrix([[Integer(1)],[Integer(0)],
↪[Integer(0)]]), A1)
>>> D = f.domain().divisor([Integer(1),Integer(1),Integer(3),Integer(4)]); D
V(z0) + V(z1) + 3*V(z2) + 4*V(z3)
```

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```
>>> fc = f.fiber_component(Cone([(Integer(1),Integer(1),Integer(0))]))
>>> fc.embedding_morphism().pullback_divisor(D)
4*V(z0) + V(z1) + 4*V(z2)
>>> fc = f.fiber_component(Cone([(Integer(1),Integer(0),Integer(0))]))
>>> fc.embedding_morphism().pullback_divisor(D)
-V(z0) - 3*V(z1) - 3*V(z2)
```

class sage.schemes.toric.morphism.**SchemeMorphism_fan_toric_variety**(*parent*, *fan_morphism*, *check=True*)

Bases: *SchemeMorphism*, Morphism

Construct a morphism determined by a fan morphism.

Warning

You should not create objects of this class directly. Use the `hom()` method of *toric varieties* instead.

INPUT:

- `parent` – Hom-set whose domain and codomain are toric varieties
- `fan_morphism` – a morphism of fans whose domain and codomain fans equal the fans of the domain and codomain in the `parent` Hom-set.
- `check` – boolean (default: `True`); whether to check the input for consistency

Warning

A fibration is a dominant morphism; if you are interested in these then you have to make sure that your fan morphism is dominant. For example, this can be achieved by *factoring the morphism*. See *SchemeMorphism_fan_toric_variety_dominant* for additional functionality for fibrations.

OUTPUT: a *SchemeMorphism_fan_toric_variety*

EXAMPLES:

```
sage: P1xP1 = toric_varieties.P1xP1()
sage: P1 = toric_varieties.P1()
sage: f = P1.hom(matrix([[1,0]]), P1xP1);  f
Scheme morphism:
  From: 1-d CPR-Fano toric variety covered by 2 affine patches
  To:   2-d CPR-Fano toric variety covered by 4 affine patches
  Defn: Defined by sending Rational polyhedral fan in 1-d lattice N
        to Rational polyhedral fan in 2-d lattice N.
sage: type(f)
<class 'sage.schemes.toric.morphism.SchemeMorphism_fan_toric_variety'>
```

```
>>> from sage.all import *
>>> P1xP1 = toric_varieties.P1xP1()
>>> P1 = toric_varieties.P1()
>>> f = P1.hom(matrix([[Integer(1),Integer(0)]]), P1xP1);  f
Scheme morphism:
```

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```
  From: 1-d CPR-Fano toric variety covered by 2 affine patches
  To:   2-d CPR-Fano toric variety covered by 4 affine patches
  Defn: Defined by sending Rational polyhedral fan in 1-d lattice N
        to Rational polyhedral fan in 2-d lattice N.
>>> type(f)
<class 'sage.schemes.toric.morphism.SchemeMorphism_fan_toric_variety'>
```

Slightly more explicit construction:

```
sage: P1xP1 = toric_varieties.P1xP1()
sage: P1 = toric_varieties.P1()
sage: hom_set = P1xP1.Hom(P1)
sage: fm = FanMorphism(matrix(ZZ, [[1],[0]]), P1xP1.fan(), P1.fan())
sage: hom_set(fm)
Scheme morphism:
  From: 2-d CPR-Fano toric variety covered by 4 affine patches
  To:   1-d CPR-Fano toric variety covered by 2 affine patches
  Defn: Defined by sending Rational polyhedral fan in 2-d lattice N
        to Rational polyhedral fan in 1-d lattice N.

sage: P1xP1.hom(fm, P1)
Scheme morphism:
  From: 2-d CPR-Fano toric variety covered by 4 affine patches
  To:   1-d CPR-Fano toric variety covered by 2 affine patches
  Defn: Defined by sending Rational polyhedral fan in 2-d lattice N
        to Rational polyhedral fan in 1-d lattice N.
```

```
>>> from sage.all import *
>>> P1xP1 = toric_varieties.P1xP1()
>>> P1 = toric_varieties.P1()
>>> hom_set = P1xP1.Hom(P1)
>>> fm = FanMorphism(matrix(ZZ, [[Integer(1)],[Integer(0)]]), P1xP1.fan(), P1.
↪fan())
>>> hom_set(fm)
Scheme morphism:
  From: 2-d CPR-Fano toric variety covered by 4 affine patches
  To:   1-d CPR-Fano toric variety covered by 2 affine patches
  Defn: Defined by sending Rational polyhedral fan in 2-d lattice N
        to Rational polyhedral fan in 1-d lattice N.

>>> P1xP1.hom(fm, P1)
Scheme morphism:
  From: 2-d CPR-Fano toric variety covered by 4 affine patches
  To:   1-d CPR-Fano toric variety covered by 2 affine patches
  Defn: Defined by sending Rational polyhedral fan in 2-d lattice N
        to Rational polyhedral fan in 1-d lattice N.
```

as_polynomial_map()

Express the morphism via homogeneous polynomials.

OUTPUT: a *SchemeMorphism_polynomial_toric_variety*

This raises a `TypeError` if the morphism cannot be written in terms of homogeneous polynomials.

EXAMPLES:

```
sage: A1 = toric_varieties.A1()
sage: square = A1.hom(matrix([[2]]), A1)
sage: square.as_polynomial_map()
Scheme endomorphism of 1-d affine toric variety
  Defn: Defined on coordinates by sending [z] to [z^2]

sage: P1 = toric_varieties.P1()
sage: patch = A1.hom(matrix([[1]]), P1)
sage: patch.as_polynomial_map()
Scheme morphism:
  From: 1-d affine toric variety
  To:   1-d CPR-Fano toric variety covered by 2 affine patches
  Defn: Defined on coordinates by sending [z] to [z : 1]
```

```
>>> from sage.all import *
>>> A1 = toric_varieties.A1()
>>> square = A1.hom(matrix([[Integer(2)]]), A1)
>>> square.as_polynomial_map()
Scheme endomorphism of 1-d affine toric variety
  Defn: Defined on coordinates by sending [z] to [z^2]

>>> P1 = toric_varieties.P1()
>>> patch = A1.hom(matrix([[Integer(1)]]), P1)
>>> patch.as_polynomial_map()
Scheme morphism:
  From: 1-d affine toric variety
  To:   1-d CPR-Fano toric variety covered by 2 affine patches
  Defn: Defined on coordinates by sending [z] to [z : 1]
```

factor()

Factor `self` into injective * birational * surjective morphisms.

OUTPUT:

- a triple of toric morphisms (ϕ_i, ϕ_b, ϕ_s), such that ϕ_s is surjective, ϕ_b is birational, ϕ_i is injective, and `self` is equal to $\phi_i \circ \phi_b \circ \phi_s$.

The intermediate varieties are universal in the following sense. Let `self` map X to X' and let X_s, X_i sit in between, that is,

$$X \twoheadrightarrow X_s \to X_i \hookrightarrow X'.$$

Then any toric morphism from X coinciding with `self` on the maximal torus factors through X_s and any toric morphism into X' coinciding with `self` on the maximal torus factors through X_i. In particular, X_i is the closure of the image of `self` in X'.

See `factor()` for a description of the toric algorithm.

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":

```
sage: A2 = toric_varieties.A2()
sage: P3 = toric_varieties.P(3)
sage: m = matrix([(2,0,0), (1,1,0)])
sage: phi = A2.hom(m, P3)
sage: phi.as_polynomial_map()
Scheme morphism:
  From: 2-d affine toric variety
  To:   3-d CPR-Fano toric variety covered by 4 affine patches
  Defn: Defined on coordinates by sending [x : y] to
        [x^2*y : y : 1 : 1]

sage: phi.is_surjective(), phi.is_birational(), phi.is_injective()
(False, False, False)
sage: phi_i, phi_b, phi_s = phi.factor()
sage: phi_s.is_surjective(), phi_b.is_birational(), phi_i.is_injective()
(True, True, True)
sage: prod(phi.factor()) == phi
True
```

```
>>> from sage.all import *
>>> A2 = toric_varieties.A2()
>>> P3 = toric_varieties.P(Integer(3))
>>> m = matrix([(Integer(2),Integer(0),Integer(0)), (Integer(1),Integer(1),
↪Integer(0))])
>>> phi = A2.hom(m, P3)
>>> phi.as_polynomial_map()
Scheme morphism:
  From: 2-d affine toric variety
  To:   3-d CPR-Fano toric variety covered by 4 affine patches
  Defn: Defined on coordinates by sending [x : y] to
        [x^2*y : y : 1 : 1]

>>> phi.is_surjective(), phi.is_birational(), phi.is_injective()
(False, False, False)
>>> phi_i, phi_b, phi_s = phi.factor()
>>> phi_s.is_surjective(), phi_b.is_birational(), phi_i.is_injective()
(True, True, True)
>>> prod(phi.factor()) == phi
True
```

Double cover (surjective):

```
sage: phi_s.as_polynomial_map()
Scheme morphism:
  From: 2-d affine toric variety
  To:   2-d affine toric variety
  Defn: Defined on coordinates by sending [x : y] to [x^2 : y]
```

```
>>> from sage.all import *
>>> phi_s.as_polynomial_map()
Scheme morphism:
  From: 2-d affine toric variety
```

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```
  To:   2-d affine toric variety
  Defn: Defined on coordinates by sending [x : y] to [x^2 : y]
```

Blowup chart (birational):

```
sage: phi_b.as_polynomial_map()
Scheme morphism:
  From: 2-d affine toric variety
  To:   2-d toric variety covered by 3 affine patches
  Defn: Defined on coordinates by sending [z0 : z1] to [1 : z1 : z0*z1]
```

```
>>> from sage.all import *
>>> phi_b.as_polynomial_map()
Scheme morphism:
  From: 2-d affine toric variety
  To:   2-d toric variety covered by 3 affine patches
  Defn: Defined on coordinates by sending [z0 : z1] to [1 : z1 : z0*z1]
```

Coordinate plane inclusion (injective):

```
sage: phi_i.as_polynomial_map()
Scheme morphism:
  From: 2-d toric variety covered by 3 affine patches
  To:   3-d CPR-Fano toric variety covered by 4 affine patches
  Defn: Defined on coordinates by sending [z0 : z1 : z2] to [z2 : z1 : z0 :␣
↪z0]
```

```
>>> from sage.all import *
>>> phi_i.as_polynomial_map()
Scheme morphism:
  From: 2-d toric variety covered by 3 affine patches
  To:   3-d CPR-Fano toric variety covered by 4 affine patches
  Defn: Defined on coordinates by sending [z0 : z1 : z2] to [z2 : z1 : z0 :␣
↪z0]
```

fan_morphism()

Return the defining fan morphism.

OUTPUT: a FanMorphism

EXAMPLES:

```
sage: P1xP1 = toric_varieties.P1xP1()
sage: P1 = toric_varieties.P1()
sage: f = P1xP1.hom(matrix([[1],[0]]), P1)
sage: f.fan_morphism()
Fan morphism defined by the matrix
[1]
[0]
Domain fan: Rational polyhedral fan in 2-d lattice N
Codomain fan: Rational polyhedral fan in 1-d lattice N
```

```
>>> from sage.all import *
>>> P1xP1 = toric_varieties.P1xP1()
>>> P1 = toric_varieties.P1()
>>> f = P1xP1.hom(matrix([[Integer(1)],[Integer(0)]]), P1)
>>> f.fan_morphism()
Fan morphism defined by the matrix
[1]
[0]
Domain fan: Rational polyhedral fan in 2-d lattice N
Codomain fan: Rational polyhedral fan in 1-d lattice N
```

is_birational()

Check if `self` is birational.

See `is_birational()` for fan morphisms for a description of the toric algorithm.

OUTPUT: boolean; whether `self` is birational

EXAMPLES:

```
sage: dP8 = toric_varieties.dP8()
sage: P2 = toric_varieties.P2()
sage: dP8.hom(identity_matrix(2), P2).is_birational()
True

sage: X = toric_varieties.A(2)
sage: Y = ToricVariety(Fan([Cone([(1,0), (1,1)])]))
sage: m = identity_matrix(2)
sage: f = Y.hom(m, X)
sage: f.is_birational()
True
```

```
>>> from sage.all import *
>>> dP8 = toric_varieties.dP8()
>>> P2 = toric_varieties.P2()
>>> dP8.hom(identity_matrix(Integer(2)), P2).is_birational()
True

>>> X = toric_varieties.A(Integer(2))
>>> Y = ToricVariety(Fan([Cone([(Integer(1),Integer(0)), (Integer(1),
↪Integer(1))])]))
>>> m = identity_matrix(Integer(2))
>>> f = Y.hom(m, X)
>>> f.is_birational()
True
```

is_bundle()

Check if `self` is a bundle.

See `is_bundle()` for fan morphisms for details.

OUTPUT: `True` if `self` is a bundle, `False` otherwise

EXAMPLES:

```
sage: P1xP1 = toric_varieties.P1xP1()
sage: P1 = toric_varieties.P1()
sage: P1xP1.hom(matrix([[1],[0]]), P1).is_bundle()
True
```

```
>>> from sage.all import *
>>> P1xP1 = toric_varieties.P1xP1()
>>> P1 = toric_varieties.P1()
>>> P1xP1.hom(matrix([[Integer(1)],[Integer(0)]]), P1).is_bundle()
True
```

is_dominant()

Return whether `self` is dominant.

See `is_dominant()` for fan morphisms for a description of the toric algorithm.

OUTPUT: boolean; whether `self` is a dominant scheme morphism

EXAMPLES:

```
sage: P1 = toric_varieties.P1()
sage: A1 = toric_varieties.A1()
sage: phi = A1.hom(identity_matrix(1), P1);  phi
Scheme morphism:
  From: 1-d affine toric variety
  To:   1-d CPR-Fano toric variety covered by 2 affine patches
  Defn: Defined by sending Rational polyhedral fan in 1-d lattice N
        to Rational polyhedral fan in 1-d lattice N.
sage: phi.is_dominant()
True
sage: phi.is_surjective()
False
```

```
>>> from sage.all import *
>>> P1 = toric_varieties.P1()
>>> A1 = toric_varieties.A1()
>>> phi = A1.hom(identity_matrix(Integer(1)), P1);  phi
Scheme morphism:
  From: 1-d affine toric variety
  To:   1-d CPR-Fano toric variety covered by 2 affine patches
  Defn: Defined by sending Rational polyhedral fan in 1-d lattice N
        to Rational polyhedral fan in 1-d lattice N.
>>> phi.is_dominant()
True
>>> phi.is_surjective()
False
```

is_fibration()

Check if `self` is a fibration.

See `is_fibration()` for fan morphisms for details.

OUTPUT: `True` if `self` is a fibration, `False` otherwise

EXAMPLES:

```
sage: P1xP1 = toric_varieties.P1xP1()
sage: P1 = toric_varieties.P1()
sage: P1xP1.hom(matrix([[1],[0]]), P1).is_fibration()
True
```

```
>>> from sage.all import *
>>> P1xP1 = toric_varieties.P1xP1()
>>> P1 = toric_varieties.P1()
>>> P1xP1.hom(matrix([[Integer(1)],[Integer(0)]]), P1).is_fibration()
True
```

is_injective()

Check if `self` is injective.

See `is_injective()` for fan morphisms for a description of the toric algorithm.

OUTPUT: boolean; whether `self` is injective

EXAMPLES:

```
sage: P1xP1 = toric_varieties.P1xP1()
sage: P1 = toric_varieties.P1()
sage: P1xP1.hom(matrix([[1],[0]]), P1).is_injective()
False

sage: X = toric_varieties.A(2)
sage: m = identity_matrix(2)
sage: f = X.hom(m, X)
sage: f.is_injective()
True

sage: Y = ToricVariety(Fan([Cone([(1,0), (1,1)])]))
sage: f = Y.hom(m, X)
sage: f.is_injective()
False
```

```
>>> from sage.all import *
>>> P1xP1 = toric_varieties.P1xP1()
>>> P1 = toric_varieties.P1()
>>> P1xP1.hom(matrix([[Integer(1)],[Integer(0)]]), P1).is_injective()
False

>>> X = toric_varieties.A(Integer(2))
>>> m = identity_matrix(Integer(2))
>>> f = X.hom(m, X)
>>> f.is_injective()
True

>>> Y = ToricVariety(Fan([Cone([(Integer(1),Integer(0)), (Integer(1),
↪Integer(1))])]))
>>> f = Y.hom(m, X)
>>> f.is_injective()
False
```

is_surjective()

Check if `self` is surjective.

See `is_surjective()` for fan morphisms for a description of the toric algorithm.

OUTPUT: boolean; whether `self` is surjective

EXAMPLES:

```
sage: P1xP1 = toric_varieties.P1xP1()
sage: P1 = toric_varieties.P1()
sage: P1xP1.hom(matrix([[1],[0]]), P1).is_surjective()
True

sage: X = toric_varieties.A(2)
sage: m = identity_matrix(2)
sage: f = X.hom(m, X)
sage: f.is_surjective()
True

sage: Y = ToricVariety(Fan([Cone([(1,0), (1,1)])]))
sage: f = Y.hom(m, X)
sage: f.is_surjective()
False
```

```
>>> from sage.all import *
>>> P1xP1 = toric_varieties.P1xP1()
>>> P1 = toric_varieties.P1()
>>> P1xP1.hom(matrix([[Integer(1)],[Integer(0)]]), P1).is_surjective()
True

>>> X = toric_varieties.A(Integer(2))
>>> m = identity_matrix(Integer(2))
>>> f = X.hom(m, X)
>>> f.is_surjective()
True

>>> Y = ToricVariety(Fan([Cone([(Integer(1),Integer(0)), (Integer(1),
↪Integer(1))])]))
>>> f = Y.hom(m, X)
>>> f.is_surjective()
False
```

pullback_divisor(*divisor*)

Pull back a toric divisor.

INPUT:

- `divisor` – a torus-invariant $\mathbf{Q}$-Cartier divisor on the codomain of `self`

OUTPUT: the pull-back divisor $f^*(D)$

EXAMPLES:

```
sage: A2_Z2 = toric_varieties.A2_Z2()
sage: A2 = toric_varieties.A2()
```

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```
sage: f = A2.hom(matrix([[1,0], [1,2]]), A2_Z2)
sage: f.pullback_divisor(A2_Z2.divisor(0))
V(x)

sage: A1 = toric_varieties.A1()
sage: square = A1.hom(matrix([[2]]), A1)
sage: D = A1.divisor(0);  D
V(z)
sage: square.pullback_divisor(D)
2*V(z)
```

```
>>> from sage.all import *
>>> A2_Z2 = toric_varieties.A2_Z2()
>>> A2 = toric_varieties.A2()
>>> f = A2.hom(matrix([[Integer(1),Integer(0)], [Integer(1),Integer(2)]]), A2_
↪Z2)
>>> f.pullback_divisor(A2_Z2.divisor(Integer(0)))
V(x)

>>> A1 = toric_varieties.A1()
>>> square = A1.hom(matrix([[Integer(2)]]), A1)
>>> D = A1.divisor(Integer(0));  D
V(z)
>>> square.pullback_divisor(D)
2*V(z)
```

class sage.schemes.toric.morphism.**SchemeMorphism_fan_toric_variety_dominant**(*parent*, *fan_morphism*, *check=True*)

Bases: *SchemeMorphism_fan_toric_variety*

Construct a morphism determined by a dominant fan morphism.

A dominant morphism is one that is surjective onto a dense subset. In the context of toric morphisms, this means that it is onto the big torus orbit.

Warning

You should not create objects of this class directly. Use the `hom()` method of *toric varieties* instead.

INPUT:

See *SchemeMorphism_fan_toric_variety*. The given fan morphism `must be dominant`.

OUTPUT: a *SchemeMorphism_fan_toric_variety_dominant*

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: dP8 = toric_varieties.dP8()
sage: f = dP8.hom(identity_matrix(2), P2);  f
Scheme morphism:
  From: 2-d CPR-Fano toric variety covered by 4 affine patches
```

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```
  To:   2-d CPR-Fano toric variety covered by 3 affine patches
  Defn: Defined by sending Rational polyhedral fan in 2-d lattice N
        to Rational polyhedral fan in 2-d lattice N.
sage: type(f)
<class 'sage.schemes.toric.morphism.SchemeMorphism_fan_toric_variety_dominant'>
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> dP8 = toric_varieties.dP8()
>>> f = dP8.hom(identity_matrix(Integer(2)), P2);  f
Scheme morphism:
  From: 2-d CPR-Fano toric variety covered by 4 affine patches
  To:   2-d CPR-Fano toric variety covered by 3 affine patches
  Defn: Defined by sending Rational polyhedral fan in 2-d lattice N
        to Rational polyhedral fan in 2-d lattice N.
>>> type(f)
<class 'sage.schemes.toric.morphism.SchemeMorphism_fan_toric_variety_dominant'>
```

fiber_component(*domain_cone*, *multiplicity=False*)

Return a fiber component corresponding to `domain_cone`.

INPUT:

- `domain_cone` – a cone of the domain fan of `self`
- `multiplicity` – boolean (default: `False`); whether to return the number of fiber components corresponding to `domain_cone` as well

OUTPUT:

- either X or a tuple (X, n), where X is a *toric variety* with the embedding morphism into domain of `self` and n is an integer.

Let $\phi : \Sigma \to \Sigma'$ be the `fan morphism` corresponding to `self`. Let $\sigma \in \Sigma$ and $\sigma' \in \Sigma'$ be the `image_cone()` of σ. The fiber over any point of the torus orbit corresponding to σ' consists of n isomorphic connected components with each component being a union of toric varieties intersecting along their torus invariant subvarieties. The latter correspond to `preimage_cones()` of σ' and X is one of the n components corresponding to σ. The irreducible components correspond to `primitive_preimage_cones()`.

EXAMPLES:

```
sage: polytope = LatticePolytope(
....:     [(-3,0,-1,-1),(-1,2,-1,-1),(0,-1,0,0),(0,0,0,1),(0,0,1,0),
....:      (0,1,0,0),(0,2,-1,-1),(1,0,0,0),(2,0,-1,-1)])
sage: coarse_fan = FaceFan(polytope)
sage: P2 = toric_varieties.P2()
sage: proj24 = matrix([[0,0], [1,0], [0,0], [0,1]])
sage: fm = FanMorphism(proj24, coarse_fan, P2.fan(), subdivide=True)
sage: fibration = ToricVariety(fm.domain_fan()).hom(fm, P2)
sage: ffm = fibration.fan_morphism()
sage: primitive_cones = ffm.primitive_preimage_cones(P2.fan(1)[0])
sage: primitive_cone = primitive_cones[0]
sage: fibration.fiber_component(primitive_cone)
2-d toric variety covered by 4 affine patches
sage: fibration.fiber_component(primitive_cone, True)
```

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```
(2-d toric variety covered by 4 affine patches, 1)

sage: for primitive_cone in primitive_cones:
....:     print(fibration.fiber_component(primitive_cone))
2-d toric variety covered by 4 affine patches
2-d toric variety covered by 3 affine patches
2-d toric variety covered by 3 affine patches
```

```
>>> from sage.all import *
>>> polytope = LatticePolytope(
...     [(-Integer(3),Integer(0),-Integer(1),-Integer(1)),(-Integer(1),
↪Integer(2),-Integer(1),-Integer(1)),(Integer(0),-Integer(1),Integer(0),
↪Integer(0)),(Integer(0),Integer(0),Integer(0),Integer(1)),(Integer(0),
↪Integer(0),Integer(1),Integer(0)),
...      (Integer(0),Integer(1),Integer(0),Integer(0)),(Integer(0),Integer(2),
↪-Integer(1),-Integer(1)),(Integer(1),Integer(0),Integer(0),Integer(0)),
↪(Integer(2),Integer(0),-Integer(1),-Integer(1))])
>>> coarse_fan = FaceFan(polytope)
>>> P2 = toric_varieties.P2()
>>> proj24 = matrix([[Integer(0),Integer(0)], [Integer(1),Integer(0)],␣
↪[Integer(0),Integer(0)], [Integer(0),Integer(1)]])
>>> fm = FanMorphism(proj24, coarse_fan, P2.fan(), subdivide=True)
>>> fibration = ToricVariety(fm.domain_fan()).hom(fm, P2)
>>> ffm = fibration.fan_morphism()
>>> primitive_cones = ffm.primitive_preimage_cones(P2.
↪fan(Integer(1))[Integer(0)])
>>> primitive_cone = primitive_cones[Integer(0)]
>>> fibration.fiber_component(primitive_cone)
2-d toric variety covered by 4 affine patches
>>> fibration.fiber_component(primitive_cone, True)
(2-d toric variety covered by 4 affine patches, 1)

>>> for primitive_cone in primitive_cones:
...     print(fibration.fiber_component(primitive_cone))
2-d toric variety covered by 4 affine patches
2-d toric variety covered by 3 affine patches
2-d toric variety covered by 3 affine patches
```

fiber_dimension(*codomain_cone*)

Return the dimension of the fiber over a particular torus orbit in the base.

INPUT:

- `codomain_cone` – a cone σ of the codomain, specifying a torus orbit $O(\sigma)$

OUTPUT:

An integer. The dimension of the fiber over the torus orbit corresponding to `codomain_cone`. If the fiber is the empty set, `-1` is returned. Note that all fibers over this torus orbit are isomorphic, and therefore have the same dimension.

EXAMPLES:

```
sage: P1xP1 = toric_varieties.P1xP1()
sage: P1 = toric_varieties.P1()
sage: f = P1xP1.hom(matrix([[1],[0]]), P1)
sage: f.fiber_dimension(P1.fan(0)[0])
1
sage: f.fiber_dimension(P1.fan(1)[0])
1
sage: f.fiber_dimension(P1.fan(1)[1])
1
```

```
>>> from sage.all import *
>>> P1xP1 = toric_varieties.P1xP1()
>>> P1 = toric_varieties.P1()
>>> f = P1xP1.hom(matrix([[Integer(1)],[Integer(0)]]), P1)
>>> f.fiber_dimension(P1.fan(Integer(0))[Integer(0)])
1
>>> f.fiber_dimension(P1.fan(Integer(1))[Integer(0)])
1
>>> f.fiber_dimension(P1.fan(Integer(1))[Integer(1)])
1
```

Here is a more complicated example that is not a flat fibration:

```
sage: A2_Z2 = toric_varieties.A2_Z2()
sage: O2_P1 = A2_Z2.resolve(new_rays=[(1,1)])
sage: blowup = O2_P1.hom(identity_matrix(2), A2_Z2)
sage: blowup.fiber_dimension(A2_Z2.fan(0)[0])
0
sage: blowup.fiber_dimension(A2_Z2.fan(1)[0])
0
sage: blowup.fiber_dimension(A2_Z2.fan(2)[0])
1
```

```
>>> from sage.all import *
>>> A2_Z2 = toric_varieties.A2_Z2()
>>> O2_P1 = A2_Z2.resolve(new_rays=[(Integer(1),Integer(1))])
>>> blowup = O2_P1.hom(identity_matrix(Integer(2)), A2_Z2)
>>> blowup.fiber_dimension(A2_Z2.fan(Integer(0))[Integer(0)])
0
>>> blowup.fiber_dimension(A2_Z2.fan(Integer(1))[Integer(0)])
0
>>> blowup.fiber_dimension(A2_Z2.fan(Integer(2))[Integer(0)])
1
```

This corresponds to the three different fibers:

```
sage: blowup.fiber_generic()
(0-d affine toric variety, 1)
sage: blowup.fiber_component(Cone([(1,0)]))
0-d affine toric variety
sage: blowup.fiber_component(Cone([(1,1)]))
1-d toric variety covered by 2 affine patches
```

```
>>> from sage.all import *
>>> blowup.fiber_generic()
(0-d affine toric variety, 1)
>>> blowup.fiber_component(Cone([(Integer(1),Integer(0))]))
0-d affine toric variety
>>> blowup.fiber_component(Cone([(Integer(1),Integer(1))]))
1-d toric variety covered by 2 affine patches
```

fiber_generic()

Return the generic fiber.

OUTPUT:

- a tuple (X, n), where X is a *toric variety* with the embedding morphism into domain of `self` and n is an integer.

The fiber over the base point with homogeneous coordinates $[1 : 1 : \cdots : 1]$ consists of n disjoint toric varieties isomorphic to X. Note that fibers of a dominant toric morphism are isomorphic over all points of a fixed torus orbit of its codomain, in particular over all points of the maximal torus, so it makes sense to talk about "the generic" fiber.

The embedding of X is a toric morphism with the `domain_fan()` being the `kernel_fan()` of the defining fan morphism. By contrast, embeddings of fiber components over lower-dimensional torus orbits of the image are not toric morphisms. Use *fiber_component()* for the latter (non-generic) fibers.

EXAMPLES:

```
sage: P1xP1 = toric_varieties.P1xP1()
sage: P1 = toric_varieties.P1()
sage: fiber = P1xP1.hom(matrix([[1],[0]]), P1).fiber_generic()
sage: fiber
(1-d toric variety covered by 2 affine patches, 1)
sage: f = fiber[0].embedding_morphism();  f
Scheme morphism:
  From: 1-d toric variety covered by 2 affine patches
  To:   2-d CPR-Fano toric variety covered by 4 affine patches
  Defn: Defined by sending Rational polyhedral fan in Sublattice <N(0, 1)> to
        Rational polyhedral fan in 2-d lattice N.
sage: f.as_polynomial_map()
Scheme morphism:
  From: 1-d toric variety covered by 2 affine patches
  To:   2-d CPR-Fano toric variety covered by 4 affine patches
  Defn: Defined on coordinates by sending [z0 : z1] to [1 : 1 : z0 : z1]

sage: A1 = toric_varieties.A1()
sage: fan = Fan([(0,1,2)], [(1,1,0), (1,0,1), (1,-1,-1)])
sage: fan = fan.subdivide(new_rays=[(1,0,0)])
sage: f = ToricVariety(fan).hom(matrix([[1],[0],[0]]), A1)
sage: f.fiber_generic()
(2-d affine toric variety, 1)
sage: _[0].fan().generating_cones()
(0-d cone of Rational polyhedral fan in Sublattice <N(0, 1, 0), N(0, 0, 1)>,)
```

```
>>> from sage.all import *
>>> P1xP1 = toric_varieties.P1xP1()
```

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```
>>> P1 = toric_varieties.P1()
>>> fiber = P1xP1.hom(matrix([[Integer(1)],[Integer(0)]]), P1).fiber_generic()
>>> fiber
(1-d toric variety covered by 2 affine patches, 1)
>>> f = fiber[Integer(0)].embedding_morphism();  f
Scheme morphism:
  From: 1-d toric variety covered by 2 affine patches
  To:   2-d CPR-Fano toric variety covered by 4 affine patches
  Defn: Defined by sending Rational polyhedral fan in Sublattice <N(0, 1)> to
        Rational polyhedral fan in 2-d lattice N.
>>> f.as_polynomial_map()
Scheme morphism:
  From: 1-d toric variety covered by 2 affine patches
  To:   2-d CPR-Fano toric variety covered by 4 affine patches
  Defn: Defined on coordinates by sending [z0 : z1] to [1 : 1 : z0 : z1]

>>> A1 = toric_varieties.A1()
>>> fan = Fan([(Integer(0),Integer(1),Integer(2))], [(Integer(1),Integer(1),
↪Integer(0)), (Integer(1),Integer(0),Integer(1)), (Integer(1),-Integer(1),-
↪Integer(1))])
>>> fan = fan.subdivide(new_rays=[(Integer(1),Integer(0),Integer(0))])
>>> f = ToricVariety(fan).hom(matrix([[Integer(1)],[Integer(0)],
↪[Integer(0)]]), A1)
>>> f.fiber_generic()
(2-d affine toric variety, 1)
>>> _[Integer(0)].fan().generating_cones()
(0-d cone of Rational polyhedral fan in Sublattice <N(0, 1, 0), N(0, 0, 1)>,)
```

fiber_graph(*codomain_cone*)

Return the fiber over a given torus orbit in the codomain.

INPUT:

- `codomain_cone` – a cone σ of the codomain, specifying a torus orbit $O(\sigma)$

OUTPUT:

A graph whose nodes are the irreducible components of a connected component of the fiber over a point of $O(\sigma)$. If two irreducible components intersect, the corresponding nodes of the graph are joined by an edge. Note that irreducible components do not have to be of the same dimension.

See also

fiber_component().

EXAMPLES:

```
sage: polytope = Polyhedron(
....:     [(-3,0,-1,-1),(-1,2,-1,-1),(0,-1,0,0),(0,0,0,1),(0,0,1,0),
....:      (0,1,0,0),(0,2,-1,-1),(1,0,0,0),(2,0,-1,-1)])
sage: coarse_fan = FaceFan(polytope, lattice=ToricLattice(4))

sage: P2 = toric_varieties.P2()
```

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```
sage: proj34 = block_matrix(2, 1, [zero_matrix(2,2),
....:                              identity_matrix(2)])
sage: fm = FanMorphism(proj34, coarse_fan, P2.fan(), subdivide=True)
sage: fibration = ToricVariety(fm.domain_fan()).hom(fm, P2)

sage: fibration.fiber_graph(P2.fan(0)[0])
Graph on 1 vertex
sage: for c1 in P2.fan(1):
....:     fibration.fiber_graph(c1)
Graph on 1 vertex
Graph on 1 vertex
Graph on 4 vertices

sage: fibration.fiber_graph(P2.fan(1)[2]).get_vertices()
{0: 2-d toric variety covered by 4 affine patches,
 1: 2-d toric variety covered by 3 affine patches,
 2: 2-d toric variety covered by 3 affine patches,
 3: 2-d toric variety covered by 4 affine patches}

sage: fibration
Scheme morphism:
  From: 4-d toric variety covered by 18 affine patches
  To:   2-d CPR-Fano toric variety covered by 3 affine patches
  Defn: Defined by sending Rational polyhedral fan in 4-d lattice N
        to Rational polyhedral fan in 2-d lattice N.
```

```
>>> from sage.all import *
>>> polytope = Polyhedron(
...     [(-Integer(3),Integer(0),-Integer(1),-Integer(1)),(-Integer(1),
↪Integer(2),-Integer(1),-Integer(1)),(Integer(0),-Integer(1),Integer(0),
↪Integer(0)),(Integer(0),Integer(0),Integer(0),Integer(1)),(Integer(0),
↪Integer(0),Integer(1),Integer(0)),
...      (Integer(0),Integer(1),Integer(0),Integer(0)),(Integer(0),Integer(2),
↪-Integer(1),-Integer(1)),(Integer(1),Integer(0),Integer(0),Integer(0)),
↪(Integer(2),Integer(0),-Integer(1),-Integer(1))])
>>> coarse_fan = FaceFan(polytope, lattice=ToricLattice(Integer(4)))

>>> P2 = toric_varieties.P2()
>>> proj34 = block_matrix(Integer(2), Integer(1), [zero_matrix(Integer(2),
↪Integer(2)),
...                                identity_matrix(Integer(2))])
>>> fm = FanMorphism(proj34, coarse_fan, P2.fan(), subdivide=True)
>>> fibration = ToricVariety(fm.domain_fan()).hom(fm, P2)

>>> fibration.fiber_graph(P2.fan(Integer(0))[Integer(0)])
Graph on 1 vertex
>>> for c1 in P2.fan(Integer(1)):
...     fibration.fiber_graph(c1)
Graph on 1 vertex
Graph on 1 vertex
Graph on 4 vertices
```

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```
>>> fibration.fiber_graph(P2.fan(Integer(1))[Integer(2)]).get_vertices()
{0: 2-d toric variety covered by 4 affine patches,
 1: 2-d toric variety covered by 3 affine patches,
 2: 2-d toric variety covered by 3 affine patches,
 3: 2-d toric variety covered by 4 affine patches}

>>> fibration
Scheme morphism:
  From: 4-d toric variety covered by 18 affine patches
  To:   2-d CPR-Fano toric variety covered by 3 affine patches
  Defn: Defined by sending Rational polyhedral fan in 4-d lattice N
        to Rational polyhedral fan in 2-d lattice N.
```

class sage.schemes.toric.morphism.**SchemeMorphism_orbit_closure_toric_variety**(*parent*, *defining_cone*, *ray_map*)

Bases: *SchemeMorphism*, Morphism

The embedding of an orbit closure.

INPUT:

- `parent` – the parent homset
- `defining_cone` – the defining cone
- `ray_map` – dictionary `{ambient ray generator: orbit ray generator}`. Note that the image of the ambient ray generator is not necessarily primitive.

Warning

You should not create objects of this class directly. Use the *orbit_closure()* method of *toric varieties* instead.

EXAMPLES:

```
sage: P1xP1 = toric_varieties.P1xP1()
sage: H = P1xP1.fan(1)[0]
sage: V = P1xP1.orbit_closure(H)
sage: V.embedding_morphism()
Scheme morphism:
  From: 1-d toric variety covered by 2 affine patches
  To:   2-d CPR-Fano toric variety covered by 4 affine patches
  Defn: Defined by embedding the torus closure associated to the 1-d
        cone of Rational polyhedral fan in 2-d lattice N.
```

```
>>> from sage.all import *
>>> P1xP1 = toric_varieties.P1xP1()
>>> H = P1xP1.fan(Integer(1))[Integer(0)]
>>> V = P1xP1.orbit_closure(H)
>>> V.embedding_morphism()
Scheme morphism:
  From: 1-d toric variety covered by 2 affine patches
```

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```
  To:   2-d CPR-Fano toric variety covered by 4 affine patches
  Defn: Defined by embedding the torus closure associated to the 1-d
        cone of Rational polyhedral fan in 2-d lattice N.
```

as_polynomial_map()

Express the morphism via homogeneous polynomials.

OUTPUT: a *SchemeMorphism_polynomial_toric_variety*

This raises a TypeError if the morphism cannot be written in terms of homogeneous polynomials.

The defining polynomials are not necessarily unique. There are choices if multiple ambient space ray generators project to the same orbit ray generator, and one such choice is made implicitly. The orbit embedding can be written as a polynomial map if and only if each primitive orbit ray generator is the image of at least one primitive ray generator of the ambient toric variety.

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: V = P2.orbit_closure(P2.fan(1)[0]);  V
1-d toric variety covered by 2 affine patches
sage: V.embedding_morphism().as_polynomial_map()
Scheme morphism:
  From: 1-d toric variety covered by 2 affine patches
  To:   2-d CPR-Fano toric variety covered by 3 affine patches
  Defn: Defined on coordinates by sending [z0 : z1] to [0 : z1 : z0]
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> V = P2.orbit_closure(P2.fan(Integer(1))[Integer(0)]);  V
1-d toric variety covered by 2 affine patches
>>> V.embedding_morphism().as_polynomial_map()
Scheme morphism:
  From: 1-d toric variety covered by 2 affine patches
  To:   2-d CPR-Fano toric variety covered by 3 affine patches
  Defn: Defined on coordinates by sending [z0 : z1] to [0 : z1 : z0]
```

If the toric variety is singular, then some orbit closure embeddings cannot be written with homogeneous polynomials:

```
sage: P2_112 = toric_varieties.P2_112()
sage: P1 = P2_112.orbit_closure(Cone([(1,0)]))
sage: P1.embedding_morphism().as_polynomial_map()
Traceback (most recent call last):
...
TypeError: the embedding cannot be written with homogeneous polynomials
```

```
>>> from sage.all import *
>>> P2_112 = toric_varieties.P2_112()
>>> P1 = P2_112.orbit_closure(Cone([(Integer(1),Integer(0))]))
>>> P1.embedding_morphism().as_polynomial_map()
Traceback (most recent call last):
...
TypeError: the embedding cannot be written with homogeneous polynomials
```

defining_cone()

Return the cone corresponding to the torus orbit.

OUTPUT: a cone of the fan of the ambient toric variety

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: cone = P2.fan(1)[0]
sage: P1 = P2.orbit_closure(cone)
sage: P1.embedding_morphism().defining_cone()
1-d cone of Rational polyhedral fan in 2-d lattice N
sage: _ is cone
True
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> cone = P2.fan(Integer(1))[Integer(0)]
>>> P1 = P2.orbit_closure(cone)
>>> P1.embedding_morphism().defining_cone()
1-d cone of Rational polyhedral fan in 2-d lattice N
>>> _ is cone
True
```

pullback_divisor(*divisor*)

Pull back a toric divisor.

INPUT:

- `divisor` – a torus-invariant $\mathbf{Q}$-Cartier divisor on the codomain of the embedding map

OUTPUT:

A divisor on the domain of the embedding map (the orbit closure) that is isomorphic to the pull-back divisor $f^*(D)$ but with possibly different linearization.

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: P1 = P2.orbit_closure(P2.fan(1)[0])
sage: f = P1.embedding_morphism()
sage: D = P2.divisor([1,2,3]); D
V(x) + 2*V(y) + 3*V(z)
sage: f.pullback_divisor(D)
4*V(z0) + 2*V(z1)
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> P1 = P2.orbit_closure(P2.fan(Integer(1))[Integer(0)])
>>> f = P1.embedding_morphism()
>>> D = P2.divisor([Integer(1),Integer(2),Integer(3)]); D
V(x) + 2*V(y) + 3*V(z)
>>> f.pullback_divisor(D)
4*V(z0) + 2*V(z1)
```

class sage.schemes.toric.morphism.**SchemeMorphism_point_toric_field**(*X*, *coordinates*, *check=True*)

Bases: *SchemeMorphism_point*, Morphism

A point of a toric variety determined by homogeneous coordinates in a field.

Warning

You should not create objects of this class directly. Use the `hom()` method of *toric varieties* instead.

INPUT:

- `X` – toric variety or subscheme of a toric variety
- `coordinates` – list of coordinates in the base field of `X`
- `check` – if `True` (default), the input will be checked for correctness

OUTPUT: a *SchemeMorphism_point_toric_field*

class sage.schemes.toric.morphism.**SchemeMorphism_polynomial_toric_variety**(*parent*, *polynomials*, *check=True*)

Bases: *SchemeMorphism_polynomial*, Morphism

A morphism determined by homogeneous polynomials.

Warning

You should not create objects of this class directly. Use the `hom()` method of *toric varieties* instead.

INPUT:

Same as for `SchemeMorphism_polynomial`.

OUTPUT: a *SchemeMorphism_polynomial_toric_variety*

as_fan_morphism()

Express the morphism as a map defined by a fan morphism.

OUTPUT: a *SchemeMorphism_polynomial_toric_variety*

This raises a `TypeError` if the morphism cannot be written in such a way.

EXAMPLES:

```
sage: A1.<z> = toric_varieties.A1()
sage: P1 = toric_varieties.P1()
sage: patch = A1.hom([1,z], P1)
sage: patch.as_fan_morphism()
Traceback (most recent call last):
...
NotImplementedError: expressing toric morphisms as fan morphisms is
not implemented yet
```

```
>>> from sage.all import *
>>> A1 = toric_varieties.A1(names=('z',)); (z,) = A1._first_ngens(1)
>>> P1 = toric_varieties.P1()
```

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```
>>> patch = A1.hom([Integer(1),z], P1)
>>> patch.as_fan_morphism()
Traceback (most recent call last):
...
NotImplementedError: expressing toric morphisms as fan morphisms is
not implemented yet
```

16.9 Subschemes of toric space

AUTHORS:

- David Kohel (2005): initial version.
- William Stein (2005): initial version.
- Andrey Novoseltsev (2010-05-17): subschemes of toric varieties.

class sage.schemes.toric.toric_subscheme.**AlgebraicScheme_subscheme_affine_toric**(*toric_variety*, *polynomials*)

Bases: *AlgebraicScheme_subscheme_toric*

Construct an algebraic subscheme of an affine toric variety.

Warning

You should not create objects of this class directly. The preferred method to construct such subschemes is to use `subscheme()` method of `toric varieties`.

INPUT:

- `toric_variety` – ambient `affine toric variety`
- `polynomials` – single polynomial, list, or ideal of defining polynomials in the coordinate ring of `toric_variety`

OUTPUT:

A *algebraic subscheme of an affine toric variety*.

dimension()

Return the dimension of `self`.

OUTPUT: integer

EXAMPLES:

```
sage: # needs sage.libs.singular
sage: P1xP1.<s0,s1,t0,t1> = toric_varieties.P1xP1()
sage: P1 = P1xP1.subscheme(s0 - s1)
sage: P1.dimension()
1
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> P1xP1 = toric_varieties.P1xP1(names=('s0', 's1', 't0', 't1',)); (s0, s1,␣
↪t0, t1,) = P1xP1._first_ngens(4)
>>> P1 = P1xP1.subscheme(s0 - s1)
>>> P1.dimension()
1
```

A more complicated example where the ambient toric variety is not smooth:

```
sage: # needs sage.libs.singular
sage: X.<x,y> = toric_varieties.A2_Z2()
sage: X.is_smooth()
False
sage: Y = X.subscheme([x*y, x^2]); Y
Closed subscheme of 2-d affine toric variety defined by:
  x*y,
  x^2
sage: Y.dimension()
1
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> X = toric_varieties.A2_Z2(names=('x', 'y',)); (x, y,) = X._first_ngens(2)
>>> X.is_smooth()
False
>>> Y = X.subscheme([x*y, x**Integer(2)]); Y
Closed subscheme of 2-d affine toric variety defined by:
  x*y,
  x^2
>>> Y.dimension()
1
```

is_smooth(*point=None*)

Test whether the algebraic subscheme is smooth.

INPUT:

- `point` – a point or `None` (default); the point to test smoothness at

OUTPUT:

boolean; if no point was specified, returns whether the algebraic subscheme is smooth everywhere. Otherwise, smoothness at the specified point is tested.

EXAMPLES:

```
sage: # needs sage.libs.singular
sage: A2.<x,y> = toric_varieties.A2()
sage: cuspidal_curve = A2.subscheme([y^2 - x^3])
sage: cuspidal_curve
Closed subscheme of 2-d affine toric variety defined by:
  -x^3 + y^2
sage: cuspidal_curve.is_smooth([1,1])
True
```

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```
sage: cuspidal_curve.is_smooth([0,0])
False
sage: cuspidal_curve.is_smooth()
False
sage: circle = A2.subscheme(x^2 + y^2 - 1)
sage: circle.is_smooth([1,0])
True
sage: circle.is_smooth()
True
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> A2 = toric_varieties.A2(names=('x', 'y',)); (x, y,) = A2._first_ngens(2)
>>> cuspidal_curve = A2.subscheme([y**Integer(2) - x**Integer(3)])
>>> cuspidal_curve
Closed subscheme of 2-d affine toric variety defined by:
  -x^3 + y^2
>>> cuspidal_curve.is_smooth([Integer(1),Integer(1)])
True
>>> cuspidal_curve.is_smooth([Integer(0),Integer(0)])
False
>>> cuspidal_curve.is_smooth()
False
>>> circle = A2.subscheme(x**Integer(2) + y**Integer(2) - Integer(1))
>>> circle.is_smooth([Integer(1),Integer(0)])
True
>>> circle.is_smooth()
True
```

A more complicated example where the ambient toric variety is not smooth:

```
sage: # needs sage.libs.singular
sage: X.<x,y> = toric_varieties.A2_Z2()     # 2-d affine space mod Z/2
sage: X.is_smooth()
False
sage: Y = X.subscheme([x*y, x^2])    # (twice the x=0 curve) mod Z/2
sage: Y
Closed subscheme of 2-d affine toric variety defined by:
  x*y,
  x^2
sage: Y.dimension()    # Y is a Weil divisor but not Cartier
1
sage: Y.is_smooth()
True
sage: Y.is_smooth([0,0])
True
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> X = toric_varieties.A2_Z2(names=('x', 'y',)); (x, y,) = X._first_ngens(2)
↪# 2-d affine space mod Z/2
>>> X.is_smooth()
```

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```
False
>>> Y = X.subscheme([x*y, x**Integer(2)])    # (twice the x=0 curve) mod Z/2
>>> Y
Closed subscheme of 2-d affine toric variety defined by:
  x*y,
  x^2
>>> Y.dimension()    # Y is a Weil divisor but not Cartier
1
>>> Y.is_smooth()
True
>>> Y.is_smooth([Integer(0),Integer(0)])
True
```

class sage.schemes.toric.toric_subscheme.**AlgebraicScheme_subscheme_toric**(*toric_variety*, *polynomials*)

Bases: *AlgebraicScheme_subscheme*

Construct an algebraic subscheme of a toric variety.

Warning

You should not create objects of this class directly. The preferred method to construct such subschemes is to use `subscheme()` method of *toric varieties*.

INPUT:

- `toric_variety` – ambient `toric variety`
- `polynomials` – single polynomial, list, or ideal of defining polynomials in the coordinate ring of `toric_variety`

OUTPUT: an *algebraic subscheme of a toric variety*.

affine_algebraic_patch(*cone=None*, *names=None*)

Return the affine patch corresponding to `cone` as an affine algebraic scheme.

INPUT:

- `cone` – a `Cone` σ of the fan. It can be omitted for an affine toric variety, in which case the single generating cone is used.

OUTPUT:

An *affine algebraic subscheme* corresponding to the patch $Spec(\sigma^\vee \cap M)$ associated to the cone σ.

See also *affine_patch()*, which expresses the patches as subvarieties of affine toric varieties instead.

REFERENCES:

David A. Cox, "The Homogeneous Coordinate Ring of a Toric Variety", Lemma 2.2. arXiv alg-geom/9210008v2

EXAMPLES:

```
sage: P2.<x,y,z> = toric_varieties.P2()
sage: cone = P2.fan().generating_cone(0)
sage: V = P2.subscheme(x^3 + y^3 + z^3)
```

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```
sage: V.affine_algebraic_patch(cone)
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  z0^3 + z1^3 + 1

sage: # needs fpylll sage.libs.singular
sage: cone = Cone([(0,1), (2,1)])
sage: A2Z2.<x,y> = AffineToricVariety(cone)
sage: A2Z2.affine_algebraic_patch()
Closed subscheme of Affine Space of dimension 3 over Rational Field defined␣
↪by:
  -z0*z1 + z2^2
sage: V = A2Z2.subscheme(x^2 + y^2 - 1)
sage: patch = V.affine_algebraic_patch();  patch
Closed subscheme of Affine Space of dimension 3 over Rational Field defined␣
↪by:
  -z0*z1 + z2^2,
  z0 + z1 - 1
sage: nbhd_patch = V.neighborhood([1,0]).affine_algebraic_patch();  nbhd_patch
Closed subscheme of Affine Space of dimension 3 over Rational Field defined␣
↪by:
  -z0*z1 + z2^2,
  z0 + z1 - 1
sage: nbhd_patch.embedding_center()
(0, 1, 0)
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2(names=('x', 'y', 'z',)); (x, y, z,) = P2._first_
↪ngens(3)
>>> cone = P2.fan().generating_cone(Integer(0))
>>> V = P2.subscheme(x**Integer(3) + y**Integer(3) + z**Integer(3))
>>> V.affine_algebraic_patch(cone)
Closed subscheme of Affine Space of dimension 2 over Rational Field defined␣
↪by:
  z0^3 + z1^3 + 1

>>> # needs fpylll sage.libs.singular
>>> cone = Cone([(Integer(0),Integer(1)), (Integer(2),Integer(1))])
>>> A2Z2 = AffineToricVariety(cone, names=('x', 'y',)); (x, y,) = A2Z2._first_
↪ngens(2)
>>> A2Z2.affine_algebraic_patch()
Closed subscheme of Affine Space of dimension 3 over Rational Field defined␣
↪by:
  -z0*z1 + z2^2
>>> V = A2Z2.subscheme(x**Integer(2) + y**Integer(2) - Integer(1))
>>> patch = V.affine_algebraic_patch();  patch
Closed subscheme of Affine Space of dimension 3 over Rational Field defined␣
↪by:
  -z0*z1 + z2^2,
  z0 + z1 - 1
>>> nbhd_patch = V.neighborhood([Integer(1),Integer(0)]).affine_algebraic_
↪patch();  nbhd_patch
```

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```
Closed subscheme of Affine Space of dimension 3 over Rational Field defined␣
↪by:
  -z0*z1 + z2^2,
  z0 + z1 - 1
>>> nbhd_patch.embedding_center()
(0, 1, 0)
```

Here we got two defining equations. The first one describes the singularity of the ambient space and the second is the pull-back of $x^2 + y^2 - 1$

```
sage: lp = LatticePolytope([(1,0,0), (1,1,0), (1,1,1), (1,0,1), (-2,-1,-1)],
....:                      lattice=ToricLattice(3))
sage: X.<x,y,u,v,t> = CPRFanoToricVariety(Delta_polar=lp)
sage: Y = X.subscheme(x*v + y*u + t)
sage: cone = Cone([(1,0,0), (1,1,0), (1,1,1), (1,0,1)])
sage: Y.affine_algebraic_patch(cone)
Closed subscheme of Affine Space of dimension 4 over Rational Field defined␣
↪by:
  z0*z2 - z1*z3,
  z1 + z3 + 1
```

```
>>> from sage.all import *
>>> lp = LatticePolytope([(Integer(1),Integer(0),Integer(0)), (Integer(1),
↪Integer(1),Integer(0)), (Integer(1),Integer(1),Integer(1)), (Integer(1),
↪Integer(0),Integer(1)), (-Integer(2),-Integer(1),-Integer(1))],
...                       lattice=ToricLattice(Integer(3)))
>>> X = CPRFanoToricVariety(Delta_polar=lp, names=('x', 'y', 'u', 'v', 't',));
↪ (x, y, u, v, t,) = X._first_ngens(5)
>>> Y = X.subscheme(x*v + y*u + t)
>>> cone = Cone([(Integer(1),Integer(0),Integer(0)), (Integer(1),Integer(1),
↪Integer(0)), (Integer(1),Integer(1),Integer(1)), (Integer(1),Integer(0),
↪Integer(1))])
>>> Y.affine_algebraic_patch(cone)
Closed subscheme of Affine Space of dimension 4 over Rational Field defined␣
↪by:
  z0*z2 - z1*z3,
  z1 + z3 + 1
```

affine_patch(*i*)

Return the `i`-th affine patch of `self` as an affine toric algebraic scheme.

INPUT:

- `i` – integer; index of a generating cone of the fan of the ambient space of `self`

OUTPUT:

- subscheme of an affine *toric variety* corresponding to the pull-back of `self` by the embedding morphism of the `i`-th *affine patch of the ambient space* of `self`.

The result is cached, so the `i`-th patch is always the same object in memory.

EXAMPLES:

```
sage: P1xP1 = toric_varieties.P1xP1()
sage: patch1 = P1xP1.affine_patch(1)
sage: patch1.embedding_morphism()
Scheme morphism:
  From: 2-d affine toric variety
  To:   2-d CPR-Fano toric variety covered by 4 affine patches
  Defn: Defined on coordinates by sending [t : x] to [1 : t : x : 1]
sage: P1xP1.inject_variables()
Defining s, t, x, y
sage: P1 = P1xP1.subscheme(x - y)
sage: subpatch = P1.affine_patch(1)
sage: subpatch
Closed subscheme of 2-d affine toric variety defined by:
  x - 1
```

```
>>> from sage.all import *
>>> P1xP1 = toric_varieties.P1xP1()
>>> patch1 = P1xP1.affine_patch(Integer(1))
>>> patch1.embedding_morphism()
Scheme morphism:
  From: 2-d affine toric variety
  To:   2-d CPR-Fano toric variety covered by 4 affine patches
  Defn: Defined on coordinates by sending [t : x] to [1 : t : x : 1]
>>> P1xP1.inject_variables()
Defining s, t, x, y
>>> P1 = P1xP1.subscheme(x - y)
>>> subpatch = P1.affine_patch(Integer(1))
>>> subpatch
Closed subscheme of 2-d affine toric variety defined by:
  x - 1
```

dimension()

Return the dimension of `self`.

OUTPUT: integer; if `self` is empty, -1 is returned

EXAMPLES:

```
sage: # needs sage.libs.singular
sage: P1xP1 = toric_varieties.P1xP1()
sage: P1xP1.inject_variables()
Defining s, t, x, y
sage: P1 = P1xP1.subscheme(s - t)
sage: P1.dimension()
1
sage: P1xP1.subscheme([s - t, (s-t)^2]).dimension()
1
sage: P1xP1.subscheme([s, t]).dimension()
-1
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> P1xP1 = toric_varieties.P1xP1()
```

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```
>>> P1xP1.inject_variables()
Defining s, t, x, y
>>> P1 = P1xP1.subscheme(s - t)
>>> P1.dimension()
1
>>> P1xP1.subscheme([s - t, (s-t)**Integer(2)]).dimension()
1
>>> P1xP1.subscheme([s, t]).dimension()
-1
```

fan()

Return the fan of the ambient space.

OUTPUT: a fan

EXAMPLES:

```
sage: P2.<x,y,z> = toric_varieties.P(2)
sage: E = P2.subscheme([x^2 + y^2 + z^2])
sage: E.fan()
Rational polyhedral fan in 2-d lattice N
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P(Integer(2), names=('x', 'y', 'z',)); (x, y, z,) =␣
↪P2._first_ngens(3)
>>> E = P2.subscheme([x**Integer(2) + y**Integer(2) + z**Integer(2)])
>>> E.fan()
Rational polyhedral fan in 2-d lattice N
```

is_nondegenerate()

Check if `self` is nondegenerate.

OUTPUT:

Whether the variety is nondegenerate, that is, the intersection with every open torus orbit is smooth and transversal.

EXAMPLES:

```
sage: P2.<x,y,z> = toric_varieties.P2()
sage: P2.subscheme([x^3 + y^3 + z^3]).is_nondegenerate()
True
sage: P2.subscheme([x*y*z]).is_nondegenerate()
False
sage: X = P2.subscheme([(x-y)^2*(x+y) + x*y*z + z^3])
sage: X.is_smooth()
True
sage: X.is_nondegenerate()
False
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2(names=('x', 'y', 'z',)); (x, y, z,) = P2._first_
↪ngens(3)
>>> P2.subscheme([x**Integer(3) + y**Integer(3) + z**Integer(3)]).is_
```

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```
↪nondegenerate()
True
>>> P2.subscheme([x*y*z]).is_nondegenerate()
False
>>> X = P2.subscheme([(x-y)**Integer(2)*(x+y) + x*y*z + z**Integer(3)])
>>> X.is_smooth()
True
>>> X.is_nondegenerate()
False
```

A K3 surface in $\mathbf{P}^1 \times \mathbf{P}^1 \times \mathbf{P}^1$:

```
sage: diamond = lattice_polytope.cross_polytope(3)
sage: fan = FaceFan(diamond)
sage: P1xP1xP1 = ToricVariety(fan)
sage: z0, z1, z2, z3, z4, z5 = P1xP1xP1.gens()
sage: t = 5
sage: F = z0^2*z1^2*z2^2 + z1^2*z2^2*z3^2 + z0^2*z2^2*z4^2\
....: + z2^2*z3^2*z4^2 + t*z0*z1*z2*z3*z4*z5 + z0^2*z1^2*z5^2\
....: + z1^2*z3^2*z5^2 + z0^2*z4^2*z5^2 + z3^2*z4^2*z5^2
sage: X = P1xP1xP1.subscheme([F])
sage: X.is_smooth()
True
sage: X.is_nondegenerate()
False
```

```
>>> from sage.all import *
>>> diamond = lattice_polytope.cross_polytope(Integer(3))
>>> fan = FaceFan(diamond)
>>> P1xP1xP1 = ToricVariety(fan)
>>> z0, z1, z2, z3, z4, z5 = P1xP1xP1.gens()
>>> t = Integer(5)
>>> F = z0**Integer(2)*z1**Integer(2)*z2**Integer(2) +␣
↪z1**Integer(2)*z2**Integer(2)*z3**Integer(2) +␣
↪z0**Integer(2)*z2**Integer(2)*z4**Integer(2)+␣
↪z2**Integer(2)*z3**Integer(2)*z4**Integer(2) + t*z0*z1*z2*z3*z4*z5 +␣
↪z0**Integer(2)*z1**Integer(2)*z5**Integer(2)+␣
↪z1**Integer(2)*z3**Integer(2)*z5**Integer(2) +␣
↪z0**Integer(2)*z4**Integer(2)*z5**Integer(2) +␣
↪z3**Integer(2)*z4**Integer(2)*z5**Integer(2)
>>> X = P1xP1xP1.subscheme([F])
>>> X.is_smooth()
True
>>> X.is_nondegenerate()
False
```

Taking a random change of variables breaks the symmetry, but makes the surface nondegenerate:

```
sage: F1 = F.subs(z0=1*z0 + 1*z3, z3=1*z0 + 2*z3,
....:             z1=-2*z1 + -1*z4, z4=1*z1 + 2*z4,
....:             z2=-3*z2 + -1*z5, z5=-3*z2 + 2*z5)
sage: Y = P1xP1xP1.subscheme([F1])
```

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```
sage: Y.is_smooth()
True
sage: Y.is_nondegenerate()
True
```

```
>>> from sage.all import *
>>> F1 = F.subs(z0=Integer(1)*z0 + Integer(1)*z3, z3=Integer(1)*z0 +␣
↪Integer(2)*z3,
...              z1=-Integer(2)*z1 + -Integer(1)*z4, z4=Integer(1)*z1 +␣
↪Integer(2)*z4,
...              z2=-Integer(3)*z2 + -Integer(1)*z5, z5=-Integer(3)*z2 +␣
↪Integer(2)*z5)
>>> Y = P1xP1xP1.subscheme([F1])
>>> Y.is_smooth()
True
>>> Y.is_nondegenerate()
True
```

This example is from Hamm, arXiv 1106.1826v1. It addresses an issue raised at Issue #15239:

```
sage: X = toric_varieties.WP([1,4,2,3], names='z0 z1 z2 z3')
sage: X.inject_variables()
Defining z0, z1, z2, z3
sage: g0 = z1^3 + z2^6 + z3^4
sage: g = g0 - 2*z3^2*z0^6 + z2*z0^10 + z0^12
sage: Y = X.subscheme([g])
sage: Y.is_nondegenerate()
False
```

```
>>> from sage.all import *
>>> X = toric_varieties.WP([Integer(1),Integer(4),Integer(2),Integer(3)],␣
↪names='z0 z1 z2 z3')
>>> X.inject_variables()
Defining z0, z1, z2, z3
>>> g0 = z1**Integer(3) + z2**Integer(6) + z3**Integer(4)
>>> g = g0 - Integer(2)*z3**Integer(2)*z0**Integer(6) + z2*z0**Integer(10) +␣
↪z0**Integer(12)
>>> Y = X.subscheme([g])
>>> Y.is_nondegenerate()
False
```

It handles nonzero characteristic:

```
sage: P2.<x,y,z> = toric_varieties.P2()
sage: f = x^5 + 2*x*y^4 + y^5 - 2*y^3*z^2 + x*z^4 - 2*z^5
sage: P2.change_ring(GF(5)).subscheme([f]).is_nondegenerate()
True
sage: P2.change_ring(GF(7)).subscheme([f]).is_nondegenerate()
False
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2(names=('x', 'y', 'z',)); (x, y, z,) = P2._first_
```

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```
↪ngens(3)
>>> f = x**Integer(5) + Integer(2)*x*y**Integer(4) + y**Integer(5) -␣
↪Integer(2)*y**Integer(3)*z**Integer(2) + x*z**Integer(4) -␣
↪Integer(2)*z**Integer(5)
>>> P2.change_ring(GF(Integer(5))).subscheme([f]).is_nondegenerate()
True
>>> P2.change_ring(GF(Integer(7))).subscheme([f]).is_nondegenerate()
False
```

is_schon()

Check if `self` is schon (nondegenerate).

See *is_nondegenerate()* for further documentation.

EXAMPLES:

```
sage: # needs sage.libs.singular
sage: P2.<x,y,z> = toric_varieties.P2()
sage: X = P2.subscheme([(x-y)^2*(x+y) + x*y*z + z^3])
sage: X.is_smooth()
True
sage: X.is_schon()
False
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> P2 = toric_varieties.P2(names=('x', 'y', 'z',)); (x, y, z,) = P2._first_
↪ngens(3)
>>> X = P2.subscheme([(x-y)**Integer(2)*(x+y) + x*y*z + z**Integer(3)])
>>> X.is_smooth()
True
>>> X.is_schon()
False
```

is_smooth(*point=None*)

Test whether the algebraic subscheme is smooth.

INPUT:

- `point` – a point or `None` (default); the point to test smoothness at

OUTPUT:

boolean; if no point was specified, returns whether the algebraic subscheme is smooth everywhere. Otherwise, smoothness at the specified point is tested.

EXAMPLES:

```
sage: # needs sage.libs.singular
sage: P2.<x,y,z> = toric_varieties.P2()
sage: cuspidal_curve = P2.subscheme([y^2*z - x^3])
sage: cuspidal_curve
Closed subscheme of 2-d CPR-Fano toric variety covered by 3 affine patches␣
↪defined by:
  -x^3 + y^2*z
```

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```
sage: cuspidal_curve.is_smooth([1,1,1])
True
sage: cuspidal_curve.is_smooth([0,0,1])
False
sage: cuspidal_curve.is_smooth()
False
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> P2 = toric_varieties.P2(names=('x', 'y', 'z',)); (x, y, z,) = P2._first_
↪ngens(3)
>>> cuspidal_curve = P2.subscheme([y**Integer(2)*z - x**Integer(3)])
>>> cuspidal_curve
Closed subscheme of 2-d CPR-Fano toric variety covered by 3 affine patches␣
↪defined by:
  -x^3 + y^2*z
>>> cuspidal_curve.is_smooth([Integer(1),Integer(1),Integer(1)])
True
>>> cuspidal_curve.is_smooth([Integer(0),Integer(0),Integer(1)])
False
>>> cuspidal_curve.is_smooth()
False
```

Any sufficiently generic cubic hypersurface is smooth:

```
sage: P2.subscheme([y^2*z-x^3+z^3+1/10*x*y*z]).is_smooth()                #␣
↪needs sage.libs.singular
True
```

```
>>> from sage.all import *
>>> P2.subscheme([y**Integer(2)*z-x**Integer(3)+z**Integer(3)+Integer(1)/
↪Integer(10)*x*y*z]).is_smooth()                  # needs sage.libs.singular
True
```

A more complicated example:

```
sage: # needs sage.libs.singular
sage: dP6.<x0,x1,x2,x3,x4,x5> = toric_varieties.dP6()
sage: disjointP1s = dP6.subscheme(x0*x3)
sage: disjointP1s.is_smooth()
True
sage: intersectingP1s = dP6.subscheme(x0*x1)
sage: intersectingP1s.is_smooth()
False
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> dP6 = toric_varieties.dP6(names=('x0', 'x1', 'x2', 'x3', 'x4', 'x5',));␣
↪(x0, x1, x2, x3, x4, x5,) = dP6._first_ngens(6)
>>> disjointP1s = dP6.subscheme(x0*x3)
>>> disjointP1s.is_smooth()
True
```

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```
>>> intersectingP1s = dP6.subscheme(x0*x1)
>>> intersectingP1s.is_smooth()
False
```

A smooth hypersurface in a compact singular toric variety:

```
sage: # needs sage.libs.singular
sage: lp = LatticePolytope([(1,0,0), (1,1,0), (1,1,1), (1,0,1), (-2,-1,-1)],
....:                      lattice=ToricLattice(3))
sage: X.<x,y,u,v,t> = CPRFanoToricVariety(Delta_polar=lp)
sage: Y = X.subscheme(x*v + y*u + t)
sage: cone = Cone([(1,0,0), (1,1,0), (1,1,1), (1,0,1)])
sage: Y.is_smooth()
True
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> lp = LatticePolytope([(Integer(1),Integer(0),Integer(0)), (Integer(1),
↪Integer(1),Integer(0)), (Integer(1),Integer(1),Integer(1)), (Integer(1),
↪Integer(0),Integer(1)), (-Integer(2),-Integer(1),-Integer(1))],
...                       lattice=ToricLattice(Integer(3)))
>>> X = CPRFanoToricVariety(Delta_polar=lp, names=('x', 'y', 'u', 'v', 't',));
↪ (x, y, u, v, t,) = X._first_ngens(5)
>>> Y = X.subscheme(x*v + y*u + t)
>>> cone = Cone([(Integer(1),Integer(0),Integer(0)), (Integer(1),Integer(1),
↪Integer(0)), (Integer(1),Integer(1),Integer(1)), (Integer(1),Integer(0),
↪Integer(1))])
>>> Y.is_smooth()
True
```

neighborhood(*point*)

Return a toric algebraic scheme isomorphic to neighborhood of the `point`.

INPUT:

- `point` – a point of the toric algebraic scheme

OUTPUT:

An affine toric algebraic scheme (polynomial equations in an affine toric variety) with fixed `embedding_morphism()` and `embedding_center()`.

EXAMPLES:

```
sage: # needs sage.libs.singular
sage: P.<x,y,z> = toric_varieties.P2()
sage: S = P.subscheme(x + 2*y + 3*z)
sage: s = S.point([0,-3,2]); s
[0 : -3 : 2]
sage: patch = S.neighborhood(s); patch
Closed subscheme of 2-d affine toric variety defined by:
  x + 2*y + 6
sage: patch.embedding_morphism()
Scheme morphism:
```

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```
  From: Closed subscheme of 2-d affine toric variety defined by: x + 2*y + 6
  To:   Closed subscheme of 2-d CPR-Fano toric variety
        covered by 3 affine patches defined by: x + 2*y + 3*z
  Defn: Defined on coordinates by sending [x : y] to [-2*y - 6 : y : 2]
sage: patch.embedding_center()
[0 : -3]
sage: patch.embedding_morphism()(patch.embedding_center())
[0 : -3 : 2]
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> P = toric_varieties.P2(names=('x', 'y', 'z',)); (x, y, z,) = P._first_
↪ngens(3)
>>> S = P.subscheme(x + Integer(2)*y + Integer(3)*z)
>>> s = S.point([Integer(0),-Integer(3),Integer(2)]); s
[0 : -3 : 2]
>>> patch = S.neighborhood(s); patch
Closed subscheme of 2-d affine toric variety defined by:
  x + 2*y + 6
>>> patch.embedding_morphism()
Scheme morphism:
  From: Closed subscheme of 2-d affine toric variety defined by: x + 2*y + 6
  To:   Closed subscheme of 2-d CPR-Fano toric variety
        covered by 3 affine patches defined by: x + 2*y + 3*z
  Defn: Defined on coordinates by sending [x : y] to [-2*y - 6 : y : 2]
>>> patch.embedding_center()
[0 : -3]
>>> patch.embedding_morphism()(patch.embedding_center())
[0 : -3 : 2]
```

A more complicated example:

```
sage: # needs sage.libs.singular
sage: dP6.<x0,x1,x2,x3,x4,x5> = toric_varieties.dP6()
sage: twoP1 = dP6.subscheme(x0*x3)
sage: patch = twoP1.neighborhood([0,1,2, 3,4,5]); patch
Closed subscheme of 2-d affine toric variety defined by:
  3*x0
sage: patch.embedding_morphism()
Scheme morphism:
  From: Closed subscheme of 2-d affine toric variety defined by: 3*x0
  To:   Closed subscheme of 2-d CPR-Fano toric variety
        covered by 6 affine patches defined by: x0*x3
  Defn: Defined on coordinates by sending [x0 : x1] to [0 : x1 : 2 : 3 : 4 :␣
↪5]
sage: patch.embedding_center()
[0 : 1]
sage: patch.embedding_morphism()(patch.embedding_center())
[0 : 1 : 2 : 3 : 4 : 5]
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
```

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```
>>> dP6 = toric_varieties.dP6(names=('x0', 'x1', 'x2', 'x3', 'x4', 'x5',));␣
↪(x0, x1, x2, x3, x4, x5,) = dP6._first_ngens(6)
>>> twoP1 = dP6.subscheme(x0*x3)
>>> patch = twoP1.neighborhood([Integer(0),Integer(1),Integer(2), Integer(3),
↪Integer(4),Integer(5)]); patch
Closed subscheme of 2-d affine toric variety defined by:
  3*x0
>>> patch.embedding_morphism()
Scheme morphism:
  From: Closed subscheme of 2-d affine toric variety defined by: 3*x0
  To:   Closed subscheme of 2-d CPR-Fano toric variety
        covered by 6 affine patches defined by: x0*x3
  Defn: Defined on coordinates by sending [x0 : x1] to [0 : x1 : 2 : 3 : 4 :␣
↪5]
>>> patch.embedding_center()
[0 : 1]
>>> patch.embedding_morphism()(patch.embedding_center())
[0 : 1 : 2 : 3 : 4 : 5]
```

16.10 Weierstrass form of a toric elliptic curve

There are 16 reflexive polygons in the plane, see `ReflexivePolytopes()`. Each of them defines a toric Fano variety. And each of them has a unique crepant resolution to a smooth toric surface (Section 10.4 in [CLS2011]) by subdividing the face fan. An anticanonical hypersurface defines an elliptic curve in this ambient space, which we call a toric elliptic curve. The purpose of this module is to write an anticanonical hypersurface equation in the short Weierstrass form $y^2 = x^3 + fx + g$. This works over any base ring as long as its characteristic $\neq 2, 3$.

For an analogous treatment of elliptic curves defined as complete intersection in higher dimensional toric varieties, see the module *weierstrass_higher*.

Technically, this module computes the Weierstrass form of the Jacobian of the elliptic curve. This is why you will never have to specify the origin (or zero section) in the following.

It turns out [Bra2011] that the anticanonical hypersurface equation of any one of the above 16 toric surfaces is a specialization (that is, set one or more of the coefficients to zero) of the following three cases. In inhomogeneous coordinates, they are

- Cubic in $\mathbb{P}^2$:

$$p(x,y) = a_{30}x^3 + a_{21}x^2y + a_{12}xy^2 + a_{03}y^3 + a_{20}x^2 + a_{11}xy + a_{02}y^2 + a_{10}x + a_{01}y + a_{00}$$

- Biquadric in $\mathbb{P}^1 \times \mathbb{P}^1$:

$$p(x,y) = a_{22}x^2y^2 + a_{21}x^2y + a_{20}x^2 + a_{12}xy^2 + a_{11}xy + xa_{10} + y^2a_{02} + ya_{01} + a_{00}$$

- Anticanonical hypersurface in weighted projective space $\mathbb{P}^2[1,1,2]$:

$$p(x,y) = a_{40}x^4 + a_{30}x^3 + a_{21}x^2y + a_{20}x^2 + a_{11}xy + a_{02}y^2 + a_{10}x + a_{01}y + a_{00}$$

EXAMPLES:

The main functionality is provided by *WeierstrassForm()*, which brings each of the above hypersurface equations into Weierstrass form:

```
sage: R.<x,y> = QQ[]
sage: cubic = x^3 + y^3 + 1
sage: WeierstrassForm(cubic)
(0, -27/4)
sage: WeierstrassForm(x^4 + y^2 + 1)
(-4, 0)
sage: WeierstrassForm(x^2*y^2 + x^2 + y^2 + 1)
(-16/3, 128/27)
```

```
>>> from sage.all import *
>>> R = QQ['x, y']; (x, y,) = R._first_ngens(2)
>>> cubic = x**Integer(3) + y**Integer(3) + Integer(1)
>>> WeierstrassForm(cubic)
(0, -27/4)
>>> WeierstrassForm(x**Integer(4) + y**Integer(2) + Integer(1))
(-4, 0)
>>> WeierstrassForm(x**Integer(2)*y**Integer(2) + x**Integer(2) + y**Integer(2) +␣
↪Integer(1))
(-16/3, 128/27)
```

Only the affine span of the Newton polytope of the polynomial matters. For example:

```
sage: R.<x,y,z> = QQ[]
sage: WeierstrassForm(x^3 + y^3 + z^3)
(0, -27/4)
sage: WeierstrassForm(x * cubic)
(0, -27/4)
```

```
>>> from sage.all import *
>>> R = QQ['x, y, z']; (x, y, z,) = R._first_ngens(3)
>>> WeierstrassForm(x**Integer(3) + y**Integer(3) + z**Integer(3))
(0, -27/4)
>>> WeierstrassForm(x * cubic)
(0, -27/4)
```

This allows you to work with either homogeneous or inhomogeneous variables. For example, here is the del Pezzo surface of degree 8:

```
sage: dP8 = toric_varieties.dP8()
sage: dP8.inject_variables()
Defining t, x, y, z
sage: WeierstrassForm(x*y^2 + y^2*z + t^2*x^3 + t^2*z^3)
(-3, -2)
sage: WeierstrassForm(x*y^2 + y^2 + x^3 + 1)
(-3, -2)
```

```
>>> from sage.all import *
>>> dP8 = toric_varieties.dP8()
```

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```
>>> dP8.inject_variables()
Defining t, x, y, z
>>> WeierstrassForm(x*y**Integer(2) + y**Integer(2)*z + t**Integer(2)*x**Integer(3) +␣
↪t**Integer(2)*z**Integer(3))
(-3, -2)
>>> WeierstrassForm(x*y**Integer(2) + y**Integer(2) + x**Integer(3) + Integer(1))
(-3, -2)
```

By specifying only certain variables we can compute the Weierstrass form over the polynomial ring generated by the remaining variables. For example, here is a cubic over $\mathbf{Q}[a]$

```
sage: R.<a, x, y, z> = QQ[]
sage: cubic = x^3 + a*y^3 + a^2*z^3
sage: WeierstrassForm(cubic, variables=[x,y,z])
(0, -27/4*a^6)
```

```
>>> from sage.all import *
>>> R = QQ['a, x, y, z']; (a, x, y, z,) = R._first_ngens(4)
>>> cubic = x**Integer(3) + a*y**Integer(3) + a**Integer(2)*z**Integer(3)
>>> WeierstrassForm(cubic, variables=[x,y,z])
(0, -27/4*a^6)
```

REFERENCES:

- [Bra2011]
- [Du2010]
- [ARVT2005]
- [CLS2011]

sage.schemes.toric.weierstrass.**Discriminant**(*polynomial*, *variables=None*)

The discriminant of the elliptic curve.

INPUT:

See *WeierstrassForm()* for how to specify the input polynomial(s) and variables.

OUTPUT: the discriminant of the elliptic curve

EXAMPLES:

```
sage: from sage.schemes.toric.weierstrass import Discriminant
sage: R.<x, y, z> = QQ[]
sage: Discriminant(x^3 + y^3 + z^3)
19683/16
sage: Discriminant(x*y*z)
0
sage: R.<w,x,y,z> = QQ[]
sage: quadratic1 = w^2 + x^2 + y^2
sage: quadratic2 = z^2 + w*x
sage: Discriminant([quadratic1, quadratic2])
-1/16
```

```
>>> from sage.all import *
>>> from sage.schemes.toric.weierstrass import Discriminant
>>> R = QQ['x, y, z']; (x, y, z,) = R._first_ngens(3)
>>> Discriminant(x**Integer(3) + y**Integer(3) + z**Integer(3))
19683/16
>>> Discriminant(x*y*z)
0
>>> R = QQ['w, x, y, z']; (w, x, y, z,) = R._first_ngens(4)
>>> quadratic1 = w**Integer(2) + x**Integer(2) + y**Integer(2)
>>> quadratic2 = z**Integer(2) + w*x
>>> Discriminant([quadratic1, quadratic2])
-1/16
```

sage.schemes.toric.weierstrass.**Newton_polygon_embedded**(*polynomial*, *variables*)

Embed the Newton polytope of the polynomial in one of the three maximal reflexive polygons.

This function is a helper for *WeierstrassForm()*

INPUT:

Same as *WeierstrassForm()* with only a single polynomial passed.

OUTPUT:

A tuple $(\Delta, P, (x, y))$ where

- Δ is the Newton polytope of `polynomial`.
- $P(x, y)$ equals the input `polynomial` but with redefined variables such that its Newton polytope is Δ.

EXAMPLES:

```
sage: from sage.schemes.toric.weierstrass import Newton_polygon_embedded
sage: R.<x,y,z> = QQ[]
sage: cubic = x^3 + y^3 + z^3
sage: Newton_polygon_embedded(cubic, [x,y,z])
(A 2-dimensional lattice polytope in ZZ^3 with 3 vertices,
 x^3 + y^3 + 1,
 (x, y))

sage: R.<a, x,y,z> = QQ[]
sage: cubic = x^3 + a*y^3 + a^2*z^3
sage: Newton_polygon_embedded(cubic, variables=[x,y,z])
(A 2-dimensional lattice polytope in ZZ^3 with 3 vertices,
 a^2*x^3 + y^3 + a,
 (x, y))

sage: R.<s,t,x,y> = QQ[]
sage: biquadric = (s+t)^2 * (x+y)^2
sage: Newton_polygon_embedded(biquadric, [s,t,x,y])
(A 2-dimensional lattice polytope in ZZ^4 with 4 vertices,
 s^2*t^2 + 2*s^2*t + 2*s*t^2 + s^2 + 4*s*t + t^2 + 2*s + 2*t + 1,
 (s, t))
```

```
>>> from sage.all import *
>>> from sage.schemes.toric.weierstrass import Newton_polygon_embedded
```

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```
>>> R = QQ['x, y, z']; (x, y, z,) = R._first_ngens(3)
>>> cubic = x**Integer(3) + y**Integer(3) + z**Integer(3)
>>> Newton_polygon_embedded(cubic, [x,y,z])
(A 2-dimensional lattice polytope in ZZ^3 with 3 vertices,
 x^3 + y^3 + 1,
 (x, y))

>>> R = QQ['a, x, y, z']; (a, x, y, z,) = R._first_ngens(4)
>>> cubic = x**Integer(3) + a*y**Integer(3) + a**Integer(2)*z**Integer(3)
>>> Newton_polygon_embedded(cubic, variables=[x,y,z])
(A 2-dimensional lattice polytope in ZZ^3 with 3 vertices,
 a^2*x^3 + y^3 + a,
 (x, y))

>>> R = QQ['s, t, x, y']; (s, t, x, y,) = R._first_ngens(4)
>>> biquadric = (s+t)**Integer(2) * (x+y)**Integer(2)
>>> Newton_polygon_embedded(biquadric, [s,t,x,y])
(A 2-dimensional lattice polytope in ZZ^4 with 4 vertices,
 s^2*t^2 + 2*s^2*t + 2*s*t^2 + s^2 + 4*s*t + t^2 + 2*s + 2*t + 1,
 (s, t))
```

sage.schemes.toric.weierstrass.**Newton_polytope_vars_coeffs**(*polynomial*, *variables*)

Return the Newton polytope in the given variables.

INPUT:

See *WeierstrassForm()* for how to specify the input polynomial and variables.

OUTPUT:

A dictionary with keys the integral values of the Newton polytope and values the corresponding coefficient of `polynomial`.

EXAMPLES:

```
sage: from sage.schemes.toric.weierstrass import Newton_polytope_vars_coeffs
sage: R.<x,y,z,a30,a21,a12,a03,a20,a11,a02,a10,a01,a00> = QQ[]
sage: p = (a30*x^3 + a21*x^2*y + a12*x*y^2 + a03*y^3 + a20*x^2*z +
....:      a11*x*y*z + a02*y^2*z + a10*x*z^2 + a01*y*z^2 + a00*z^3)
sage: p_data = Newton_polytope_vars_coeffs(p, [x,y,z]);  p_data
{(0, 0, 3): a00,
 (0, 1, 2): a01,
 (0, 2, 1): a02,
 (0, 3, 0): a03,
 (1, 0, 2): a10,
 (1, 1, 1): a11,
 (1, 2, 0): a12,
 (2, 0, 1): a20,
 (2, 1, 0): a21,
 (3, 0, 0): a30}

sage: from sage.geometry.polyhedron.ppl_lattice_polytope import LatticePolytope_
↪PPL
sage: polytope = LatticePolytope_PPL(list(p_data));  polytope
```

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```
A 2-dimensional lattice polytope in ZZ^3 with 3 vertices
sage: polytope.vertices()
((0, 0, 3), (3, 0, 0), (0, 3, 0))
sage: polytope.embed_in_reflexive_polytope()
The map A*x+b with A=
[-1 -1]
[ 0  1]
[ 1  0]
b =
(3, 0, 0)
```

```
>>> from sage.all import *
>>> from sage.schemes.toric.weierstrass import Newton_polytope_vars_coeffs
>>> R = QQ['x, y, z, a30, a21, a12, a03, a20, a11, a02, a10, a01, a00']; (x, y, z,
↪ a30, a21, a12, a03, a20, a11, a02, a10, a01, a00,) = R._first_ngens(13)
>>> p = (a30*x**Integer(3) + a21*x**Integer(2)*y + a12*x*y**Integer(2) +␣
↪a03*y**Integer(3) + a20*x**Integer(2)*z +
...       a11*x*y*z + a02*y**Integer(2)*z + a10*x*z**Integer(2) +␣
↪a01*y*z**Integer(2) + a00*z**Integer(3))
>>> p_data = Newton_polytope_vars_coeffs(p, [x,y,z]);  p_data
{(0, 0, 3): a00,
 (0, 1, 2): a01,
 (0, 2, 1): a02,
 (0, 3, 0): a03,
 (1, 0, 2): a10,
 (1, 1, 1): a11,
 (1, 2, 0): a12,
 (2, 0, 1): a20,
 (2, 1, 0): a21,
 (3, 0, 0): a30}

>>> from sage.geometry.polyhedron.ppl_lattice_polytope import LatticePolytope_PPL
>>> polytope = LatticePolytope_PPL(list(p_data));  polytope
A 2-dimensional lattice polytope in ZZ^3 with 3 vertices
>>> polytope.vertices()
((0, 0, 3), (3, 0, 0), (0, 3, 0))
>>> polytope.embed_in_reflexive_polytope()
The map A*x+b with A=
[-1 -1]
[ 0  1]
[ 1  0]
b =
(3, 0, 0)
```

sage.schemes.toric.weierstrass.**WeierstrassForm**(*polynomial*, *variables=None*, *transformation=False*)

Return the Weierstrass form of an elliptic curve inside either inside a toric surface or $\mathbb{P}^3$.

INPUT:

- `polynomial` – either a polynomial or a list of polynomials defining the elliptic curve. A single polynomial can be either a cubic, a biquadric, or the hypersurface in $\mathbb{P}^2[1,1,2]$. In this case the equation need not be in any standard form, only its Newton polyhedron is used. If two polynomials are passed, they must both be quadratics in $\mathbb{P}^3$.

- `variables` – list of variables of the parent polynomial ring or `None` (default). In the latter case, all variables are taken to be polynomial ring variables. If a subset of polynomial ring variables are given, the Weierstrass form is determined over the function field generated by the remaining variables.
- `transformation` – boolean (default: `False`); whether to return the new variables that bring `polynomial` into Weierstrass form

OUTPUT:

The pair of coefficients (f, g) of the Weierstrass form $y^2 = x^3 + fx + g$ of the hypersurface equation.

If `transformation=True`, a triple (X, Y, Z) of polynomials defining a rational map of the toric hypersurface or complete intersection in $\mathbb{P}^3$ to its Weierstrass form in $\mathbb{P}^2[2, 3, 1]$ is returned. That is, the triple satisfies

$$Y^2 = X^3 + fXZ^4 + gZ^6$$

when restricted to the toric hypersurface or complete intersection.

EXAMPLES:

```
sage: R.<x,y,z> = QQ[]
sage: cubic = x^3 + y^3 + z^3
sage: f, g = WeierstrassForm(cubic);  (f, g)
(0, -27/4)
```

```
>>> from sage.all import *
>>> R = QQ['x, y, z']; (x, y, z,) = R._first_ngens(3)
>>> cubic = x**Integer(3) + y**Integer(3) + z**Integer(3)
>>> f, g = WeierstrassForm(cubic);  (f, g)
(0, -27/4)
```

Same in inhomogeneous coordinates:

```
sage: R.<x,y> = QQ[]
sage: cubic = x^3 + y^3 + 1
sage: f, g = WeierstrassForm(cubic);  (f, g)
(0, -27/4)

sage: X,Y,Z = WeierstrassForm(cubic, transformation=True);  (X,Y,Z)
(-x^3*y^3 - x^3 - y^3,
 1/2*x^6*y^3 - 1/2*x^3*y^6 - 1/2*x^6 + 1/2*y^6 + 1/2*x^3 - 1/2*y^3,
 x*y)
```

```
>>> from sage.all import *
>>> R = QQ['x, y']; (x, y,) = R._first_ngens(2)
>>> cubic = x**Integer(3) + y**Integer(3) + Integer(1)
>>> f, g = WeierstrassForm(cubic);  (f, g)
(0, -27/4)

>>> X,Y,Z = WeierstrassForm(cubic, transformation=True);  (X,Y,Z)
(-x^3*y^3 - x^3 - y^3,
 1/2*x^6*y^3 - 1/2*x^3*y^6 - 1/2*x^6 + 1/2*y^6 + 1/2*x^3 - 1/2*y^3,
 x*y)
```

Note that plugging in $[X : Y : Z]$ to the Weierstrass equation is a complicated polynomial, but contains the hypersurface equation as a factor:

```
sage: -Y^2 + X^3 + f*X*Z^4 + g*Z^6
-1/4*x^12*y^6 - 1/2*x^9*y^9 - 1/4*x^6*y^12 + 1/2*x^12*y^3
- 7/2*x^9*y^6 - 7/2*x^6*y^9 + 1/2*x^3*y^12 - 1/4*x^12 - 7/2*x^9*y^3
- 45/4*x^6*y^6 - 7/2*x^3*y^9 - 1/4*y^12 - 1/2*x^9 - 7/2*x^6*y^3
- 7/2*x^3*y^6 - 1/2*y^9 - 1/4*x^6 + 1/2*x^3*y^3 - 1/4*y^6
sage: cubic.divides(-Y^2 + X^3 + f*X*Z^4 + g*Z^6)
True
```

```
>>> from sage.all import *
>>> -Y**Integer(2) + X**Integer(3) + f*X*Z**Integer(4) + g*Z**Integer(6)
-1/4*x^12*y^6 - 1/2*x^9*y^9 - 1/4*x^6*y^12 + 1/2*x^12*y^3
- 7/2*x^9*y^6 - 7/2*x^6*y^9 + 1/2*x^3*y^12 - 1/4*x^12 - 7/2*x^9*y^3
- 45/4*x^6*y^6 - 7/2*x^3*y^9 - 1/4*y^12 - 1/2*x^9 - 7/2*x^6*y^3
- 7/2*x^3*y^6 - 1/2*y^9 - 1/4*x^6 + 1/2*x^3*y^3 - 1/4*y^6
>>> cubic.divides(-Y**Integer(2) + X**Integer(3) + f*X*Z**Integer(4) +␣
↪g*Z**Integer(6))
True
```

Only the affine span of the Newton polytope of the polynomial matters. For example:

```
sage: R.<x,y,z> = QQ[]
sage: cubic = x^3 + y^3 + z^3
sage: WeierstrassForm(cubic.subs(z=1))
(0, -27/4)
sage: WeierstrassForm(x * cubic)
(0, -27/4)
```

```
>>> from sage.all import *
>>> R = QQ['x, y, z']; (x, y, z,) = R._first_ngens(3)
>>> cubic = x**Integer(3) + y**Integer(3) + z**Integer(3)
>>> WeierstrassForm(cubic.subs(z=Integer(1)))
(0, -27/4)
>>> WeierstrassForm(x * cubic)
(0, -27/4)
```

This allows you to work with either homogeneous or inhomogeneous variables. For example, here is the del Pezzo surface of degree 8:

```
sage: dP8 = toric_varieties.dP8()
sage: dP8.inject_variables()
Defining t, x, y, z
sage: WeierstrassForm(x*y^2 + y^2*z + t^2*x^3 + t^2*z^3)
(-3, -2)
sage: WeierstrassForm(x*y^2 + y^2 + x^3 + 1)
(-3, -2)
```

```
>>> from sage.all import *
>>> dP8 = toric_varieties.dP8()
>>> dP8.inject_variables()
Defining t, x, y, z
>>> WeierstrassForm(x*y**Integer(2) + y**Integer(2)*z +␣
↪t**Integer(2)*x**Integer(3) + t**Integer(2)*z**Integer(3))
```

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```
(-3, -2)
>>> WeierstrassForm(x*y**Integer(2) + y**Integer(2) + x**Integer(3) + Integer(1))
(-3, -2)
```

By specifying only certain variables we can compute the Weierstrass form over the function field generated by the remaining variables. For example, here is a cubic over $\mathbf{Q}[a]$

```
sage: R.<a, x,y,z> = QQ[]
sage: cubic = x^3 + a*y^3 + a^2*z^3
sage: WeierstrassForm(cubic, variables=[x,y,z])
(0, -27/4*a^6)
```

```
>>> from sage.all import *
>>> R = QQ['a, x, y, z']; (a, x, y, z,) = R._first_ngens(4)
>>> cubic = x**Integer(3) + a*y**Integer(3) + a**Integer(2)*z**Integer(3)
>>> WeierstrassForm(cubic, variables=[x,y,z])
(0, -27/4*a^6)
```

sage.schemes.toric.weierstrass.**WeierstrassForm_P1xP1**(*biquadric*, *variables=None*)

Bring a biquadric into Weierstrass form.

Input/output is the same as *WeierstrassForm()*, except that the input polynomial must be a standard biquadric in $\mathbb{P}^2$,

$$p(x,y) = a_{40}x^4 + a_{30}x^3 + a_{21}x^2y + a_{20}x^2 + a_{11}xy + a_{02}y^2 + a_{10}x + a_{01}y + a_{00}$$

EXAMPLES:

```
sage: from sage.schemes.toric.weierstrass import WeierstrassForm_P1xP1
sage: R.<x0,x1,y0,y1> = QQ[]
sage: biquadric = (x0^2*y0^2 + x0*x1*y0^2*2 + x1^2*y0^2*3
....:     + x0^2*y0*y1*4 + x0*x1*y0*y1*5 + x1^2*y0*y1*6
....:     + x0^2*y1^2*7 + x0*x1*y1^2*8)
sage: WeierstrassForm_P1xP1(biquadric, [x0, x1, y0, y1])
(1581/16, -3529/32)
```

```
>>> from sage.all import *
>>> from sage.schemes.toric.weierstrass import WeierstrassForm_P1xP1
>>> R = QQ['x0, x1, y0, y1']; (x0, x1, y0, y1,) = R._first_ngens(4)
>>> biquadric = (x0**Integer(2)*y0**Integer(2) + x0*x1*y0**Integer(2)*Integer(2)␣
↪+ x1**Integer(2)*y0**Integer(2)*Integer(3)
...     + x0**Integer(2)*y0*y1*Integer(4) + x0*x1*y0*y1*Integer(5) +␣
↪x1**Integer(2)*y0*y1*Integer(6)
...     + x0**Integer(2)*y1**Integer(2)*Integer(7) +␣
↪x0*x1*y1**Integer(2)*Integer(8))
>>> WeierstrassForm_P1xP1(biquadric, [x0, x1, y0, y1])
(1581/16, -3529/32)
```

Since there is no $x_1^2y_1^2$ term in `biquadric`, we can dehomogenize it and get a cubic:

```
sage: from sage.schemes.toric.weierstrass import WeierstrassForm_P2
sage: WeierstrassForm_P2(biquadric(x0=1,y0=1))
(1581/16, -3529/32)
```

```
>>> from sage.all import *
>>> from sage.schemes.toric.weierstrass import WeierstrassForm_P2
>>> WeierstrassForm_P2(biquadric(x0=Integer(1),y0=Integer(1)))
(1581/16, -3529/32)
```

sage.schemes.toric.weierstrass.**WeierstrassForm_P2**(*polynomial*, *variables=None*)

Bring a cubic into Weierstrass form.

Input/output is the same as *WeierstrassForm()*, except that the input polynomial must be a standard cubic in $\mathbb{P}^2$,

$$p(x,y) = a_{30}x^3 + a_{21}x^2y + a_{12}xy^2 + a_{03}y^3 + a_{20}x^2 + a_{11}xy + a_{02}y^2 + a_{10}x + a_{01}y + a_{00}$$

EXAMPLES:

```
sage: from sage.schemes.toric.weierstrass import WeierstrassForm_P2
sage: R.<x,y,z> = QQ[]
sage: WeierstrassForm_P2(x^3 + y^3 + z^3)
(0, -27/4)

sage: R.<x,y,z, a,b> = QQ[]
sage: WeierstrassForm_P2(-y^2*z + x^3 + a*x*z^2 + b*z^3, [x,y,z])
(a, b)
```

```
>>> from sage.all import *
>>> from sage.schemes.toric.weierstrass import WeierstrassForm_P2
>>> R = QQ['x, y, z']; (x, y, z,) = R._first_ngens(3)
>>> WeierstrassForm_P2(x**Integer(3) + y**Integer(3) + z**Integer(3))
(0, -27/4)

>>> R = QQ['x, y, z, a, b']; (x, y, z, a, b,) = R._first_ngens(5)
>>> WeierstrassForm_P2(-y**Integer(2)*z + x**Integer(3) + a*x*z**Integer(2) +␣
↪b*z**Integer(3), [x,y,z])
(a, b)
```

sage.schemes.toric.weierstrass.**WeierstrassForm_P2_112**(*polynomial*, *variables=None*)

Bring an anticanonical hypersurface in $\mathbb{P}^2[1,1,2]$ into Weierstrass form.

Input/output is the same as *WeierstrassForm()*, except that the input polynomial must be a standard anticanonical hypersurface in weighted projective space $\mathbb{P}^2[1,1,2]$:

$$p(x,y) = a_{40}x^4 + a_{30}x^3 + a_{21}x^2y + a_{20}x^2 + a_{11}xy + a_{02}y^2 + a_{10}x + a_{01}y + a_{00}$$

EXAMPLES:

```
sage: from sage.schemes.toric.weierstrass import WeierstrassForm_P2_112
sage: fan = Fan(rays=[(1,0),(0,1),(-1,-2),(0,-1)],
```

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```
....:           cones=[[0,1],[1,2],[2,3],[3,0]])
sage: P112.<x,y,z,t> = ToricVariety(fan)
sage: (-P112.K()).sections_monomials()
(z^4*t^2, x*z^3*t^2, x^2*z^2*t^2, x^3*z*t^2,
 x^4*t^2, y*z^2*t, x*y*z*t, x^2*y*t, y^2)
sage: WeierstrassForm_P2_112(sum(_), [x,y,z,t])
(-97/48, 17/864)
```

```
>>> from sage.all import *
>>> from sage.schemes.toric.weierstrass import WeierstrassForm_P2_112
>>> fan = Fan(rays=[(Integer(1),Integer(0)),(Integer(0),Integer(1)),(-Integer(1),-
↪Integer(2)),(Integer(0),-Integer(1))],
...           cones=[[Integer(0),Integer(1)],[Integer(1),Integer(2)],[Integer(2),
↪Integer(3)],[Integer(3),Integer(0)]])
>>> P112 = ToricVariety(fan, names=('x', 'y', 'z', 't',)); (x, y, z, t,) = P112._
↪first_ngens(4)
>>> (-P112.K()).sections_monomials()
(z^4*t^2, x*z^3*t^2, x^2*z^2*t^2, x^3*z*t^2,
 x^4*t^2, y*z^2*t, x*y*z*t, x^2*y*t, y^2)
>>> WeierstrassForm_P2_112(sum(_), [x,y,z,t])
(-97/48, 17/864)
```

sage.schemes.toric.weierstrass.**j_invariant**(*polynomial*, *variables=None*)

Return the j-invariant of the elliptic curve.

INPUT:

See *WeierstrassForm()* for how to specify the input polynomial(s) and variables.

OUTPUT:

The j-invariant of the (irreducible) cubic. Notable special values:

- The Fermat cubic: $j(x^3+y^3+z^3)=0$
- A nodal cubic: $j(-y^2+x^2+x^3)=\infty$
- A cuspidal cubic $y^2=x^3$ has undefined j-invariant. In this case, a `ValueError` is raised.

EXAMPLES:

```
sage: from sage.schemes.toric.weierstrass import j_invariant
sage: R.<x,y,z> = QQ[]
sage: j_invariant(x^3 + y^3 + z^3)
0
sage: j_invariant(-y^2 + x^2 + x^3)
+Infinity
sage: R.<x,y,z, a,b> = QQ[]
sage: j_invariant( -y^2*z + x^3 + a*x*z^2, [x,y,z])
1728
```

```
>>> from sage.all import *
>>> from sage.schemes.toric.weierstrass import j_invariant
>>> R = QQ['x, y, z']; (x, y, z,) = R._first_ngens(3)
>>> j_invariant(x**Integer(3) + y**Integer(3) + z**Integer(3))
```

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```
0
>>> j_invariant(-y**Integer(2) + x**Integer(2) + x**Integer(3))
+Infinity
>>> R = QQ['x, y, z, a, b']; (x, y, z, a, b,) = R._first_ngens(5)
>>> j_invariant( -y**Integer(2)*z + x**Integer(3) + a*x*z**Integer(2), [x,y,z])
1728
```

16.11 Map to the Weierstrass form of a toric elliptic curve

There are 16 reflexive polygons in 2-d. Each defines a toric Fano variety, which (since it is 2-d) has a unique crepant resolution to a smooth toric surface. An anticanonical hypersurface defines a genus one curve C in this ambient space, with Jacobian elliptic curve $J(C)$ which can be defined by the Weierstrass model $y^2 = x^3 + fx + g$. The coefficients f and g can be computed with the *weierstrass* module. The purpose of this model is to give an explicit rational map $C \to J(C)$. This is an n^2-cover, where n is the minimal multi-section of C.

Since it is technically often easier to deal with polynomials than with fractions, we return the rational map in terms of homogeneous coordinates. That is, the ambient space for the Weierstrass model is the weighted projective space $\mathbb{P}^2[2,3,1]$ with homogeneous coordinates $[X:Y:Z] = [\lambda^2 X, \lambda^3 Y, \lambda Z]$. The homogenized Weierstrass equation is

$$Y^2 = X^3 + fXZ^4 + gZ^6$$

EXAMPLES:

```
sage: R.<x,y> = QQ[]
sage: cubic = x^3 + y^3 + 1
sage: f, g = WeierstrassForm(cubic);  (f,g)
(0, -27/4)
```

```
>>> from sage.all import *
>>> R = QQ['x, y']; (x, y,) = R._first_ngens(2)
>>> cubic = x**Integer(3) + y**Integer(3) + Integer(1)
>>> f, g = WeierstrassForm(cubic);  (f,g)
(0, -27/4)
```

That is, this hypersurface $C \in \mathbb{P}^2$ has a Weierstrass equation $Y^2 = X^3 + 0 \cdot XZ^4 - \frac{27}{4}Z^6$ where $[X:Y:Z]$ are projective coordinates on $\mathbb{P}^2[2,3,1]$. The form of the map $C \to J(C)$ is:

```
sage: X,Y,Z = WeierstrassForm(cubic, transformation=True);  (X,Y,Z)
(-x^3*y^3 - x^3 - y^3,
 1/2*x^6*y^3 - 1/2*x^3*y^6 - 1/2*x^6 + 1/2*y^6 + 1/2*x^3 - 1/2*y^3,
 x*y)
```

```
>>> from sage.all import *
>>> X,Y,Z = WeierstrassForm(cubic, transformation=True);  (X,Y,Z)
(-x^3*y^3 - x^3 - y^3,
 1/2*x^6*y^3 - 1/2*x^3*y^6 - 1/2*x^6 + 1/2*y^6 + 1/2*x^3 - 1/2*y^3,
 x*y)
```

Note that plugging in $[X:Y:Z]$ to the Weierstrass equation is a complicated polynomial, but contains the hypersurface equation as a factor:

```
sage: -Y^2 + X^3 + f*X*Z^4 + g*Z^6
-1/4*x^12*y^6 - 1/2*x^9*y^9 - 1/4*x^6*y^12 + 1/2*x^12*y^3
- 7/2*x^9*y^6 - 7/2*x^6*y^9 + 1/2*x^3*y^12 - 1/4*x^12 - 7/2*x^9*y^3
- 45/4*x^6*y^6 - 7/2*x^3*y^9 - 1/4*y^12 - 1/2*x^9 - 7/2*x^6*y^3
- 7/2*x^3*y^6 - 1/2*y^9 - 1/4*x^6 + 1/2*x^3*y^3 - 1/4*y^6
sage: cubic.divides(-Y^2 + X^3 + f*X*Z^4 + g*Z^6)
True
```

```
>>> from sage.all import *
>>> -Y**Integer(2) + X**Integer(3) + f*X*Z**Integer(4) + g*Z**Integer(6)
-1/4*x^12*y^6 - 1/2*x^9*y^9 - 1/4*x^6*y^12 + 1/2*x^12*y^3
- 7/2*x^9*y^6 - 7/2*x^6*y^9 + 1/2*x^3*y^12 - 1/4*x^12 - 7/2*x^9*y^3
- 45/4*x^6*y^6 - 7/2*x^3*y^9 - 1/4*y^12 - 1/2*x^9 - 7/2*x^6*y^3
- 7/2*x^3*y^6 - 1/2*y^9 - 1/4*x^6 + 1/2*x^3*y^3 - 1/4*y^6
>>> cubic.divides(-Y**Integer(2) + X**Integer(3) + f*X*Z**Integer(4) +␣
↪g*Z**Integer(6))
True
```

If you prefer you can also use homogeneous coordinates for $C \in \mathbb{P}^2$

```
sage: R.<x,y,z> = QQ[]
sage: cubic = x^3 + y^3 + z^3
sage: f, g = WeierstrassForm(cubic);  (f,g)
(0, -27/4)
sage: X,Y,Z = WeierstrassForm(cubic, transformation=True)
sage: cubic.divides(-Y^2 + X^3 + f*X*Z^4 + g*Z^6)
True
```

```
>>> from sage.all import *
>>> R = QQ['x, y, z']; (x, y, z,) = R._first_ngens(3)
>>> cubic = x**Integer(3) + y**Integer(3) + z**Integer(3)
>>> f, g = WeierstrassForm(cubic);  (f,g)
(0, -27/4)
>>> X,Y,Z = WeierstrassForm(cubic, transformation=True)
>>> cubic.divides(-Y**Integer(2) + X**Integer(3) + f*X*Z**Integer(4) +␣
↪g*Z**Integer(6))
True
```

The 16 toric surfaces corresponding to the 16 reflexive polygons can all be blown down to $\mathbb{P}^2$, $\mathbb{P}^1 \times \mathbb{P}^1$, or $\mathbb{P}^2[1,1,2]$. Their (and hence in all 16 cases) anticanonical hypersurface can equally be brought into Weierstrass form. For example, here is an anticanonical hypersurface in $\mathbb{P}^2[1,1,2]$

```
sage: P2_112 = toric_varieties.P2_112()
sage: C = P2_112.anticanonical_hypersurface(coefficients=[1]*4);  C
Closed subscheme of 2-d CPR-Fano toric variety
covered by 3 affine patches defined by:
  z0^4 + z2^4 + z0*z1*z2 + z1^2
sage: eq = C.defining_polynomials()[0]
sage: f, g = WeierstrassForm(eq)
sage: X,Y,Z = WeierstrassForm(eq, transformation=True)
sage: (-Y^2 + X^3 + f*X*Z^4 + g*Z^6).reduce(C.defining_ideal())
0
```

```
>>> from sage.all import *
>>> P2_112 = toric_varieties.P2_112()
>>> C = P2_112.anticanonical_hypersurface(coefficients=[Integer(1)]*Integer(4));  C
Closed subscheme of 2-d CPR-Fano toric variety
covered by 3 affine patches defined by:
  z0^4 + z2^4 + z0*z1*z2 + z1^2
>>> eq = C.defining_polynomials()[Integer(0)]
>>> f, g = WeierstrassForm(eq)
>>> X,Y,Z = WeierstrassForm(eq, transformation=True)
>>> (-Y**Integer(2) + X**Integer(3) + f*X*Z**Integer(4) + g*Z**Integer(6)).reduce(C.
↪defining_ideal())
0
```

Finally, you sometimes have to manually specify the variables to use. This is either because the equation is degenerate or because it contains additional variables that you want to treat as coefficients:

```
sage: R.<a, x,y,z> = QQ[]
sage: cubic = x^3 + y^3 + z^3 + a*x*y*z
sage: f, g = WeierstrassForm(cubic, variables=[x,y,z])
sage: X,Y,Z = WeierstrassForm(cubic, variables=[x,y,z], transformation=True)
sage: cubic.divides(-Y^2 + X^3 + f*X*Z^4 + g*Z^6)
True
```

```
>>> from sage.all import *
>>> R = QQ['a, x, y, z']; (a, x, y, z,) = R._first_ngens(4)
>>> cubic = x**Integer(3) + y**Integer(3) + z**Integer(3) + a*x*y*z
>>> f, g = WeierstrassForm(cubic, variables=[x,y,z])
>>> X,Y,Z = WeierstrassForm(cubic, variables=[x,y,z], transformation=True)
>>> cubic.divides(-Y**Integer(2) + X**Integer(3) + f*X*Z**Integer(4) +␣
↪g*Z**Integer(6))
True
```

REFERENCES:

- [AKMMMP2002]

sage.schemes.toric.weierstrass_covering.**WeierstrassMap**(*polynomial*, *variables=None*)

Return the Weierstrass form of an anticanonical hypersurface.

You should use *sage.schemes.toric.weierstrass.WeierstrassForm()* with `transformation=True` to get the transformation. This function is only for internal use.

INPUT:

- `polynomial` – a polynomial. The toric hypersurface equation. Can be either a cubic, a biquadric, or the hypersurface in $\mathbb{P}^2[1,1,2]$. The equation need not be in any standard form, only its Newton polyhedron is used.
- `variables` – list of variables of the parent polynomial ring or `None` (default). In the latter case, all variables are taken to be polynomial ring variables. If a subset of polynomial ring variables are given, the Weierstrass form is determined over the function field generated by the remaining variables.

OUTPUT:

A triple (X, Y, Z) of polynomials defining a rational map of the toric hypersurface to its Weierstrass form in $\mathbb{P}^2[2,3,1]$. That is, the triple satisfies

$$Y^2 = X^3 + fXZ^4 + gZ^6$$

when restricted to the toric hypersurface.

EXAMPLES:

```
sage: R.<x,y,z> = QQ[]
sage: cubic = x^3 + y^3 + z^3
sage: X,Y,Z = WeierstrassForm(cubic, transformation=True);  (X,Y,Z)
(-x^3*y^3 - x^3*z^3 - y^3*z^3,
 1/2*x^6*y^3 - 1/2*x^3*y^6 - 1/2*x^6*z^3 + 1/2*y^6*z^3
     + 1/2*x^3*z^6 - 1/2*y^3*z^6,
 x*y*z)
sage: f, g = WeierstrassForm(cubic);  (f,g)
(0, -27/4)
sage: cubic.divides(-Y^2 + X^3 + f*X*Z^4 + g*Z^6)
True
```

```
>>> from sage.all import *
>>> R = QQ['x, y, z']; (x, y, z,) = R._first_ngens(3)
>>> cubic = x**Integer(3) + y**Integer(3) + z**Integer(3)
>>> X,Y,Z = WeierstrassForm(cubic, transformation=True);  (X,Y,Z)
(-x^3*y^3 - x^3*z^3 - y^3*z^3,
 1/2*x^6*y^3 - 1/2*x^3*y^6 - 1/2*x^6*z^3 + 1/2*y^6*z^3
     + 1/2*x^3*z^6 - 1/2*y^3*z^6,
 x*y*z)
>>> f, g = WeierstrassForm(cubic);  (f,g)
(0, -27/4)
>>> cubic.divides(-Y**Integer(2) + X**Integer(3) + f*X*Z**Integer(4) +␣
↪g*Z**Integer(6))
True
```

Only the affine span of the Newton polytope of the polynomial matters. For example:

```
sage: WeierstrassForm(cubic.subs(z=1), transformation=True)
(-x^3*y^3 - x^3 - y^3,
 1/2*x^6*y^3 - 1/2*x^3*y^6 - 1/2*x^6
     + 1/2*y^6 + 1/2*x^3 - 1/2*y^3,
 x*y)
sage: WeierstrassForm(x * cubic, transformation=True)
(-x^3*y^3 - x^3*z^3 - y^3*z^3,
 1/2*x^6*y^3 - 1/2*x^3*y^6 - 1/2*x^6*z^3 + 1/2*y^6*z^3
     + 1/2*x^3*z^6 - 1/2*y^3*z^6,
 x*y*z)
```

```
>>> from sage.all import *
>>> WeierstrassForm(cubic.subs(z=Integer(1)), transformation=True)
(-x^3*y^3 - x^3 - y^3,
 1/2*x^6*y^3 - 1/2*x^3*y^6 - 1/2*x^6
     + 1/2*y^6 + 1/2*x^3 - 1/2*y^3,
 x*y)
>>> WeierstrassForm(x * cubic, transformation=True)
(-x^3*y^3 - x^3*z^3 - y^3*z^3,
 1/2*x^6*y^3 - 1/2*x^3*y^6 - 1/2*x^6*z^3 + 1/2*y^6*z^3
     + 1/2*x^3*z^6 - 1/2*y^3*z^6,
 x*y*z)
```

This allows you to work with either homogeneous or inhomogeneous variables. For example, here is the del Pezzo surface of degree 8:

```
sage: dP8 = toric_varieties.dP8()
sage: dP8.inject_variables()
Defining t, x, y, z
sage: WeierstrassForm(x*y^2 + y^2*z + t^2*x^3 + t^2*z^3, transformation=True)
(-1/27*t^4*x^6 - 2/27*t^4*x^5*z - 5/27*t^4*x^4*z^2
     - 8/27*t^4*x^3*z^3 - 5/27*t^4*x^2*z^4 - 2/27*t^4*x*z^5
     - 1/27*t^4*z^6 - 4/81*t^2*x^4*y^2 - 4/81*t^2*x^3*y^2*z
     - 4/81*t^2*x*y^2*z^3 - 4/81*t^2*y^2*z^4 - 2/81*x^2*y^4
     - 4/81*x*y^4*z - 2/81*y^4*z^2,
 0,
 1/3*t^2*x^2*z + 1/3*t^2*x*z^2 - 1/9*x*y^2 - 1/9*y^2*z)
sage: WeierstrassForm(x*y^2 + y^2 + x^3 + 1, transformation=True)
(-1/27*x^6 - 4/81*x^4*y^2 - 2/81*x^2*y^4 - 2/27*x^5
     - 4/81*x^3*y^2 - 4/81*x*y^4 - 5/27*x^4 - 2/81*y^4 - 8/27*x^3
     - 4/81*x*y^2 - 5/27*x^2 - 4/81*y^2 - 2/27*x - 1/27,
 0,
 -1/9*x*y^2 + 1/3*x^2 - 1/9*y^2 + 1/3*x)
```

```
>>> from sage.all import *
>>> dP8 = toric_varieties.dP8()
>>> dP8.inject_variables()
Defining t, x, y, z
>>> WeierstrassForm(x*y**Integer(2) + y**Integer(2)*z +␣
↪t**Integer(2)*x**Integer(3) + t**Integer(2)*z**Integer(3), transformation=True)
(-1/27*t^4*x^6 - 2/27*t^4*x^5*z - 5/27*t^4*x^4*z^2
     - 8/27*t^4*x^3*z^3 - 5/27*t^4*x^2*z^4 - 2/27*t^4*x*z^5
     - 1/27*t^4*z^6 - 4/81*t^2*x^4*y^2 - 4/81*t^2*x^3*y^2*z
     - 4/81*t^2*x*y^2*z^3 - 4/81*t^2*y^2*z^4 - 2/81*x^2*y^4
     - 4/81*x*y^4*z - 2/81*y^4*z^2,
 0,
 1/3*t^2*x^2*z + 1/3*t^2*x*z^2 - 1/9*x*y^2 - 1/9*y^2*z)
>>> WeierstrassForm(x*y**Integer(2) + y**Integer(2) + x**Integer(3) + Integer(1),␣
↪transformation=True)
(-1/27*x^6 - 4/81*x^4*y^2 - 2/81*x^2*y^4 - 2/27*x^5
     - 4/81*x^3*y^2 - 4/81*x*y^4 - 5/27*x^4 - 2/81*y^4 - 8/27*x^3
     - 4/81*x*y^2 - 5/27*x^2 - 4/81*y^2 - 2/27*x - 1/27,
 0,
 -1/9*x*y^2 + 1/3*x^2 - 1/9*y^2 + 1/3*x)
```

By specifying only certain variables we can compute the Weierstrass form over the function field generated by the remaining variables. For example, here is a cubic over $\mathbf{Q}[a]$

```
sage: R.<a, x,y,z> = QQ[]
sage: cubic = x^3 + a*y^3 + a^2*z^3
sage: WeierstrassForm(cubic, variables=[x,y,z], transformation=True)
(-a^9*y^3*z^3 - a^8*x^3*z^3 - a^7*x^3*y^3,
 -1/2*a^14*y^3*z^6 + 1/2*a^13*y^6*z^3 + 1/2*a^13*x^3*z^6
     - 1/2*a^11*x^3*y^6 - 1/2*a^11*x^6*z^3 + 1/2*a^10*x^6*y^3,
 a^3*x*y*z)
```

```
>>> from sage.all import *
>>> R = QQ['a, x, y, z']; (a, x, y, z,) = R._first_ngens(4)
>>> cubic = x**Integer(3) + a*y**Integer(3) + a**Integer(2)*z**Integer(3)
>>> WeierstrassForm(cubic, variables=[x,y,z], transformation=True)
(-a^9*y^3*z^3 - a^8*x^3*z^3 - a^7*x^3*y^3,
 -1/2*a^14*y^3*z^6 + 1/2*a^13*y^6*z^3 + 1/2*a^13*x^3*z^6
     - 1/2*a^11*x^3*y^6 - 1/2*a^11*x^6*z^3 + 1/2*a^10*x^6*y^3,
 a^3*x*y*z)
```

sage.schemes.toric.weierstrass_covering.**WeierstrassMap_P1xP1**(*polynomial*, *variables=None*)

Map an anticanonical hypersurface in $\mathbb{P}^1 \times \mathbb{P}^1$ into Weierstrass form.

Input/output is the same as *WeierstrassMap()*, except that the input polynomial must be a standard anticanonical hypersurface in the toric surface $\mathbb{P}^1 \times \mathbb{P}^1$:

EXAMPLES:

```
sage: from sage.schemes.toric.weierstrass_covering import WeierstrassMap_P1xP1
sage: from sage.schemes.toric.weierstrass import WeierstrassForm_P1xP1
sage: R.<x0,x1,y0,y1,a> = QQ[]
sage: biquadric = (x0^2*y0^2 + x1^2*y0^2 + x0^2*y1^2 + x1^2*y1^2 +
....:     a * x0*x1*y0*y1*5)
sage: f, g = WeierstrassForm_P1xP1(biquadric, [x0, x1, y0, y1]);  (f,g)
(-625/48*a^4 + 25/3*a^2 - 16/3, 15625/864*a^6 - 625/36*a^4 - 100/9*a^2 + 128/27)
sage: X, Y, Z = WeierstrassMap_P1xP1(biquadric, [x0, x1, y0, y1])
sage: (-Y^2 + X^3 + f*X*Z^4 + g*Z^6).reduce(R.ideal(biquadric))                #␣
↪needs sage.libs.singular
0

sage: R = PolynomialRing(QQ, 'x,y,s,t', order='lex')
sage: R.inject_variables()
Defining x, y, s, t
sage: equation = (s^2*(x^2+2*x*y+3*y^2) + s*t*(4*x^2+5*x*y+6*y^2)
....:             + t^2*(7*x^2+8*x*y+9*y^2))
sage: X, Y, Z = WeierstrassMap_P1xP1(equation, [x,y,s,t])
sage: f, g = WeierstrassForm_P1xP1(equation, variables=[x,y,s,t])
sage: (-Y^2 + X^3 + f*X*Z^4 + g*Z^6).reduce(R.ideal(equation))                 #␣
↪needs sage.libs.singular
0

sage: R = PolynomialRing(QQ, 'x,s', order='lex')
sage: R.inject_variables()
Defining x, s
sage: equation = s^2*(x^2+2*x+3) + s*(4*x^2+5*x+6) + (7*x^2+8*x+9)
sage: X, Y, Z = WeierstrassMap_P1xP1(equation)
sage: f, g = WeierstrassForm_P1xP1(equation)
sage: (-Y^2 + X^3 + f*X*Z^4 + g*Z^6).reduce(R.ideal(equation))                 #␣
↪needs sage.libs.singular
0
```

```
>>> from sage.all import *
>>> from sage.schemes.toric.weierstrass_covering import WeierstrassMap_P1xP1
>>> from sage.schemes.toric.weierstrass import WeierstrassForm_P1xP1
```

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```
>>> R = QQ['x0, x1, y0, y1, a']; (x0, x1, y0, y1, a,) = R._first_ngens(5)
>>> biquadric = (x0**Integer(2)*y0**Integer(2) + x1**Integer(2)*y0**Integer(2) +␣
↪x0**Integer(2)*y1**Integer(2) + x1**Integer(2)*y1**Integer(2) +
...      a * x0*x1*y0*y1*Integer(5))
>>> f, g = WeierstrassForm_P1xP1(biquadric, [x0, x1, y0, y1]);  (f,g)
(-625/48*a^4 + 25/3*a^2 - 16/3, 15625/864*a^6 - 625/36*a^4 - 100/9*a^2 + 128/27)
>>> X, Y, Z = WeierstrassMap_P1xP1(biquadric, [x0, x1, y0, y1])
>>> (-Y**Integer(2) + X**Integer(3) + f*X*Z**Integer(4) + g*Z**Integer(6)).
↪reduce(R.ideal(biquadric))                  # needs sage.libs.singular
0

>>> R = PolynomialRing(QQ, 'x,y,s,t', order='lex')
>>> R.inject_variables()
Defining x, y, s, t
>>> equation =␣
↪(s**Integer(2)*(x**Integer(2)+Integer(2)*x*y+Integer(3)*y**Integer(2)) +␣
↪s*t*(Integer(4)*x**Integer(2)+Integer(5)*x*y+Integer(6)*y**Integer(2))
...              +␣
↪t**Integer(2)*(Integer(7)*x**Integer(2)+Integer(8)*x*y+Integer(9)*y**Integer(2)))
>>> X, Y, Z = WeierstrassMap_P1xP1(equation, [x,y,s,t])
>>> f, g = WeierstrassForm_P1xP1(equation, variables=[x,y,s,t])
>>> (-Y**Integer(2) + X**Integer(3) + f*X*Z**Integer(4) + g*Z**Integer(6)).
↪reduce(R.ideal(equation))                   # needs sage.libs.singular
0

>>> R = PolynomialRing(QQ, 'x,s', order='lex')
>>> R.inject_variables()
Defining x, s
>>> equation = s**Integer(2)*(x**Integer(2)+Integer(2)*x+Integer(3)) +␣
↪s*(Integer(4)*x**Integer(2)+Integer(5)*x+Integer(6)) +␣
↪(Integer(7)*x**Integer(2)+Integer(8)*x+Integer(9))
>>> X, Y, Z = WeierstrassMap_P1xP1(equation)
>>> f, g = WeierstrassForm_P1xP1(equation)
>>> (-Y**Integer(2) + X**Integer(3) + f*X*Z**Integer(4) + g*Z**Integer(6)).
↪reduce(R.ideal(equation))                   # needs sage.libs.singular
0
```

sage.schemes.toric.weierstrass_covering.**WeierstrassMap_P2**(*polynomial*, *variables=None*)

Map a cubic to its Weierstrass form.

Input/output is the same as *WeierstrassMap()*, except that the input polynomial must be a cubic in $\mathbb{P}^2$,

$$p(x,y) = a_{30}x^3 + a_{21}x^2y + a_{12}xy^2 + a_{03}y^3 + a_{20}x^2 + a_{11}xy + a_{02}y^2 + a_{10}x + a_{01}y + a_{00}$$

EXAMPLES:

```
sage: from sage.schemes.toric.weierstrass import WeierstrassForm_P2
sage: from sage.schemes.toric.weierstrass_covering import WeierstrassMap_P2
sage: R.<x,y,z> = QQ[]
sage: equation =  x^3 + y^3 + z^3 + x*y*z
sage: f, g = WeierstrassForm_P2(equation)
sage: X,Y,Z = WeierstrassMap_P2(equation)
```

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```
sage: equation.divides(-Y^2 + X^3 + f*X*Z^4 + g*Z^6)
True

sage: from sage.schemes.toric.weierstrass import WeierstrassForm_P2
sage: from sage.schemes.toric.weierstrass_covering import WeierstrassMap_P2
sage: R.<x,y> = QQ[]
sage: equation =  x^3 + y^3 + 1
sage: f, g = WeierstrassForm_P2(equation)
sage: X,Y,Z = WeierstrassMap_P2(equation)
sage: equation.divides(-Y^2 + X^3 + f*X*Z^4 + g*Z^6)
True
```

```
>>> from sage.all import *
>>> from sage.schemes.toric.weierstrass import WeierstrassForm_P2
>>> from sage.schemes.toric.weierstrass_covering import WeierstrassMap_P2
>>> R = QQ['x, y, z']; (x, y, z,) = R._first_ngens(3)
>>> equation =  x**Integer(3) + y**Integer(3) + z**Integer(3) + x*y*z
>>> f, g = WeierstrassForm_P2(equation)
>>> X,Y,Z = WeierstrassMap_P2(equation)
>>> equation.divides(-Y**Integer(2) + X**Integer(3) + f*X*Z**Integer(4) +␣
↪g*Z**Integer(6))
True

>>> from sage.schemes.toric.weierstrass import WeierstrassForm_P2
>>> from sage.schemes.toric.weierstrass_covering import WeierstrassMap_P2
>>> R = QQ['x, y']; (x, y,) = R._first_ngens(2)
>>> equation =  x**Integer(3) + y**Integer(3) + Integer(1)
>>> f, g = WeierstrassForm_P2(equation)
>>> X,Y,Z = WeierstrassMap_P2(equation)
>>> equation.divides(-Y**Integer(2) + X**Integer(3) + f*X*Z**Integer(4) +␣
↪g*Z**Integer(6))
True
```

sage.schemes.toric.weierstrass_covering.**WeierstrassMap_P2_112**(*polynomial*, *variables=None*)

Map an anticanonical hypersurface in $\mathbb{P}^2[1,1,2]$ into Weierstrass form.

Input/output is the same as *WeierstrassMap()*, except that the input polynomial must be a standard anticanonical hypersurface in weighted projective space $\mathbb{P}^2[1,1,2]$:

$$p(x,y) = a_{40}x^4 + a_{30}x^3 + a_{21}x^2y + a_{20}x^2 + a_{11}xy + a_{02}y^2 + a_{10}x + a_{01}y + a_{00}$$

EXAMPLES:

```
sage: from sage.schemes.toric.weierstrass_covering import WeierstrassMap_P2_112
sage: from sage.schemes.toric.weierstrass import WeierstrassForm_P2_112
sage: R = PolynomialRing(QQ, 'x,y,a0,a1,a2,a3,a4', order='lex')
sage: R.inject_variables()
Defining x, y, a0, a1, a2, a3, a4
sage: equation = y^2 + a0*x^4 + 4*a1*x^3 + 6*a2*x^2 + 4*a3*x + a4
sage: X, Y, Z = WeierstrassMap_P2_112(equation, [x,y])
sage: f, g = WeierstrassForm_P2_112(equation, variables=[x,y])
sage: (-Y^2 + X^3 + f*X*Z^4 + g*Z^6).reduce(R.ideal(equation))                #␣
```

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```
↪needs sage.libs.singular
0
```

```
>>> from sage.all import *
>>> from sage.schemes.toric.weierstrass_covering import WeierstrassMap_P2_112
>>> from sage.schemes.toric.weierstrass import WeierstrassForm_P2_112
>>> R = PolynomialRing(QQ, 'x,y,a0,a1,a2,a3,a4', order='lex')
>>> R.inject_variables()
Defining x, y, a0, a1, a2, a3, a4
>>> equation = y**Integer(2) + a0*x**Integer(4) + Integer(4)*a1*x**Integer(3) +␣
↪Integer(6)*a2*x**Integer(2) + Integer(4)*a3*x + a4
>>> X, Y, Z = WeierstrassMap_P2_112(equation, [x,y])
>>> f, g = WeierstrassForm_P2_112(equation, variables=[x,y])
>>> (-Y**Integer(2) + X**Integer(3) + f*X*Z**Integer(4) + g*Z**Integer(6)).
↪reduce(R.ideal(equation))                  # needs sage.libs.singular
0
```

Another example, this time in homogeneous coordinates:

```
sage: fan = Fan(rays=[(1,0),(0,1),(-1,-2),(0,-1)],
....:           cones=[[0,1],[1,2],[2,3],[3,0]])
sage: P112.<x,y,z,t> = ToricVariety(fan)
sage: (-P112.K()).sections_monomials()
(z^4*t^2, x*z^3*t^2, x^2*z^2*t^2, x^3*z*t^2,
 x^4*t^2, y*z^2*t, x*y*z*t, x^2*y*t, y^2)
sage: C_eqn = sum(_)
sage: C = P112.subscheme(C_eqn)
sage: WeierstrassForm_P2_112(C_eqn, [x,y,z,t])
(-97/48, 17/864)
sage: X, Y, Z = WeierstrassMap_P2_112(C_eqn, [x,y,z,t])
sage: (-Y^2 + X^3 - 97/48*X*Z^4 + 17/864*Z^6).reduce(C.defining_ideal())        #␣
↪needs sage.libs.singular
0
```

```
>>> from sage.all import *
>>> fan = Fan(rays=[(Integer(1),Integer(0)),(Integer(0),Integer(1)),(-Integer(1),-
↪Integer(2)),(Integer(0),-Integer(1))],
...           cones=[[Integer(0),Integer(1)],[Integer(1),Integer(2)],[Integer(2),
↪Integer(3)],[Integer(3),Integer(0)]])
>>> P112 = ToricVariety(fan, names=('x', 'y', 'z', 't',)); (x, y, z, t,) = P112._
↪first_ngens(4)
>>> (-P112.K()).sections_monomials()
(z^4*t^2, x*z^3*t^2, x^2*z^2*t^2, x^3*z*t^2,
 x^4*t^2, y*z^2*t, x*y*z*t, x^2*y*t, y^2)
>>> C_eqn = sum(_)
>>> C = P112.subscheme(C_eqn)
>>> WeierstrassForm_P2_112(C_eqn, [x,y,z,t])
(-97/48, 17/864)
>>> X, Y, Z = WeierstrassMap_P2_112(C_eqn, [x,y,z,t])
>>> (-Y**Integer(2) + X**Integer(3) - Integer(97)/Integer(48)*X*Z**Integer(4) +␣
↪Integer(17)/Integer(864)*Z**Integer(6)).reduce(C.defining_ideal())        #␣
↪needs sage.libs.singular
```

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```
0
```

16.12 Weierstrass for elliptic curves in higher codimension

The *weierstrass* module lets you transform a genus-one curve, given as a hypersurface in a toric surface, into Weierstrass form. The purpose of this module is to extend this to higher codimension subschemes of toric varieties. In general, this is an unsolved problem. However, for certain special cases this is known.

The simplest codimension-two case is the complete intersection of two quadratic equations in $\mathbb{P}^3$

```
sage: R.<w,x,y,z> = QQ[]
sage: quadratic1 = w^2 + x^2 + y^2
sage: quadratic2 = z^2 + w*x
sage: WeierstrassForm([quadratic1, quadratic2])
(-1/4, 0)
```

```
>>> from sage.all import *
>>> R = QQ['w, x, y, z']; (w, x, y, z,) = R._first_ngens(4)
>>> quadratic1 = w**Integer(2) + x**Integer(2) + y**Integer(2)
>>> quadratic2 = z**Integer(2) + w*x
>>> WeierstrassForm([quadratic1, quadratic2])
(-1/4, 0)
```

Hence, the Weierstrass form of this complete intersection is $Y^2 = X^3 - \frac{1}{4}XZ^4$.

sage.schemes.toric.weierstrass_higher.**WeierstrassForm2**(*polynomial*, *variables=None*, *transformation=False*)

Helper function for *WeierstrassForm()*.

Currently, only the case of the complete intersection of two quadratic equations in $\mathbb{P}^3$ is supported.

INPUT / OUTPUT: see *WeierstrassForm()*

sage.schemes.toric.weierstrass_higher.**WeierstrassForm_P3**(*quadratic1*, *quadratic2*, *variables=None*)

Bring a complete intersection of two quadratics into Weierstrass form.

Input/output is the same as *sage.schemes.toric.weierstrass.WeierstrassForm()*, except that the two input polynomials must be quadratic polynomials in $\mathbb{P}^3$.

EXAMPLES:

```
sage: from sage.schemes.toric.weierstrass_higher import WeierstrassForm_P3
sage: R.<w,x,y,z> = QQ[]
sage: quadratic1 = w^2 + x^2 + y^2
sage: quadratic2 = z^2 + w*x
sage: WeierstrassForm_P3(quadratic1, quadratic2)
(-1/4, 0)
```

```
>>> from sage.all import *
>>> from sage.schemes.toric.weierstrass_higher import WeierstrassForm_P3
>>> R = QQ['w, x, y, z']; (w, x, y, z,) = R._first_ngens(4)
>>> quadratic1 = w**Integer(2) + x**Integer(2) + y**Integer(2)
>>> quadratic2 = z**Integer(2) + w*x
```

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```
>>> WeierstrassForm_P3(quadratic1, quadratic2)
(-1/4, 0)
```

sage.schemes.toric.weierstrass_higher.**WeierstrassMap_P3**(*quadratic1*, *quadratic2*, *variables=None*)

Bring a complete intersection of two quadratics into Weierstrass form.

Input/output is the same as *sage.schemes.toric.weierstrass.WeierstrassForm()*, except that the two input polynomials must be quadratic polynomials in $\mathbb{P}^3$.

EXAMPLES:

```
sage: from sage.schemes.toric.weierstrass_higher import \
....:     WeierstrassMap_P3, WeierstrassForm_P3
sage: R.<w,x,y,z> = QQ[]
sage: quadratic1 = w^2 + x^2 + y^2
sage: quadratic2 = z^2 + w*x
sage: X, Y, Z = WeierstrassMap_P3(quadratic1, quadratic2)
sage: X
1/1024*w^8 + 3/256*w^6*x^2 + 19/512*w^4*x^4 + 3/256*w^2*x^6 + 1/1024*x^8
sage: Y
1/32768*w^12 - 7/16384*w^10*x^2 - 145/32768*w^8*x^4 - 49/8192*w^6*x^6
- 145/32768*w^4*x^8 - 7/16384*w^2*x^10 + 1/32768*x^12
sage: Z
-1/8*w^2*y*z + 1/8*x^2*y*z

sage: a, b = WeierstrassForm_P3(quadratic1, quadratic2);  a, b
(-1/4, 0)

sage: ideal = R.ideal(quadratic1, quadratic2)
sage: (-Y^2 + X^3 + a*X*Z^4 + b*Z^6).reduce(ideal)                              #␣
↪needs sage.libs.singular
0
```

```
>>> from sage.all import *
>>> from sage.schemes.toric.weierstrass_higher import     WeierstrassMap_P3,␣
↪WeierstrassForm_P3
>>> R = QQ['w, x, y, z']; (w, x, y, z,) = R._first_ngens(4)
>>> quadratic1 = w**Integer(2) + x**Integer(2) + y**Integer(2)
>>> quadratic2 = z**Integer(2) + w*x
>>> X, Y, Z = WeierstrassMap_P3(quadratic1, quadratic2)
>>> X
1/1024*w^8 + 3/256*w^6*x^2 + 19/512*w^4*x^4 + 3/256*w^2*x^6 + 1/1024*x^8
>>> Y
1/32768*w^12 - 7/16384*w^10*x^2 - 145/32768*w^8*x^4 - 49/8192*w^6*x^6
- 145/32768*w^4*x^8 - 7/16384*w^2*x^10 + 1/32768*x^12
>>> Z
-1/8*w^2*y*z + 1/8*x^2*y*z

>>> a, b = WeierstrassForm_P3(quadratic1, quadratic2);  a, b
(-1/4, 0)

>>> ideal = R.ideal(quadratic1, quadratic2)
>>> (-Y**Integer(2) + X**Integer(3) + a*X*Z**Integer(4) + b*Z**Integer(6)).
```

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```
↪reduce(ideal)                                    # needs sage.libs.singular
0
```

16.13 Set of homomorphisms between two toric varieties

For schemes X and Y, this module implements the set of morphisms $Hom(X, Y)$. This is done by *SchemeHomset_generic*.

As a special case, the Hom-sets can also represent the points of a scheme. Recall that the K-rational points of a scheme X over k can be identified with the set of morphisms $Spec(K) \to X$. In Sage, the rational points are implemented by such scheme morphisms. This is done by *SchemeHomset_points* and its subclasses.

Note

You should not create the Hom-sets manually. Instead, use the `Hom()` method that is inherited by all schemes.

AUTHORS:

- Volker Braun (2012-02-18): Initial version

EXAMPLES:

Here is a simple example, the projection of $\mathbb{P}^1 \times \mathbb{P}^1 \to \mathbb{P}^1$

```
sage: P1xP1 = toric_varieties.P1xP1()
sage: P1 = toric_varieties.P1()
sage: hom_set = P1xP1.Hom(P1);  hom_set
Set of morphisms
  From: 2-d CPR-Fano toric variety covered by 4 affine patches
  To:   1-d CPR-Fano toric variety covered by 2 affine patches
```

```
>>> from sage.all import *
>>> P1xP1 = toric_varieties.P1xP1()
>>> P1 = toric_varieties.P1()
>>> hom_set = P1xP1.Hom(P1);  hom_set
Set of morphisms
  From: 2-d CPR-Fano toric variety covered by 4 affine patches
  To:   1-d CPR-Fano toric variety covered by 2 affine patches
```

In terms of the fan, we can define this morphism by the projection onto the first coordinate. The Hom-set can construct the morphism from the projection matrix alone:

```
sage: hom_set(matrix([[1],[0]]))
Scheme morphism:
  From: 2-d CPR-Fano toric variety covered by 4 affine patches
  To:   1-d CPR-Fano toric variety covered by 2 affine patches
  Defn: Defined by sending Rational polyhedral fan in 2-d lattice N
        to Rational polyhedral fan in 1-d lattice N.
sage: _.as_polynomial_map()
Scheme morphism:
  From: 2-d CPR-Fano toric variety covered by 4 affine patches
```

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```
  To:   1-d CPR-Fano toric variety covered by 2 affine patches
  Defn: Defined on coordinates by sending [s : t : x : y] to [s : t]
```

```
>>> from sage.all import *
>>> hom_set(matrix([[Integer(1)],[Integer(0)]]))
Scheme morphism:
  From: 2-d CPR-Fano toric variety covered by 4 affine patches
  To:   1-d CPR-Fano toric variety covered by 2 affine patches
  Defn: Defined by sending Rational polyhedral fan in 2-d lattice N
        to Rational polyhedral fan in 1-d lattice N.
>>> _.as_polynomial_map()
Scheme morphism:
  From: 2-d CPR-Fano toric variety covered by 4 affine patches
  To:   1-d CPR-Fano toric variety covered by 2 affine patches
  Defn: Defined on coordinates by sending [s : t : x : y] to [s : t]
```

In the case of toric algebraic schemes (defined by polynomials in toric varieties), this module defines the underlying morphism of the ambient toric varieties:

```
sage: P1xP1.inject_variables()
Defining s, t, x, y
sage: S = P1xP1.subscheme([s*x - t*y])
sage: type(S.Hom(S))
<class 'sage.schemes.toric.homset.SchemeHomset_toric_variety_with_category'>
```

```
>>> from sage.all import *
>>> P1xP1.inject_variables()
Defining s, t, x, y
>>> S = P1xP1.subscheme([s*x - t*y])
>>> type(S.Hom(S))
<class 'sage.schemes.toric.homset.SchemeHomset_toric_variety_with_category'>
```

Finally, you can have morphisms defined through homogeneous coordinates where the codomain is not implemented as a toric variety:

```
sage: P2_toric.<x,y,z> = toric_varieties.P2()
sage: P2_native.<u,v,w> = ProjectiveSpace(QQ, 2)
sage: toric_to_native = P2_toric.Hom(P2_native);  toric_to_native
Set of morphisms
  From: 2-d CPR-Fano toric variety covered by 3 affine patches
  To:   Projective Space of dimension 2 over Rational Field
sage: type(toric_to_native)
<class 'sage.schemes.toric.homset.SchemeHomset_toric_variety_with_category'>
sage: toric_to_native([x^2, y^2, z^2])
Scheme morphism:
  From: 2-d CPR-Fano toric variety covered by 3 affine patches
  To:   Projective Space of dimension 2 over Rational Field
  Defn: Defined on coordinates by sending [x : y : z] to (x^2 : y^2 : z^2)

sage: native_to_toric = P2_native.Hom(P2_toric);  native_to_toric
Set of morphisms
  From: Projective Space of dimension 2 over Rational Field
```

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```
  To:   2-d CPR-Fano toric variety covered by 3 affine patches
sage: type(native_to_toric)
<class 'sage.schemes.projective.projective_homset.SchemeHomset_polynomial_projective_
↪space_with_category'>
sage: native_to_toric([u^2, v^2, w^2])
Scheme morphism:
  From: Projective Space of dimension 2 over Rational Field
  To:   2-d CPR-Fano toric variety covered by 3 affine patches
  Defn: Defined on coordinates by sending (u : v : w) to [u^2 : v^2 : w^2]
```

```
>>> from sage.all import *
>>> P2_toric = toric_varieties.P2(names=('x', 'y', 'z',)); (x, y, z,) = P2_toric._
↪first_ngens(3)
>>> P2_native = ProjectiveSpace(QQ, Integer(2), names=('u', 'v', 'w',)); (u, v, w,) =␣
↪P2_native._first_ngens(3)
>>> toric_to_native = P2_toric.Hom(P2_native);  toric_to_native
Set of morphisms
  From: 2-d CPR-Fano toric variety covered by 3 affine patches
  To:   Projective Space of dimension 2 over Rational Field
>>> type(toric_to_native)
<class 'sage.schemes.toric.homset.SchemeHomset_toric_variety_with_category'>
>>> toric_to_native([x**Integer(2), y**Integer(2), z**Integer(2)])
Scheme morphism:
  From: 2-d CPR-Fano toric variety covered by 3 affine patches
  To:   Projective Space of dimension 2 over Rational Field
  Defn: Defined on coordinates by sending [x : y : z] to (x^2 : y^2 : z^2)

>>> native_to_toric = P2_native.Hom(P2_toric);  native_to_toric
Set of morphisms
  From: Projective Space of dimension 2 over Rational Field
  To:   2-d CPR-Fano toric variety covered by 3 affine patches
>>> type(native_to_toric)
<class 'sage.schemes.projective.projective_homset.SchemeHomset_polynomial_projective_
↪space_with_category'>
>>> native_to_toric([u**Integer(2), v**Integer(2), w**Integer(2)])
Scheme morphism:
  From: Projective Space of dimension 2 over Rational Field
  To:   2-d CPR-Fano toric variety covered by 3 affine patches
  Defn: Defined on coordinates by sending (u : v : w) to [u^2 : v^2 : w^2]
```

class sage.schemes.toric.homset.**SchemeHomset_points_subscheme_toric_field**(*X*, *Y*, *category=None*, *check=True*, *base=Integer Ring*)

Bases: *SchemeHomset_points_toric_base*

cardinality()

Return the number of points of the toric variety.

OUTPUT: integer or infinity; the cardinality of the set of points

EXAMPLES:

```
sage: # needs sage.libs.singular
sage: P2.<x,y,z> = toric_varieties.P2(base_ring=GF(5))
sage: cubic = P2.subscheme([x^3 + y^3 + z^3])
sage: list(cubic.point_set())
[[0 : 1 : 4], [1 : 0 : 4], [1 : 4 : 0], [1 : 1 : 2], [1 : 2 : 1], [1 : 3 : 3]]
sage: cubic.point_set().cardinality()
6
```

```
>>> from sage.all import *
>>> # needs sage.libs.singular
>>> P2 = toric_varieties.P2(base_ring=GF(Integer(5)), names=('x', 'y', 'z',));
↪ (x, y, z,) = P2._first_ngens(3)
>>> cubic = P2.subscheme([x**Integer(3) + y**Integer(3) + z**Integer(3)])
>>> list(cubic.point_set())
[[0 : 1 : 4], [1 : 0 : 4], [1 : 4 : 0], [1 : 1 : 2], [1 : 2 : 1], [1 : 3 : 3]]
>>> cubic.point_set().cardinality()
6
```

class sage.schemes.toric.homset.**SchemeHomset_points_toric_base**(*X*, *Y*, *category=None*, *check=True*, *base=Integer Ring*)

Bases: *SchemeHomset_points*

Base class for homsets with toric ambient spaces.

INPUT:

- same as for *SchemeHomset_points*.

OUTPUT: a scheme morphism of type *SchemeHomset_points_toric_base*

EXAMPLES:

```
sage: P1xP1 = toric_varieties.P1xP1()
sage: P1xP1(QQ)
Set of rational points of 2-d CPR-Fano toric variety
covered by 4 affine patches
```

```
>>> from sage.all import *
>>> P1xP1 = toric_varieties.P1xP1()
>>> P1xP1(QQ)
Set of rational points of 2-d CPR-Fano toric variety
covered by 4 affine patches
```

is_finite()

Return whether there are finitely many points.

OUTPUT: boolean

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: P2.point_set().is_finite()
False
sage: P2.change_ring(GF(7)).point_set().is_finite()
True
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> P2.point_set().is_finite()
False
>>> P2.change_ring(GF(Integer(7))).point_set().is_finite()
True
```

class sage.schemes.toric.homset.**SchemeHomset_points_toric_field**(*X*, *Y*, *category=None*, *check=True*, *base=Integer Ring*)

Bases: *SchemeHomset_points_toric_base*

Set of rational points of a toric variety.

You should not use this class directly. Instead, use the *point_set()* method to construct the point set of a toric variety.

INPUT:

- same as for *SchemeHomset_points*.

OUTPUT: a scheme morphism of type *SchemeHomset_points_toric_field*

EXAMPLES:

```
sage: P1xP1 = toric_varieties.P1xP1()
sage: P1xP1.point_set()
Set of rational points of 2-d CPR-Fano toric variety
covered by 4 affine patches
sage: P1xP1(QQ)
Set of rational points of 2-d CPR-Fano toric variety
covered by 4 affine patches
```

```
>>> from sage.all import *
>>> P1xP1 = toric_varieties.P1xP1()
>>> P1xP1.point_set()
Set of rational points of 2-d CPR-Fano toric variety
covered by 4 affine patches
>>> P1xP1(QQ)
Set of rational points of 2-d CPR-Fano toric variety
covered by 4 affine patches
```

The quotient $\mathbb{P}^2/\mathbf{Z}_3$ over $GF(7)$ by the diagonal action. This is tricky because the base field has a 3-rd root of unity:

```
sage: fan = NormalFan(ReflexivePolytope(2, 0))
sage: X = ToricVariety(fan, base_field=GF(7))
sage: point_set = X.point_set()
sage: point_set.cardinality()
21
sage: sorted(X.point_set().list())
[[0 : 0 : 1], [0 : 1 : 0], [0 : 1 : 1], [0 : 1 : 3],
 [1 : 0 : 0], [1 : 0 : 1], [1 : 0 : 3], [1 : 1 : 0],
 [1 : 1 : 1], [1 : 1 : 2], [1 : 1 : 3], [1 : 1 : 4],
 [1 : 1 : 5], [1 : 1 : 6], [1 : 3 : 0], [1 : 3 : 1],
```

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```
 [1 : 3 : 2], [1 : 3 : 3], [1 : 3 : 4], [1 : 3 : 5],
 [1 : 3 : 6]]
```

```
>>> from sage.all import *
>>> fan = NormalFan(ReflexivePolytope(Integer(2), Integer(0)))
>>> X = ToricVariety(fan, base_field=GF(Integer(7)))
>>> point_set = X.point_set()
>>> point_set.cardinality()
21
>>> sorted(X.point_set().list())
[[0 : 0 : 1], [0 : 1 : 0], [0 : 1 : 1], [0 : 1 : 3],
 [1 : 0 : 0], [1 : 0 : 1], [1 : 0 : 3], [1 : 1 : 0],
 [1 : 1 : 1], [1 : 1 : 2], [1 : 1 : 3], [1 : 1 : 4],
 [1 : 1 : 5], [1 : 1 : 6], [1 : 3 : 0], [1 : 3 : 1],
 [1 : 3 : 2], [1 : 3 : 3], [1 : 3 : 4], [1 : 3 : 5],
 [1 : 3 : 6]]
```

As for a non-compact example, the blow-up of the plane is the line bundle $O_{\mathbf{P}^1}(-1)$. Its point set is the Cartesian product of the points on the base $\mathbf{P}^1$ with the points on the fiber:

```
sage: fan = Fan([Cone([(1,0), (1,1)]), Cone([(1,1), (0,1)])])
sage: blowup_plane = ToricVariety(fan, base_ring=GF(3))
sage: point_set = blowup_plane.point_set()
sage: sorted(point_set.list())
[[0 : 1 : 0], [0 : 1 : 1], [0 : 1 : 2],
 [1 : 0 : 0], [1 : 0 : 1], [1 : 0 : 2],
 [1 : 1 : 0], [1 : 1 : 1], [1 : 1 : 2],
 [1 : 2 : 0], [1 : 2 : 1], [1 : 2 : 2]]
```

```
>>> from sage.all import *
>>> fan = Fan([Cone([(Integer(1),Integer(0)), (Integer(1),Integer(1))]),␣
↪Cone([(Integer(1),Integer(1)), (Integer(0),Integer(1))])])
>>> blowup_plane = ToricVariety(fan, base_ring=GF(Integer(3)))
>>> point_set = blowup_plane.point_set()
>>> sorted(point_set.list())
[[0 : 1 : 0], [0 : 1 : 1], [0 : 1 : 2],
 [1 : 0 : 0], [1 : 0 : 1], [1 : 0 : 2],
 [1 : 1 : 0], [1 : 1 : 1], [1 : 1 : 2],
 [1 : 2 : 0], [1 : 2 : 1], [1 : 2 : 2]]
```

Toric varieties with torus factors (that is, where the fan is not full-dimensional) also work:

```
sage: F_times_Fstar = ToricVariety(Fan([Cone([(1,0)])]), base_field=GF(3))
sage: sorted(F_times_Fstar.point_set().list())
[[0 : 1], [0 : 2], [1 : 1], [1 : 2], [2 : 1], [2 : 2]]
```

```
>>> from sage.all import *
>>> F_times_Fstar = ToricVariety(Fan([Cone([(Integer(1),Integer(0))])]), base_
↪field=GF(Integer(3)))
>>> sorted(F_times_Fstar.point_set().list())
[[0 : 1], [0 : 2], [1 : 1], [1 : 2], [2 : 1], [2 : 2]]
```

cardinality()

Return the number of points of the toric variety.

OUTPUT: integer or infinity; the cardinality of the set of points

EXAMPLES:

```
sage: o = lattice_polytope.cross_polytope(3)
sage: V = ToricVariety(FaceFan(o))
sage: V.change_ring(GF(2)).point_set().cardinality()
27
sage: V.change_ring(GF(8, "a")).point_set().cardinality()                    #␣
↪needs sage.rings.finite_rings
729
sage: V.change_ring(GF(101)).point_set().cardinality()
1061208
```

```
>>> from sage.all import *
>>> o = lattice_polytope.cross_polytope(Integer(3))
>>> V = ToricVariety(FaceFan(o))
>>> V.change_ring(GF(Integer(2))).point_set().cardinality()
27
>>> V.change_ring(GF(Integer(8), "a")).point_set().cardinality()              ␣
↪     # needs sage.rings.finite_rings
729
>>> V.change_ring(GF(Integer(101))).point_set().cardinality()
1061208
```

For non-smooth varieties over finite fields, the homogeneous rescalings are solved. This is somewhat slower:

```
sage: fan = NormalFan(ReflexivePolytope(2, 0))
sage: X = ToricVariety(fan, base_field=GF(7))
sage: X.point_set().cardinality()
21
```

```
>>> from sage.all import *
>>> fan = NormalFan(ReflexivePolytope(Integer(2), Integer(0)))
>>> X = ToricVariety(fan, base_field=GF(Integer(7)))
>>> X.point_set().cardinality()
21
```

Fulton's formula does not apply since the variety is not smooth. And, indeed, naive application gives a different result:

```
sage: q = X.base_ring().order()
sage: n = X.dimension()
sage: d = map(len, fan().cones())
sage: sum(dk * (q-1)**(n-k) for k, dk in enumerate(d))
57
```

```
>>> from sage.all import *
>>> q = X.base_ring().order()
>>> n = X.dimension()
>>> d = map(len, fan().cones())
```

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```
>>> sum(dk * (q-Integer(1))**(n-k) for k, dk in enumerate(d))
57
```

Over infinite fields the number of points is not very tricky:

```
sage: V.count_points()
+Infinity
```

```
>>> from sage.all import *
>>> V.count_points()
+Infinity
```

ALGORITHM:

Uses the formula in Fulton [Ful1993], section 4.5.

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class sage.schemes.toric.homset.**SchemeHomset_toric_variety**(*X*, *Y*, *category=None*, *check=True*, *base=Integer Ring*)

Bases: *SchemeHomset_generic*

Set of homomorphisms between two toric varieties.

EXAMPLES:

```
sage: P1xP1 = toric_varieties.P1xP1()
sage: P1 = toric_varieties.P1()
sage: hom_set = P1xP1.Hom(P1);  hom_set
Set of morphisms
  From: 2-d CPR-Fano toric variety covered by 4 affine patches
  To:   1-d CPR-Fano toric variety covered by 2 affine patches
sage: type(hom_set)
<class 'sage.schemes.toric.homset.SchemeHomset_toric_variety_with_category'>

sage: hom_set(matrix([[1],[0]]))
Scheme morphism:
  From: 2-d CPR-Fano toric variety covered by 4 affine patches
  To:   1-d CPR-Fano toric variety covered by 2 affine patches
  Defn: Defined by sending Rational polyhedral fan in 2-d lattice N
        to Rational polyhedral fan in 1-d lattice N.
```

```
>>> from sage.all import *
>>> P1xP1 = toric_varieties.P1xP1()
>>> P1 = toric_varieties.P1()
>>> hom_set = P1xP1.Hom(P1);  hom_set
```

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```
Set of morphisms
  From: 2-d CPR-Fano toric variety covered by 4 affine patches
  To:   1-d CPR-Fano toric variety covered by 2 affine patches
>>> type(hom_set)
<class 'sage.schemes.toric.homset.SchemeHomset_toric_variety_with_category'>

>>> hom_set(matrix([[Integer(1)],[Integer(0)]]))
Scheme morphism:
  From: 2-d CPR-Fano toric variety covered by 4 affine patches
  To:   1-d CPR-Fano toric variety covered by 2 affine patches
  Defn: Defined by sending Rational polyhedral fan in 2-d lattice N
        to Rational polyhedral fan in 1-d lattice N.
```

16.14 Enumerate points of a toric variety

The classes here are not meant to be instantiated manually. Instead, you should always use the methods of the *point set* of the variety.

In this module, points are always represented by tuples instead of Sage's class for points of the toric variety. All Sage library code must then convert it to proper point objects before returning it to the user.

EXAMPLES:

```
sage: P2 = toric_varieties.P2(base_ring=GF(3))
sage: point_set = P2.point_set()
sage: point_set.cardinality()
13
sage: next(iter(point_set))
[0 : 0 : 1]
sage: list(point_set)[0:5]
[[0 : 0 : 1], [1 : 0 : 0], [0 : 1 : 0], [0 : 1 : 1], [0 : 1 : 2]]
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2(base_ring=GF(Integer(3)))
>>> point_set = P2.point_set()
>>> point_set.cardinality()
13
>>> next(iter(point_set))
[0 : 0 : 1]
>>> list(point_set)[Integer(0):Integer(5)]
[[0 : 0 : 1], [1 : 0 : 0], [0 : 1 : 0], [0 : 1 : 1], [0 : 1 : 2]]
```

class sage.schemes.toric.points.**FiniteFieldPointEnumerator**(*fan*, *ring*)

Bases: *NaiveFinitePointEnumerator*

cardinality()

Return the cardinality of the point set.

OUTPUT: integer; the number of points

EXAMPLES:

```
sage: fan = NormalFan(ReflexivePolytope(2, 0))
sage: X = ToricVariety(fan, base_ring=GF(7))
sage: point_set = X.point_set()
sage: ffe = point_set._finite_field_enumerator()
sage: ffe.cardinality()
21
```

```
>>> from sage.all import *
>>> fan = NormalFan(ReflexivePolytope(Integer(2), Integer(0)))
>>> X = ToricVariety(fan, base_ring=GF(Integer(7)))
>>> point_set = X.point_set()
>>> ffe = point_set._finite_field_enumerator()
>>> ffe.cardinality()
21
```

cone_points_iter()

Iterate over the open torus orbits and yield distinct points.

OUTPUT:

For each open torus orbit (cone): A triple consisting of the cone, the nonzero homogeneous coordinates in that orbit (list of integers), and the nonzero log coordinates of distinct points as a cokernel.

EXAMPLES:

```
sage: fan = NormalFan(ReflexivePolytope(2, 0))
sage: X = ToricVariety(fan, base_ring=GF(7))
sage: point_set = X.point_set()
sage: ffe = point_set._finite_field_enumerator()
sage: cpi = ffe.cone_points_iter()
sage: cone, nonzero_points, cokernel = list(cpi)[5]
sage: cone
1-d cone of Rational polyhedral fan in 2-d lattice N
sage: cone.ambient_ray_indices()
(2,)
sage: nonzero_points
[0, 1]
sage: cokernel
Finitely generated module V/W over Integer Ring with invariants (2)
sage: list(cokernel)
[(0), (1)]
sage: [p.lift() for p in cokernel]
[(0, 0), (0, 1)]
```

```
>>> from sage.all import *
>>> fan = NormalFan(ReflexivePolytope(Integer(2), Integer(0)))
>>> X = ToricVariety(fan, base_ring=GF(Integer(7)))
>>> point_set = X.point_set()
>>> ffe = point_set._finite_field_enumerator()
>>> cpi = ffe.cone_points_iter()
>>> cone, nonzero_points, cokernel = list(cpi)[Integer(5)]
>>> cone
1-d cone of Rational polyhedral fan in 2-d lattice N
>>> cone.ambient_ray_indices()
```

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```
(2,)
>>> nonzero_points
[0, 1]
>>> cokernel
Finitely generated module V/W over Integer Ring with invariants (2)
>>> list(cokernel)
[(0), (1)]
>>> [p.lift() for p in cokernel]
[(0, 0), (0, 1)]
```

exp(*powers*)

Return the component-wise exp of `z`.

INPUT:

- `powers` – list/tuple/iterable of integers

OUTPUT:

Tuple of finite field elements. The powers of the *multiplicative_generator()*.

EXAMPLES:

```
sage: # needs sage.rings.finite_rings
sage: F.<a> = GF(5^2)
sage: point_set = toric_varieties.P2_123(base_ring=F).point_set()
sage: ffe = point_set._finite_field_enumerator()
sage: powers = list(range(24))
sage: ffe.exp(powers)
(1, a, a + 3, 4*a + 3, 2*a + 2, 4*a + 1, 2, 2*a, 2*a + 1, 3*a + 1,
 4*a + 4, 3*a + 2, 4, 4*a, 4*a + 2, a + 2, 3*a + 3, a + 4, 3, 3*a,
 3*a + 4, 2*a + 4, a + 1, 2*a + 3)
sage: ffe.log(ffe.exp(powers)) == tuple(powers)
True
```

```
>>> from sage.all import *
>>> # needs sage.rings.finite_rings
>>> F = GF(Integer(5)**Integer(2), names=('a',)); (a,) = F._first_ngens(1)
>>> point_set = toric_varieties.P2_123(base_ring=F).point_set()
>>> ffe = point_set._finite_field_enumerator()
>>> powers = list(range(Integer(24)))
>>> ffe.exp(powers)
(1, a, a + 3, 4*a + 3, 2*a + 2, 4*a + 1, 2, 2*a, 2*a + 1, 3*a + 1,
 4*a + 4, 3*a + 2, 4, 4*a, 4*a + 2, a + 2, 3*a + 3, a + 4, 3, 3*a,
 3*a + 4, 2*a + 4, a + 1, 2*a + 3)
>>> ffe.log(ffe.exp(powers)) == tuple(powers)
True
```

log(*z*)

Return the component-wise log of `z`.

INPUT:

- `z` – list/tuple/iterable of nonzero finite field elements

OUTPUT:

Tuple of integers. The logarithm with base the *multiplicative_generator()*.

EXAMPLES:

```
sage: # needs sage.rings.finite_rings
sage: F.<a> = GF(5^2)
sage: point_set = toric_varieties.P2_123(base_ring=F).point_set()
sage: ffe = point_set._finite_field_enumerator()
sage: z = tuple(a^i for i in range(25));  z
(1, a, a + 3, 4*a + 3, 2*a + 2, 4*a + 1, 2, 2*a, 2*a + 1, 3*a + 1,
 4*a + 4, 3*a + 2, 4, 4*a, 4*a + 2, a + 2, 3*a + 3, a + 4, 3, 3*a,
 3*a + 4, 2*a + 4, a + 1, 2*a + 3, 1)
sage: ffe.log(z)
(0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16,
 17, 18, 19, 20, 21, 22, 23, 0)
sage: ffe.exp(ffe.log(z)) == z
True
sage: ffe.log(ffe.exp(range(24))) == tuple(range(24))
True
```

```
>>> from sage.all import *
>>> # needs sage.rings.finite_rings
>>> F = GF(Integer(5)**Integer(2), names=('a',)); (a,) = F._first_ngens(1)
>>> point_set = toric_varieties.P2_123(base_ring=F).point_set()
>>> ffe = point_set._finite_field_enumerator()
>>> z = tuple(a**i for i in range(Integer(25)));  z
(1, a, a + 3, 4*a + 3, 2*a + 2, 4*a + 1, 2, 2*a, 2*a + 1, 3*a + 1,
 4*a + 4, 3*a + 2, 4, 4*a, 4*a + 2, a + 2, 3*a + 3, a + 4, 3, 3*a,
 3*a + 4, 2*a + 4, a + 1, 2*a + 3, 1)
>>> ffe.log(z)
(0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16,
 17, 18, 19, 20, 21, 22, 23, 0)
>>> ffe.exp(ffe.log(z)) == z
True
>>> ffe.log(ffe.exp(range(Integer(24)))) == tuple(range(Integer(24)))
True
```

multiplicative_generator()

Return the multiplicative generator of the finite field.

OUTPUT: a finite field element

EXAMPLES:

```
sage: point_set = toric_varieties.P2(base_ring=GF(5^2, 'a')).point_set()    #␣
↪needs sage.rings.finite_rings
sage: ffe = point_set._finite_field_enumerator()                            #␣
↪needs sage.rings.finite_rings
sage: ffe.multiplicative_generator()                                        #␣
↪needs sage.rings.finite_rings
a
```

```
>>> from sage.all import *
>>> point_set = toric_varieties.P2(base_ring=GF(Integer(5)**Integer(2), 'a')).
```

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```
↪point_set()    # needs sage.rings.finite_rings
>>> ffe = point_set._finite_field_enumerator()                          #␣
↪needs sage.rings.finite_rings
>>> ffe.multiplicative_generator()                                      #␣
↪needs sage.rings.finite_rings
a
```

multiplicative_group_order()

EXAMPLES:

```
sage: class Foo:
....:     def __init__(self, x):
....:         self._x = x
....:     @cached_method
....:     def f(self):
....:         return self._x^2
sage: a = Foo(2)
sage: print(a.f.cache)
None
sage: a.f()
4
sage: a.f.cache
4
```

```
>>> from sage.all import *
>>> class Foo:
...     def __init__(self, x):
...         self._x = x
...     @cached_method
...     def f(self):
...         return self._x**Integer(2)
>>> a = Foo(Integer(2))
>>> print(a.f.cache)
None
>>> a.f()
4
>>> a.f.cache
4
```

rescaling_log_generators()

Return the log generators of `rescalings()`.

OUTPUT:

A tuple containing the logarithms (see *log()*) of the generators of the multiplicative group of `rescalings()`.

EXAMPLES:

```
sage: point_set = toric_varieties.P2_123(base_ring=GF(5)).point_set()
sage: ffe = point_set._finite_field_enumerator()
sage: ffe.rescalings()
((1, 1, 1), (1, 4, 4), (4, 2, 3), (4, 3, 2))
```

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```
sage: list(map(ffe.log, ffe.rescalings()))
[(0, 0, 0), (0, 2, 2), (2, 1, 3), (2, 3, 1)]
sage: ffe.rescaling_log_generators()
((2, 3, 1),)
```

```
>>> from sage.all import *
>>> point_set = toric_varieties.P2_123(base_ring=GF(Integer(5))).point_set()
>>> ffe = point_set._finite_field_enumerator()
>>> ffe.rescalings()
((1, 1, 1), (1, 4, 4), (4, 2, 3), (4, 3, 2))
>>> list(map(ffe.log, ffe.rescalings()))
[(0, 0, 0), (0, 2, 2), (2, 1, 3), (2, 3, 1)]
>>> ffe.rescaling_log_generators()
((2, 3, 1),)
```

root_generator(*n*)

Return a generator for `roots()`.

INPUT:

- `n` – integer

OUTPUT: a multiplicative generator for `roots()`

EXAMPLES:

```
sage: point_set = toric_varieties.P2(base_ring=GF(5)).point_set()
sage: ffe = point_set._finite_field_enumerator()
sage: ffe.root_generator(2)
4
sage: ffe.root_generator(3)
1
sage: ffe.root_generator(4)
2
```

```
>>> from sage.all import *
>>> point_set = toric_varieties.P2(base_ring=GF(Integer(5))).point_set()
>>> ffe = point_set._finite_field_enumerator()
>>> ffe.root_generator(Integer(2))
4
>>> ffe.root_generator(Integer(3))
1
>>> ffe.root_generator(Integer(4))
2
```

class sage.schemes.toric.points.**FiniteFieldSubschemePointEnumerator**(*polynomials*, *ambient*)

Bases: *NaiveSubschemePointEnumerator*

cardinality()

Return the cardinality of the point set.

OUTPUT: integer; the number of points

EXAMPLES:

```
sage: fan = NormalFan(ReflexivePolytope(2, 0))
sage: X.<u,v,w> = ToricVariety(fan, base_ring=GF(7))
sage: Y = X.subscheme(u^3 + v^3 + w^3 + u*v*w)
sage: point_set = Y.point_set()
sage: list(point_set)                                                    #␣
↪needs fplll
[[0 : 1 : 3],
 [1 : 0 : 3],
 [1 : 3 : 0],
 [1 : 1 : 6],
 [1 : 1 : 4],
 [1 : 3 : 2],
 [1 : 3 : 5]]
sage: ffe = point_set._enumerator()                                      #␣
↪needs fplll
sage: ffe.cardinality()                                                  #␣
↪needs fplll
7
```

```
>>> from sage.all import *
>>> fan = NormalFan(ReflexivePolytope(Integer(2), Integer(0)))
>>> X = ToricVariety(fan, base_ring=GF(Integer(7)), names=('u', 'v', 'w',));␣
↪(u, v, w,) = X._first_ngens(3)
>>> Y = X.subscheme(u**Integer(3) + v**Integer(3) + w**Integer(3) + u*v*w)
>>> point_set = Y.point_set()
>>> list(point_set)                                                      #␣
↪needs fplll
[[0 : 1 : 3],
 [1 : 0 : 3],
 [1 : 3 : 0],
 [1 : 1 : 6],
 [1 : 1 : 4],
 [1 : 3 : 2],
 [1 : 3 : 5]]
>>> ffe = point_set._enumerator()                                        #␣
↪needs fplll
>>> ffe.cardinality()                                                    #␣
↪needs fplll
7
```

homogeneous_coordinates(*log_t*, *nonzero_coordinates*, *cokernel*)

Convert the log of inhomogeneous coordinates back to homogeneous coordinates.

INPUT:

- `log_t` – log of inhomogeneous coordinates of a point
- `nonzero_coordinates` – the nonzero homogeneous coordinates in the patch
- `cokernel` – the logs of the nonzero coordinates of all distinct points as a cokernel. See *FiniteFieldPointEnumerator.cone_points_iter()*.

OUTPUT: the same point, but as a tuple of homogeneous coordinates

EXAMPLES:

```
sage: P2.<x,y,z> = toric_varieties.P2(base_ring=GF(7))
sage: X = P2.subscheme([x^3 + 2*y^3 + 3*z^3, x*y*z + x*y^2])
sage: point_set = X.point_set()
sage: ffe = point_set._enumerator()
sage: cone, nonzero_coordinates, cokernel = list(ffe.ambient.cone_points_
↪iter())[5]
sage: cone.ambient_ray_indices(), nonzero_coordinates
((2,), [0, 1])
sage: ffe.homogeneous_coordinates([0], nonzero_coordinates, cokernel)
(1, 1, 0)
sage: ffe.homogeneous_coordinates([1], nonzero_coordinates, cokernel)
(1, 3, 0)
sage: ffe.homogeneous_coordinates([2], nonzero_coordinates, cokernel)
(1, 2, 0)
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2(base_ring=GF(Integer(7)), names=('x', 'y', 'z',));
↪ (x, y, z,) = P2._first_ngens(3)
>>> X = P2.subscheme([x**Integer(3) + Integer(2)*y**Integer(3) +␣
↪Integer(3)*z**Integer(3), x*y*z + x*y**Integer(2)])
>>> point_set = X.point_set()
>>> ffe = point_set._enumerator()
>>> cone, nonzero_coordinates, cokernel = list(ffe.ambient.cone_points_
↪iter())[Integer(5)]
>>> cone.ambient_ray_indices(), nonzero_coordinates
((2,), [0, 1])
>>> ffe.homogeneous_coordinates([Integer(0)], nonzero_coordinates, cokernel)
(1, 1, 0)
>>> ffe.homogeneous_coordinates([Integer(1)], nonzero_coordinates, cokernel)
(1, 3, 0)
>>> ffe.homogeneous_coordinates([Integer(2)], nonzero_coordinates, cokernel)
(1, 2, 0)
```

inhomogeneous_equations(*ring*, *nonzero_coordinates*, *cokernel*)

Inhomogenize the defining polynomials.

INPUT:

- `ring` – the polynomial ring for inhomogeneous coordinates
- `nonzero_coordinates` – list of integers. The indices of the nonzero homogeneous coordinates in the patch
- `cokernel` – the logs of the nonzero coordinates of all distinct points as a cokernel. See *FiniteFieldPointEnumerator.cone_points_iter()*.

EXAMPLES:

```
sage: R.<s> = QQ[]
sage: P2.<x,y,z> = toric_varieties.P2(base_ring=GF(7))
sage: X = P2.subscheme([x^3 + 2*y^3 + 3*z^3, x*y*z + x*y^2])
sage: point_set = X.point_set()
sage: ffe = point_set._enumerator()
sage: cone, nonzero_coordinates, cokernel = list(ffe.ambient.cone_points_
↪iter())[5]
```

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```
sage: cone.ambient_ray_indices(), nonzero_coordinates
((2,), [0, 1])
sage: ffe.inhomogeneous_equations(R, nonzero_coordinates, cokernel)
[2*s^3 + 1, s^2]
```

```
>>> from sage.all import *
>>> R = QQ['s']; (s,) = R._first_ngens(1)
>>> P2 = toric_varieties.P2(base_ring=GF(Integer(7)), names=('x', 'y', 'z',));
↪ (x, y, z,) = P2._first_ngens(3)
>>> X = P2.subscheme([x**Integer(3) + Integer(2)*y**Integer(3) +␣
↪Integer(3)*z**Integer(3), x*y*z + x*y**Integer(2)])
>>> point_set = X.point_set()
>>> ffe = point_set._enumerator()
>>> cone, nonzero_coordinates, cokernel = list(ffe.ambient.cone_points_
↪iter())[Integer(5)]
>>> cone.ambient_ray_indices(), nonzero_coordinates
((2,), [0, 1])
>>> ffe.inhomogeneous_equations(R, nonzero_coordinates, cokernel)
[2*s^3 + 1, s^2]
```

solutions(*inhomogeneous_equations*, *log_range*)

Parallel version of *solutions_serial()*.

INPUT/OUTPUT:

Same as *solutions_serial()*, except that the output points are in random order. Order depends on the number of processors and relative speed of separate processes.

EXAMPLES:

```
sage: R.<s> = GF(7)[]
sage: P2.<x,y,z> = toric_varieties.P2(base_ring=GF(7))
sage: X = P2.subscheme(1)
sage: point_set = X.point_set()
sage: ffe = point_set._enumerator()
sage: ffe.solutions([s^2 - 1, s^6 - s^2], [range(6)])
<generator object ...solutions at 0x...>
sage: sorted(_)
[(0,), (3,)]
```

```
>>> from sage.all import *
>>> R = GF(Integer(7))['s']; (s,) = R._first_ngens(1)
>>> P2 = toric_varieties.P2(base_ring=GF(Integer(7)), names=('x', 'y', 'z',));
↪ (x, y, z,) = P2._first_ngens(3)
>>> X = P2.subscheme(Integer(1))
>>> point_set = X.point_set()
>>> ffe = point_set._enumerator()
>>> ffe.solutions([s**Integer(2) - Integer(1), s**Integer(6) - s**Integer(2)],
↪ [range(Integer(6))])
<generator object ...solutions at 0x...>
>>> sorted(_)
[(0,), (3,)]
```

solutions_serial(*inhomogeneous_equations*, *log_range*)

Iterate over solutions in a range.

INPUT:

- `inhomogeneous_equations` – list/tuple/iterable of inhomogeneous equations (i.e. output from *inhomogeneous_equations()*).
- `log_range` – list/tuple/iterable of integer ranges. One for each inhomogeneous coordinate. The logarithms of the homogeneous coordinates.

OUTPUT:

All solutions (as tuple of log inhomogeneous coordinates) in the Cartesian product of the ranges.

EXAMPLES:

```
sage: R.<s> = GF(7)[]
sage: P2.<x,y,z> = toric_varieties.P2(base_ring=GF(7))
sage: X = P2.subscheme(1)
sage: point_set = X.point_set()
sage: ffe = point_set._enumerator()
sage: ffe.solutions_serial([s^2 - 1, s^6 - s^2], [range(6)])
<generator object ...solutions_serial at 0x...>
sage: list(_)
[(0,), (3,)]
```

```
>>> from sage.all import *
>>> R = GF(Integer(7))['s']; (s,) = R._first_ngens(1)
>>> P2 = toric_varieties.P2(base_ring=GF(Integer(7)), names=('x', 'y', 'z',));
 ↪ (x, y, z,) = P2._first_ngens(3)
>>> X = P2.subscheme(Integer(1))
>>> point_set = X.point_set()
>>> ffe = point_set._enumerator()
>>> ffe.solutions_serial([s**Integer(2) - Integer(1), s**Integer(6) -␣
↪s**Integer(2)], [range(Integer(6))])
<generator object ...solutions_serial at 0x...>
>>> list(_)
[(0,), (3,)]
```

class sage.schemes.toric.points.**InfinitePointEnumerator**(*fan*, *ring*)

Bases: `object`

Point enumerator for infinite fields.

INPUT:

- `fan` – fan of the toric variety
- `ring` – infinite base ring over which to enumerate points

class sage.schemes.toric.points.**NaiveFinitePointEnumerator**(*fan*, *ring*)

Bases: `object`

The naive point enumerator.

This is very slow.

INPUT:

- `fan` – fan of the toric variety

- `ring` – finite base ring over which to enumerate points

EXAMPLES:

```
sage: from sage.schemes.toric.points import NaiveFinitePointEnumerator
sage: fan = toric_varieties.P2().fan()
sage: n = NaiveFinitePointEnumerator(fan, GF(3))
sage: next(iter(n))
(0, 0, 1)
```

```
>>> from sage.all import *
>>> from sage.schemes.toric.points import NaiveFinitePointEnumerator
>>> fan = toric_varieties.P2().fan()
>>> n = NaiveFinitePointEnumerator(fan, GF(Integer(3)))
>>> next(iter(n))
(0, 0, 1)
```

cone_iter()

Iterate over all cones of the fan.

OUTPUT:

Iterator over the cones, starting with the high-dimensional ones.

EXAMPLES:

```
sage: dP6 = toric_varieties.dP6(base_ring=GF(11))
sage: ne = dP6.point_set()._naive_enumerator()
sage: for cone in ne.cone_iter():
....:     print(cone.ambient_ray_indices())
(0, 1)
(1, 2)
(2, 3)
(3, 4)
(4, 5)
(0, 5)
(0,)
(1,)
(2,)
(3,)
(4,)
(5,)
()
```

```
>>> from sage.all import *
>>> dP6 = toric_varieties.dP6(base_ring=GF(Integer(11)))
>>> ne = dP6.point_set()._naive_enumerator()
>>> for cone in ne.cone_iter():
...     print(cone.ambient_ray_indices())
(0, 1)
(1, 2)
(2, 3)
(3, 4)
(4, 5)
(0, 5)
```

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```
(0,)
(1,)
(2,)
(3,)
(4,)
(5,)
()
```

coordinate_iter()

Iterate over all distinct homogeneous coordinates.

This method does NOT identify homogeneous coordinates that are equivalent by a homogeneous rescaling.

OUTPUT: an iterator over the points

EXAMPLES:

```
sage: P2 = toric_varieties.P2(base_ring=GF(2))
sage: ni = P2.point_set()._naive_enumerator()
sage: list(ni.coordinate_iter())
[(0, 0, 1), (1, 0, 0), (0, 1, 0), (0, 1, 1),
 (1, 0, 1), (1, 1, 0), (1, 1, 1)]

sage: P1xP1 = toric_varieties.P1xP1(base_ring=GF(2))
sage: ni = P1xP1.point_set()._naive_enumerator()
sage: list(ni.coordinate_iter())
[(0, 1, 0, 1), (1, 0, 0, 1), (1, 0, 1, 0),
 (0, 1, 1, 0), (0, 1, 1, 1), (1, 0, 1, 1),
 (1, 1, 0, 1), (1, 1, 1, 0), (1, 1, 1, 1)]
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2(base_ring=GF(Integer(2)))
>>> ni = P2.point_set()._naive_enumerator()
>>> list(ni.coordinate_iter())
[(0, 0, 1), (1, 0, 0), (0, 1, 0), (0, 1, 1),
 (1, 0, 1), (1, 1, 0), (1, 1, 1)]

>>> P1xP1 = toric_varieties.P1xP1(base_ring=GF(Integer(2)))
>>> ni = P1xP1.point_set()._naive_enumerator()
>>> list(ni.coordinate_iter())
[(0, 1, 0, 1), (1, 0, 0, 1), (1, 0, 1, 0),
 (0, 1, 1, 0), (0, 1, 1, 1), (1, 0, 1, 1),
 (1, 1, 0, 1), (1, 1, 1, 0), (1, 1, 1, 1)]
```

orbit(*point*)

Return the orbit of homogeneous coordinates under rescalings.

OUTPUT: the set of all homogeneous coordinates that are equivalent to `point`

EXAMPLES:

```
sage: P2_123 = toric_varieties.P2_123(base_ring=GF(7))
sage: ne = P2_123.point_set()._naive_enumerator()
sage: sorted(ne.orbit([1, 0, 0]))
```

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```
[(1, 0, 0), (2, 0, 0), (4, 0, 0)]
sage: sorted(ne.orbit([0, 1, 0]))
[(0, 1, 0), (0, 6, 0)]
sage: sorted(ne.orbit([0, 0, 1]))
[(0, 0, 1), (0, 0, 2), (0, 0, 3), (0, 0, 4), (0, 0, 5), (0, 0, 6)]
sage: sorted(ne.orbit([1, 1, 0]))
[(1, 1, 0), (1, 6, 0), (2, 1, 0), (2, 6, 0), (4, 1, 0), (4, 6, 0)]
```

```
>>> from sage.all import *
>>> P2_123 = toric_varieties.P2_123(base_ring=GF(Integer(7)))
>>> ne = P2_123.point_set()._naive_enumerator()
>>> sorted(ne.orbit([Integer(1), Integer(0), Integer(0)]))
[(1, 0, 0), (2, 0, 0), (4, 0, 0)]
>>> sorted(ne.orbit([Integer(0), Integer(1), Integer(0)]))
[(0, 1, 0), (0, 6, 0)]
>>> sorted(ne.orbit([Integer(0), Integer(0), Integer(1)]))
[(0, 0, 1), (0, 0, 2), (0, 0, 3), (0, 0, 4), (0, 0, 5), (0, 0, 6)]
>>> sorted(ne.orbit([Integer(1), Integer(1), Integer(0)]))
[(1, 1, 0), (1, 6, 0), (2, 1, 0), (2, 6, 0), (4, 1, 0), (4, 6, 0)]
```

rays()

Return all rays (real and virtual).

OUTPUT: tuple of rays of the fan

EXAMPLES:

```
sage: from sage.schemes.toric.points import NaiveFinitePointEnumerator
sage: fan = toric_varieties.torus(2).fan()
sage: fan.rays()
Empty collection
in 2-d lattice N
sage: n = NaiveFinitePointEnumerator(fan, GF(3))
sage: n.rays()
N(1, 0),
N(0, 1)
in 2-d lattice N
```

```
>>> from sage.all import *
>>> from sage.schemes.toric.points import NaiveFinitePointEnumerator
>>> fan = toric_varieties.torus(Integer(2)).fan()
>>> fan.rays()
Empty collection
in 2-d lattice N
>>> n = NaiveFinitePointEnumerator(fan, GF(Integer(3)))
>>> n.rays()
N(1, 0),
N(0, 1)
in 2-d lattice N
```

rescalings()

Return the rescalings of homogeneous coordinates.

OUTPUT:

A tuple containing all points that are equivalent to $[1 : 1 : \cdots : 1]$, the distinguished point of the big torus orbit.

EXAMPLES:

```
sage: P2_123 = toric_varieties.P2_123(base_ring=GF(5))
sage: ni = P2_123.point_set()._naive_enumerator()
sage: ni.rescalings()
((1, 1, 1), (1, 4, 4), (4, 2, 3), (4, 3, 2))

sage: dP8 = toric_varieties.dP8(base_ring=GF(3))
sage: ni = dP8.point_set()._naive_enumerator()
sage: ni.rescalings()
((1, 1, 1, 1), (1, 2, 2, 2), (2, 1, 2, 1), (2, 2, 1, 2))

sage: P1xP1 = toric_varieties.P1xP1(base_ring=GF(3))
sage: ni = P1xP1.point_set()._naive_enumerator()
sage: ni.rescalings()
((1, 1, 1, 1), (1, 1, 2, 2), (2, 2, 1, 1), (2, 2, 2, 2))
```

```
>>> from sage.all import *
>>> P2_123 = toric_varieties.P2_123(base_ring=GF(Integer(5)))
>>> ni = P2_123.point_set()._naive_enumerator()
>>> ni.rescalings()
((1, 1, 1), (1, 4, 4), (4, 2, 3), (4, 3, 2))

>>> dP8 = toric_varieties.dP8(base_ring=GF(Integer(3)))
>>> ni = dP8.point_set()._naive_enumerator()
>>> ni.rescalings()
((1, 1, 1, 1), (1, 2, 2, 2), (2, 1, 2, 1), (2, 2, 1, 2))

>>> P1xP1 = toric_varieties.P1xP1(base_ring=GF(Integer(3)))
>>> ni = P1xP1.point_set()._naive_enumerator()
>>> ni.rescalings()
((1, 1, 1, 1), (1, 1, 2, 2), (2, 2, 1, 1), (2, 2, 2, 2))
```

roots(n)

Return the n-th roots in the base field.

INPUT:

- `n` – integer

OUTPUT:

Tuple containing all n-th roots (not only the primitive ones). In particular, 1 is included.

EXAMPLES:

```
sage: P2 = toric_varieties.P2(base_ring=GF(5))
sage: ne = P2.point_set()._naive_enumerator()
sage: ne.roots(2)
(1, 4)
sage: ne.roots(3)
(1,)
```

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```
sage: ne.roots(4)
(1, 2, 3, 4)
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2(base_ring=GF(Integer(5)))
>>> ne = P2.point_set()._naive_enumerator()
>>> ne.roots(Integer(2))
(1, 4)
>>> ne.roots(Integer(3))
(1,)
>>> ne.roots(Integer(4))
(1, 2, 3, 4)
```

units()

Return the units in the base field.

EXAMPLES:

```
sage: P2 = toric_varieties.P2(base_ring=GF(5))
sage: ne = P2.point_set()._naive_enumerator()
sage: ne.units()
(1, 2, 3, 4)
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2(base_ring=GF(Integer(5)))
>>> ne = P2.point_set()._naive_enumerator()
>>> ne.units()
(1, 2, 3, 4)
```

class sage.schemes.toric.points.**NaiveSubschemePointEnumerator**(*polynomials*, *ambient*)

Bases: object

Point enumerator for algebraic subschemes of toric varieties.

INPUT:

- polynomials – list/tuple/iterable of polynomials; the defining polynomials
- ambient – enumerator for ambient space points

16.15 Construct sheaves on toric varieties

A toric vector bundle (on a toric variety) is a vector bundle that is equivariant with respect to the algebraic torus action.

sage.schemes.toric.sheaf.constructor.**CotangentBundle**(*X*)

Construct the cotangent bundle of a toric variety.

INPUT:

- X – a toric variety; the base space of the bundle

OUTPUT: the cotangent bundle as a Klyachko bundle

EXAMPLES:

```
sage: dP7 = toric_varieties.dP7()
sage: from sage.schemes.toric.sheaf.constructor import CotangentBundle
sage: CotangentBundle(dP7)
Rank 2 bundle on 2-d CPR-Fano toric variety covered by 5 affine patches.
```

```
>>> from sage.all import *
>>> dP7 = toric_varieties.dP7()
>>> from sage.schemes.toric.sheaf.constructor import CotangentBundle
>>> CotangentBundle(dP7)
Rank 2 bundle on 2-d CPR-Fano toric variety covered by 5 affine patches.
```

sage.schemes.toric.sheaf.constructor.**LineBundle**(X, D)

Construct the rank-1 bundle $O(D)$.

INPUT:

- `X` – a toric variety; the base space of the bundle
- `D` – a toric divisor

OUTPUT:

The line bundle $O(D)$ as a Klyachko bundle of rank 1.

EXAMPLES:

```
sage: X = toric_varieties.dP8()
sage: D = X.divisor(0)
sage: from sage.schemes.toric.sheaf.constructor import LineBundle
sage: O_D = LineBundle(X, D)
sage: O_D.cohomology(dim=True, weight=(0,0))
(1, 0, 0)
```

```
>>> from sage.all import *
>>> X = toric_varieties.dP8()
>>> D = X.divisor(Integer(0))
>>> from sage.schemes.toric.sheaf.constructor import LineBundle
>>> O_D = LineBundle(X, D)
>>> O_D.cohomology(dim=True, weight=(Integer(0),Integer(0)))
(1, 0, 0)
```

class sage.schemes.toric.sheaf.constructor.**SheafLibrary**(*toric_variety*)

Bases: `object`

Utility object to construct sheaves on toric varieties.

Warning

You should never construct instances manually. Can be accessed from a toric variety via the *sage.schemes.toric.variety.ToricVariety_field.sheaves* attribute.

EXAMPLES:

```
sage: type(toric_varieties.P2().sheaves)
<class 'sage.schemes.toric.sheaf.constructor.SheafLibrary'>
```

```
>>> from sage.all import *
>>> type(toric_varieties.P2().sheaves)
<class 'sage.schemes.toric.sheaf.constructor.SheafLibrary'>
```

Klyachko(*multi_filtration*)

Construct a Klyachko bundle (sheaf) from filtration data.

INPUT:

- `multi_filtration` – a multi-filtered vectors space with multiple filtrations being indexed by the rays of the fan. Either an instance of `MultiFilteredVectorSpace()` or something (like a dictionary of ordinary filtered vector spaces).

OUTPUT:

The Klyachko bundle defined by the filtrations, one for each ray, of a vector space.

EXAMPLES:

```
sage: P1 = toric_varieties.P1()
sage: v1, v2, v3 = [(1,0,0), (0,1,0), (0,0,1)]
sage: F1 = FilteredVectorSpace({1: [v1, v2, v3], 3: [v1]})
sage: F2 = FilteredVectorSpace({0: [v1, v2, v3], 2: [v2, v3]})
sage: P1 = toric_varieties.P1()
sage: r1, r2 = P1.fan().rays()
sage: F = MultiFilteredVectorSpace({r1:F1, r2:F2});  F
Filtrations
    N(-1): QQ^3 >= QQ^2 >= QQ^2 >=  0   >= 0
     N(1): QQ^3 >= QQ^3 >= QQ^1 >= QQ^1 >= 0
sage: P1.sheaves.Klyachko(F)
Rank 3 bundle on 1-d CPR-Fano toric variety covered by 2 affine patches.
```

```
>>> from sage.all import *
>>> P1 = toric_varieties.P1()
>>> v1, v2, v3 = [(Integer(1),Integer(0),Integer(0)), (Integer(0),Integer(1),
↪Integer(0)), (Integer(0),Integer(0),Integer(1))]
>>> F1 = FilteredVectorSpace({Integer(1): [v1, v2, v3], Integer(3): [v1]})
>>> F2 = FilteredVectorSpace({Integer(0): [v1, v2, v3], Integer(2): [v2, v3]})
>>> P1 = toric_varieties.P1()
>>> r1, r2 = P1.fan().rays()
>>> F = MultiFilteredVectorSpace({r1:F1, r2:F2});  F
Filtrations
    N(-1): QQ^3 >= QQ^2 >= QQ^2 >=  0   >= 0
     N(1): QQ^3 >= QQ^3 >= QQ^1 >= QQ^1 >= 0
>>> P1.sheaves.Klyachko(F)
Rank 3 bundle on 1-d CPR-Fano toric variety covered by 2 affine patches.
```

cotangent_bundle()

Return the cotangent bundle of the toric variety.

OUTPUT: the cotangent bundle as a Klyachko bundle

EXAMPLES:

```
sage: dP6 = toric_varieties.dP6()
sage: TX = dP6.sheaves.tangent_bundle()
```

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```
sage: TXdual = dP6.sheaves.cotangent_bundle()
sage: TXdual == TX.dual()
True
```

```
>>> from sage.all import *
>>> dP6 = toric_varieties.dP6()
>>> TX = dP6.sheaves.tangent_bundle()
>>> TXdual = dP6.sheaves.cotangent_bundle()
>>> TXdual == TX.dual()
True
```

divisor(**args*, ***kwds*)

Return a toric divisor.

INPUT:

This is just an alias for *sage.schemes.toric.variety.ToricVariety_field.divisor()*, see there for details.

By abuse of notation, you can usually use the divisor D interchangeably with the line bundle $O(D)$.

OUTPUT: a toric divisor

EXAMPLES:

```
sage: dP6 = toric_varieties.dP6()
sage: dP6.inject_variables()
Defining x, u, y, v, z, w
sage: D = dP6.sheaves.divisor(x*u^3);  D
V(x) + 3*V(u)
sage: D == dP6.divisor(x*u^3)
True
```

```
>>> from sage.all import *
>>> dP6 = toric_varieties.dP6()
>>> dP6.inject_variables()
Defining x, u, y, v, z, w
>>> D = dP6.sheaves.divisor(x*u**Integer(3));  D
V(x) + 3*V(u)
>>> D == dP6.divisor(x*u**Integer(3))
True
```

line_bundle(*divisor*)

Construct the rank-1 bundle $O(D)$.

INPUT:

- `divisor` – a toric divisor

OUTPUT:

The line bundle $O(D)$ for the given divisor as a Klyachko bundle of rank 1.

EXAMPLES:

```
sage: X = toric_varieties.dP8()
sage: D = X.divisor(0)
sage: O_D = X.sheaves.line_bundle(D)
sage: O_D.cohomology(dim=True, weight=(0,0))
(1, 0, 0)
```

```
>>> from sage.all import *
>>> X = toric_varieties.dP8()
>>> D = X.divisor(Integer(0))
>>> O_D = X.sheaves.line_bundle(D)
>>> O_D.cohomology(dim=True, weight=(Integer(0),Integer(0)))
(1, 0, 0)
```

tangent_bundle()

Return the tangent bundle of the toric variety.

OUTPUT: the tangent bundle as a Klyachko bundle

EXAMPLES:

```
sage: toric_varieties.dP6().sheaves.tangent_bundle()
Rank 2 bundle on 2-d CPR-Fano toric variety covered by 6 affine patches.
```

```
>>> from sage.all import *
>>> toric_varieties.dP6().sheaves.tangent_bundle()
Rank 2 bundle on 2-d CPR-Fano toric variety covered by 6 affine patches.
```

trivial_bundle(*rank=1*)

Return the trivial bundle of rank `r`.

INPUT:

- `rank` – integer (default: 1); the rank of the bundle

OUTPUT: the trivial bundle as a Klyachko bundle

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: I3 = P2.sheaves.trivial_bundle(3);  I3
Rank 3 bundle on 2-d CPR-Fano toric variety covered by 3 affine patches.
sage: I3.cohomology(weight=(0,0), dim=True)
(3, 0, 0)
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> I3 = P2.sheaves.trivial_bundle(Integer(3));  I3
Rank 3 bundle on 2-d CPR-Fano toric variety covered by 3 affine patches.
>>> I3.cohomology(weight=(Integer(0),Integer(0)), dim=True)
(3, 0, 0)
```

sage.schemes.toric.sheaf.constructor.**TangentBundle**(*X*)

Construct the tangent bundle of a toric variety.

INPUT:

- X – a toric variety; the base space of the bundle

OUTPUT: the tangent bundle as a Klyachko bundle

EXAMPLES:

```
sage: dP7 = toric_varieties.dP7()
sage: from sage.schemes.toric.sheaf.constructor import TangentBundle
sage: TangentBundle(dP7)
Rank 2 bundle on 2-d CPR-Fano toric variety covered by 5 affine patches.
```

```
>>> from sage.all import *
>>> dP7 = toric_varieties.dP7()
>>> from sage.schemes.toric.sheaf.constructor import TangentBundle
>>> TangentBundle(dP7)
Rank 2 bundle on 2-d CPR-Fano toric variety covered by 5 affine patches.
```

sage.schemes.toric.sheaf.constructor.**TrivialBundle**(*X*, *rank=1*)

Return the trivial bundle of rank r.

INPUT:

- X – a toric variety; the base space of the bundle
- rank – the rank of the bundle

OUTPUT: the trivial bundle as a Klyachko bundle

EXAMPLES:

```
sage: P2 = toric_varieties.P2()
sage: from sage.schemes.toric.sheaf.constructor import TrivialBundle
sage: I3 = TrivialBundle(P2, 3);  I3
Rank 3 bundle on 2-d CPR-Fano toric variety covered by 3 affine patches.
sage: I3.cohomology(weight=(0,0), dim=True)
(3, 0, 0)
```

```
>>> from sage.all import *
>>> P2 = toric_varieties.P2()
>>> from sage.schemes.toric.sheaf.constructor import TrivialBundle
>>> I3 = TrivialBundle(P2, Integer(3));  I3
Rank 3 bundle on 2-d CPR-Fano toric variety covered by 3 affine patches.
>>> I3.cohomology(weight=(Integer(0),Integer(0)), dim=True)
(3, 0, 0)
```

16.16 Klyachko bundles and sheaves

Klyachko bundles are torus-equivariant bundles on toric varieties. That is, the action of the maximal torus on the toric variety lifts to an action on the bundle. There is an equivalence of categories between Klyachko bundles [Kly1990] and multiple filtrations (one for each ray of the fan) of a vector space. The multi-filtrations are implemented in sage.modules.multi_filtered_vector_space.

EXAMPLES:

```
sage: X = toric_varieties.dP6xdP6()
sage: TX = X.sheaves.tangent_bundle()
```

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```
sage: Alt2TX = TX.exterior_power(2);  Alt2TX
Rank 6 bundle on 4-d CPR-Fano toric variety covered by 36 affine patches.

sage: K = X.sheaves.line_bundle(X.K())
sage: antiK = X.sheaves.line_bundle(-X.K())
sage: (Alt2TX * K).cohomology(dim=True, weight=(0,0,0,0))  # long time
(0, 0, 18, 0, 0)

sage: G_sum = TX + X.sheaves.trivial_bundle(2)
sage: V_sum = G_sum.wedge(2) * K                      # long time
sage: V_sum.cohomology(dim=True, weight=(0,0,0,0))    # long time
(0, 0, 18, 16, 1)
sage: Gtilde = G_sum.random_deformation()
sage: V = Gtilde.wedge(2) * K                       # long time
sage: V.cohomology(dim=True, weight=(0,0,0,0))    # long time  # random failure (see
↪#32773)
(0, 0, 3, 0, 0)
```

```
>>> from sage.all import *
>>> X = toric_varieties.dP6xdP6()
>>> TX = X.sheaves.tangent_bundle()
>>> Alt2TX = TX.exterior_power(Integer(2));  Alt2TX
Rank 6 bundle on 4-d CPR-Fano toric variety covered by 36 affine patches.

>>> K = X.sheaves.line_bundle(X.K())
>>> antiK = X.sheaves.line_bundle(-X.K())
>>> (Alt2TX * K).cohomology(dim=True, weight=(Integer(0),Integer(0),Integer(0),
↪Integer(0)))  # long time
(0, 0, 18, 0, 0)

>>> G_sum = TX + X.sheaves.trivial_bundle(Integer(2))
>>> V_sum = G_sum.wedge(Integer(2)) * K                      # long time
>>> V_sum.cohomology(dim=True, weight=(Integer(0),Integer(0),Integer(0),Integer(0))) ␣
↪  # long time
(0, 0, 18, 16, 1)
>>> Gtilde = G_sum.random_deformation()
>>> V = Gtilde.wedge(Integer(2)) * K                       # long time
>>> V.cohomology(dim=True, weight=(Integer(0),Integer(0),Integer(0),Integer(0)))    #␣
↪long time  # random failure (see #32773)
(0, 0, 3, 0, 0)
```

REFERENCES:

- [Kly1990]
- [BIP]

sage.schemes.toric.sheaf.klyachko.**Bundle**(*toric_variety*, *multi_filtration*, *check=True*)

Construct a Klyacho bundle.

INPUT:

- `toric_variety` – a toric variety; the base space of the bundle
- `multi_filtration` – a multi-filtered vectors space with multiple filtrations being indexed by the

one-dimensional cones of the fan. Either an instance of `MultiFilteredVectorSpace()` or something (like a dictionary of ordinary filtered vector spaces).

EXAMPLES:

```
sage: P1 = toric_varieties.P1()
sage: v1, v2, v3 = [(1,0,0), (0,1,0), (0,0,1)]
sage: F1 = FilteredVectorSpace({1: [v1, v2, v3], 3: [v1]})
sage: F2 = FilteredVectorSpace({0: [v1, v2, v3], 2: [v2, v3]})
sage: P1 = toric_varieties.P1()
sage: r1, r2 = P1.fan().rays()
sage: F = MultiFilteredVectorSpace({r1: F1, r2: F2});  F
Filtrations
    N(-1): QQ^3 >= QQ^2 >= QQ^2 >=  0   >= 0
     N(1): QQ^3 >= QQ^3 >= QQ^1 >= QQ^1 >= 0
```

```
>>> from sage.all import *
>>> P1 = toric_varieties.P1()
>>> v1, v2, v3 = [(Integer(1),Integer(0),Integer(0)), (Integer(0),Integer(1),
↪Integer(0)), (Integer(0),Integer(0),Integer(1))]
>>> F1 = FilteredVectorSpace({Integer(1): [v1, v2, v3], Integer(3): [v1]})
>>> F2 = FilteredVectorSpace({Integer(0): [v1, v2, v3], Integer(2): [v2, v3]})
>>> P1 = toric_varieties.P1()
>>> r1, r2 = P1.fan().rays()
>>> F = MultiFilteredVectorSpace({r1: F1, r2: F2});  F
Filtrations
    N(-1): QQ^3 >= QQ^2 >= QQ^2 >=  0   >= 0
     N(1): QQ^3 >= QQ^3 >= QQ^1 >= QQ^1 >= 0
```

You should use the *`Klyachko()`* method to construct instances:

```
sage: P1.sheaves.Klyachko(F)
Rank 3 bundle on 1-d CPR-Fano toric variety covered by 2 affine patches.

sage: P1.sheaves.Klyachko({r1: F1, r2: F2})    # alternative
Rank 3 bundle on 1-d CPR-Fano toric variety covered by 2 affine patches.
```

```
>>> from sage.all import *
>>> P1.sheaves.Klyachko(F)
Rank 3 bundle on 1-d CPR-Fano toric variety covered by 2 affine patches.

>>> P1.sheaves.Klyachko({r1: F1, r2: F2})    # alternative
Rank 3 bundle on 1-d CPR-Fano toric variety covered by 2 affine patches.
```

The above is just a shorthand for:

```
sage: from sage.schemes.toric.sheaf.klyachko import Bundle
sage: Bundle(P1, F)
Rank 3 bundle on 1-d CPR-Fano toric variety covered by 2 affine patches.
```

```
>>> from sage.all import *
>>> from sage.schemes.toric.sheaf.klyachko import Bundle
>>> Bundle(P1, F)
Rank 3 bundle on 1-d CPR-Fano toric variety covered by 2 affine patches.
```

class sage.schemes.toric.sheaf.klyachko.**KlyachkoBundle_class**(*toric_variety*, *multi_filtration*, *check=True*)

Bases: SageObject

A toric bundle using Klyachko's representation.

Warning

You should always use the *Bundle()* factory function to construct instances.

INPUT:

- toric_variety – a toric variety; the base space of the bundle
- multi_filtration – a MultiFilteredVectorSpace() with index set the rays of the fan.
- check – boolean (default: True); whether to perform consistency checks

EXAMPLES:

```
sage: P1 = toric_varieties.P1()
sage: r1, r2 = P1.fan().rays()
sage: F = MultiFilteredVectorSpace({
....:       r1: FilteredVectorSpace(3,1),
....:       r2: FilteredVectorSpace(3,0)});  F
Filtrations
    N(-1): QQ^3 >=  0   >= 0
     N(1): QQ^3 >= QQ^3 >= 0
sage: from sage.schemes.toric.sheaf.klyachko import Bundle
sage: Bundle(P1, F)
Rank 3 bundle on 1-d CPR-Fano toric variety covered by 2 affine patches.
```

```
>>> from sage.all import *
>>> P1 = toric_varieties.P1()
>>> r1, r2 = P1.fan().rays()
>>> F = MultiFilteredVectorSpace({
...       r1: FilteredVectorSpace(Integer(3),Integer(1)),
...       r2: FilteredVectorSpace(Integer(3),Integer(0))});  F
Filtrations
    N(-1): QQ^3 >=  0   >= 0
     N(1): QQ^3 >= QQ^3 >= 0
>>> from sage.schemes.toric.sheaf.klyachko import Bundle
>>> Bundle(P1, F)
Rank 3 bundle on 1-d CPR-Fano toric variety covered by 2 affine patches.
```

E_degree(*alpha*, *m*)

Return the vector subspace $E^\alpha(m)$.

INPUT:

- alpha – a ray of the fan. Can be specified by its index (an integer), a one-dimensional cone, or a N-lattice point.
- m – tuple of integers or M-lattice point. A point in the dual lattice of the fan.

OUTPUT:

The subspace $E^\alpha(\alpha m)$ of the filtration indexed by the ray α and at the filtration degree $\alpha * m$

EXAMPLES:

```
sage: X = toric_varieties.P2()
sage: M = X.fan().dual_lattice()
sage: V = X.sheaves.tangent_bundle()
sage: V.E_degree(X.fan().ray(0), (1,0))
Vector space of degree 2 and dimension 1 over Rational Field
Basis matrix: [1 0]
sage: V.E_degree(X.fan(1)[0], (1,0))
Vector space of degree 2 and dimension 1 over Rational Field
Basis matrix: [1 0]
sage: V.E_degree(0, (1,0))
Vector space of degree 2 and dimension 1 over Rational Field
Basis matrix: [1 0]
```

```
>>> from sage.all import *
>>> X = toric_varieties.P2()
>>> M = X.fan().dual_lattice()
>>> V = X.sheaves.tangent_bundle()
>>> V.E_degree(X.fan().ray(Integer(0)), (Integer(1),Integer(0)))
Vector space of degree 2 and dimension 1 over Rational Field
Basis matrix: [1 0]
>>> V.E_degree(X.fan(Integer(1))[Integer(0)], (Integer(1),Integer(0)))
Vector space of degree 2 and dimension 1 over Rational Field
Basis matrix: [1 0]
>>> V.E_degree(Integer(0), (Integer(1),Integer(0)))
Vector space of degree 2 and dimension 1 over Rational Field
Basis matrix: [1 0]
```

E_intersection(*sigma*, *m*)

Return the vector subspace $E^\sigma(m)$.

See [Kly1990], equation 4.1.

INPUT:

- `sigma` – a cone of the fan of the base toric variety
- `m` – tuple of integers or M-lattice point. A point in the dual lattice of the fan. Must be immutable.

OUTPUT: the subspace $E^\sigma(m)$.

EXAMPLES:

```
sage: X = toric_varieties.P2()
sage: fan = X.fan()
sage: V = X.sheaves.tangent_bundle()
sage: V.E_intersection(fan(1)[0], (1,0))
Vector space of degree 2 and dimension 1 over Rational Field
Basis matrix: [1 0]
sage: V.E_intersection(fan(2)[0], (-1,1))
Vector space of degree 2 and dimension 1 over Rational Field
Basis matrix: [0 1]
```

```
>>> from sage.all import *
>>> X = toric_varieties.P2()
>>> fan = X.fan()
>>> V = X.sheaves.tangent_bundle()
>>> V.E_intersection(fan(Integer(1))[Integer(0)], (Integer(1),Integer(0)))
Vector space of degree 2 and dimension 1 over Rational Field
Basis matrix: [1 0]
>>> V.E_intersection(fan(Integer(2))[Integer(0)], (-Integer(1),Integer(1)))
Vector space of degree 2 and dimension 1 over Rational Field
Basis matrix: [0 1]
```

For the empty cone, this is always the whole vector space:

```
sage: V.E_intersection(fan(0)[0], (1,0))
Vector space of dimension 2 over Rational Field
```

```
>>> from sage.all import *
>>> V.E_intersection(fan(Integer(0))[Integer(0)], (Integer(1),Integer(0)))
Vector space of dimension 2 over Rational Field
```

E_quotient(*sigma*, *m*)

Return the vector space quotient $E_\sigma(m)$.

See [Kly1990], equation 4.1.

INPUT:

- `sigma` – a cone of the fan of the base toric variety
- `m` – tuple of integers or M-lattice point. A point in the dual lattice of the fan. Must be immutable.

OUTPUT: the subspace $E_\sigma(m)$.

EXAMPLES:

```
sage: X = toric_varieties.P2()
sage: fan = X.fan()
sage: M = fan.dual_lattice()
sage: cone = fan(1)[0]
sage: V = X.sheaves.tangent_bundle()
sage: m = M(1, 0)
sage: m.set_immutable()
sage: V.E_quotient(cone, m)
Vector space quotient V/W of dimension 1 over Rational Field where
 V: Vector space of dimension 2 over Rational Field
 W: Vector space of degree 2 and dimension 1 over Rational Field
    Basis matrix: [1 0]
sage: V.E_quotient(fan(2)[0], (-1,1))
Vector space quotient V/W of dimension 0 over Rational Field where
 V: Vector space of dimension 2 over Rational Field
 W: Vector space of degree 2 and dimension 2 over Rational Field
    Basis matrix:
    [1 0]
    [0 1]
```

```
>>> from sage.all import *
>>> X = toric_varieties.P2()
>>> fan = X.fan()
>>> M = fan.dual_lattice()
>>> cone = fan(Integer(1))[Integer(0)]
>>> V = X.sheaves.tangent_bundle()
>>> m = M(Integer(1), Integer(0))
>>> m.set_immutable()
>>> V.E_quotient(cone, m)
Vector space quotient V/W of dimension 1 over Rational Field where
 V: Vector space of dimension 2 over Rational Field
 W: Vector space of degree 2 and dimension 1 over Rational Field
    Basis matrix: [1 0]
>>> V.E_quotient(fan(Integer(2))[Integer(0)], (-Integer(1),Integer(1)))
Vector space quotient V/W of dimension 0 over Rational Field where
 V: Vector space of dimension 2 over Rational Field
 W: Vector space of degree 2 and dimension 2 over Rational Field
    Basis matrix:
    [1 0]
    [0 1]
```

E_quotient_projection(*sigma*, *tau*, *m*)

Return the projection map $E_\sigma(m) \to E_\tau(m)$ where σ is a face of τ.

INPUT:

- `sigma` – a cone of the fan of the base toric variety
- `tau` – a cone of the fan containing `sigma`
- `m` – tuple of integers or M-lattice point. A point in the dual lattice of the fan. Must be immutable.

OUTPUT: the restriction map

$$E_\sigma(m) \to E_\tau(m)$$

EXAMPLES:

```
sage: P3 = toric_varieties.P(3)
sage: rays = [(1,0,0), (0,1,0), (0,0,1)]
sage: F1 = FilteredVectorSpace(rays, {0: [0], 1: [2], 2: [1]})
sage: F2 = FilteredVectorSpace(3, 0)
sage: r = P3.fan().rays()
sage: V = P3.sheaves.Klyachko({r[0]: F1, r[1]: F2, r[2]: F2, r[3]: F2})
sage: tau = Cone([(1,0,0), (0,1,0)])
sage: sigma = Cone([(1,0,0)])
sage: M = P3.fan().dual_lattice()
sage: m = M(2,1,0)
sage: m.set_immutable()
sage: V.E_quotient(sigma, m)
Vector space quotient V/W of dimension 2 over Rational Field where
 V: Vector space of dimension 3 over Rational Field
 W: Vector space of degree 3 and dimension 1 over Rational Field
    Basis matrix: [0 1 0]
sage: V.E_quotient(tau, m)
```

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```
Vector space quotient V/W of dimension 2 over Rational Field where
 V: Vector space of dimension 3 over Rational Field
 W: Vector space of degree 3 and dimension 1 over Rational Field
    Basis matrix: [0 1 0]
sage: V.E_quotient_projection(sigma, tau, m)
Vector space morphism represented by the matrix:
 [1 0]
 [0 1]
 Domain:   Vector space quotient V/W of dimension 2 over Rational Field where
           V: Vector space of dimension 3 over Rational Field
           W: Vector space of degree 3 and dimension 1 over Rational Field
              Basis matrix: [0 1 0]
 Codomain: Vector space quotient V/W of dimension 2 over Rational Field where
           V: Vector space of dimension 3 over Rational Field
           W: Vector space of degree 3 and dimension 1 over Rational Field
              Basis matrix: [0 1 0]
```

```
>>> from sage.all import *
>>> P3 = toric_varieties.P(Integer(3))
>>> rays = [(Integer(1),Integer(0),Integer(0)), (Integer(0),Integer(1),
↪Integer(0)), (Integer(0),Integer(0),Integer(1))]
>>> F1 = FilteredVectorSpace(rays, {Integer(0): [Integer(0)], Integer(1):␣
↪[Integer(2)], Integer(2): [Integer(1)]})
>>> F2 = FilteredVectorSpace(Integer(3), Integer(0))
>>> r = P3.fan().rays()
>>> V = P3.sheaves.Klyachko({r[Integer(0)]: F1, r[Integer(1)]: F2,␣
↪r[Integer(2)]: F2, r[Integer(3)]: F2})
>>> tau = Cone([(Integer(1),Integer(0),Integer(0)), (Integer(0),Integer(1),
↪Integer(0))])
>>> sigma = Cone([(Integer(1),Integer(0),Integer(0))])
>>> M = P3.fan().dual_lattice()
>>> m = M(Integer(2),Integer(1),Integer(0))
>>> m.set_immutable()
>>> V.E_quotient(sigma, m)
Vector space quotient V/W of dimension 2 over Rational Field where
 V: Vector space of dimension 3 over Rational Field
 W: Vector space of degree 3 and dimension 1 over Rational Field
    Basis matrix: [0 1 0]
>>> V.E_quotient(tau, m)
Vector space quotient V/W of dimension 2 over Rational Field where
 V: Vector space of dimension 3 over Rational Field
 W: Vector space of degree 3 and dimension 1 over Rational Field
    Basis matrix: [0 1 0]
>>> V.E_quotient_projection(sigma, tau, m)
Vector space morphism represented by the matrix:
 [1 0]
 [0 1]
 Domain:   Vector space quotient V/W of dimension 2 over Rational Field where
           V: Vector space of dimension 3 over Rational Field
           W: Vector space of degree 3 and dimension 1 over Rational Field
              Basis matrix: [0 1 0]
 Codomain: Vector space quotient V/W of dimension 2 over Rational Field where
```

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```
          V: Vector space of dimension 3 over Rational Field
          W: Vector space of degree 3 and dimension 1 over Rational Field
             Basis matrix: [0 1 0]
```

base_ring()

Return the base field.

OUTPUT: a field

EXAMPLES:

```
sage: T_P2 = toric_varieties.P2().sheaves.tangent_bundle()
sage: T_P2.base_ring()
Rational Field
```

```
>>> from sage.all import *
>>> T_P2 = toric_varieties.P2().sheaves.tangent_bundle()
>>> T_P2.base_ring()
Rational Field
```

cohomology(*degree=None*, *weight=None*, *dim=False*)

Return the bundle cohomology groups.

INPUT:

- `degree` – `None` (default) or an integer; the degree of the cohomology group
- `weight` – `None` (default) or a tuple of integers or a M-lattice point. A point in the dual lattice of the fan defining a torus character. The weight of the cohomology group.
- `dim` – boolean (default: `False`); whether to return vector spaces or only their dimension

OUTPUT:

The cohomology group of given cohomological `degree` and torus `weight`.

- If no `weight` is specified, the unweighted group (sum over all weights) is returned.
- If no `degree` is specified, a dictionary whose keys are integers and whose values are the cohomology groups is returned. If, in addition, `dim=True`, then an integral vector of the dimensions is returned.

EXAMPLES:

```
sage: V = toric_varieties.P2().sheaves.tangent_bundle()
sage: V.cohomology(degree=0, weight=(0,0))
Vector space of dimension 2 over Rational Field
sage: V.cohomology(weight=(0,0), dim=True)
(2, 0, 0)
sage: for i,j in cartesian_product((list(range(-2,3)), list(range(-2,3)))):
....:       HH = V.cohomology(weight=(i,j), dim=True)
....:       if HH.is_zero(): continue
....:       print('H^*i(P^2, TP^2)_M({}, {}) = {}'.format(i,j,HH))
H^*i(P^2, TP^2)_M(-1, 0) = (1, 0, 0)
H^*i(P^2, TP^2)_M(-1, 1) = (1, 0, 0)
H^*i(P^2, TP^2)_M(0, -1) = (1, 0, 0)
H^*i(P^2, TP^2)_M(0, 0) = (2, 0, 0)
H^*i(P^2, TP^2)_M(0, 1) = (1, 0, 0)
```

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```
H^*i(P^2, TP^2)_M(1, -1) = (1, 0, 0)
H^*i(P^2, TP^2)_M(1, 0) = (1, 0, 0)
```

```
>>> from sage.all import *
>>> V = toric_varieties.P2().sheaves.tangent_bundle()
>>> V.cohomology(degree=Integer(0), weight=(Integer(0),Integer(0)))
Vector space of dimension 2 over Rational Field
>>> V.cohomology(weight=(Integer(0),Integer(0)), dim=True)
(2, 0, 0)
>>> for i,j in cartesian_product((list(range(-Integer(2),Integer(3))),␣
↪list(range(-Integer(2),Integer(3))))):
...       HH = V.cohomology(weight=(i,j), dim=True)
...       if HH.is_zero(): continue
...       print('H^*i(P^2, TP^2)_M({}, {}) = {}'.format(i,j,HH))
H^*i(P^2, TP^2)_M(-1, 0) = (1, 0, 0)
H^*i(P^2, TP^2)_M(-1, 1) = (1, 0, 0)
H^*i(P^2, TP^2)_M(0, -1) = (1, 0, 0)
H^*i(P^2, TP^2)_M(0, 0) = (2, 0, 0)
H^*i(P^2, TP^2)_M(0, 1) = (1, 0, 0)
H^*i(P^2, TP^2)_M(1, -1) = (1, 0, 0)
H^*i(P^2, TP^2)_M(1, 0) = (1, 0, 0)
```

cohomology_complex(m)

Return the "cohomology complex" $C^*(m)$.

See [Kly1990], equation 4.2.

INPUT:

- `m` – tuple of integers or M-lattice point. A point in the dual lattice of the fan. Must be immutable.

OUTPUT:

The "cohomology complex" as a chain complex over the *base_ring()*.

EXAMPLES:

```
sage: P3 = toric_varieties.P(3)
sage: rays = [(1,0,0), (0,1,0), (0,0,1)]
sage: F1 = FilteredVectorSpace(rays, {0: [0], 1: [2], 2: [1]})
sage: F2 = FilteredVectorSpace(rays, {0: [1,2], 1: [0]})
sage: r = P3.fan().rays()
sage: V = P3.sheaves.Klyachko({r[0]: F1, r[1]: F2, r[2]: F2, r[3]: F2})
sage: tau = Cone([(1,0,0), (0,1,0)])
sage: sigma = Cone([(1, 0, 0)])
sage: M = P3.fan().dual_lattice()
sage: m = M(1, 1, 0); m.set_immutable()
sage: V.cohomology_complex(m)
Chain complex with at most 2 nonzero terms over Rational Field

sage: F = CyclotomicField(3)
sage: P3 = toric_varieties.P(3).change_ring(F)
sage: V = P3.sheaves.Klyachko({r[0]: F1, r[1]: F2, r[2]: F2, r[3]: F2})
sage: V.cohomology_complex(m)
```

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```
Chain complex with at most 2 nonzero terms over Cyclotomic
Field of order 3 and degree 2
```

```
>>> from sage.all import *
>>> P3 = toric_varieties.P(Integer(3))
>>> rays = [(Integer(1),Integer(0),Integer(0)), (Integer(0),Integer(1),
↪Integer(0)), (Integer(0),Integer(0),Integer(1))]
>>> F1 = FilteredVectorSpace(rays, {Integer(0): [Integer(0)], Integer(1):␣
↪[Integer(2)], Integer(2): [Integer(1)]})
>>> F2 = FilteredVectorSpace(rays, {Integer(0): [Integer(1),Integer(2)],␣
↪Integer(1): [Integer(0)]})
>>> r = P3.fan().rays()
>>> V = P3.sheaves.Klyachko({r[Integer(0)]: F1, r[Integer(1)]: F2,␣
↪r[Integer(2)]: F2, r[Integer(3)]: F2})
>>> tau = Cone([(Integer(1),Integer(0),Integer(0)), (Integer(0),Integer(1),
↪Integer(0))])
>>> sigma = Cone([(Integer(1), Integer(0), Integer(0))])
>>> M = P3.fan().dual_lattice()
>>> m = M(Integer(1), Integer(1), Integer(0)); m.set_immutable()
>>> V.cohomology_complex(m)
Chain complex with at most 2 nonzero terms over Rational Field

>>> F = CyclotomicField(Integer(3))
>>> P3 = toric_varieties.P(Integer(3)).change_ring(F)
>>> V = P3.sheaves.Klyachko({r[Integer(0)]: F1, r[Integer(1)]: F2,␣
↪r[Integer(2)]: F2, r[Integer(3)]: F2})
>>> V.cohomology_complex(m)
Chain complex with at most 2 nonzero terms over Cyclotomic
Field of order 3 and degree 2
```

direct_sum(*other*)

Return the sum of two vector bundles.

INPUT:

- `other` – a Klyachko bundle over the same base

OUTPUT: the direct sum as a new Klyachko bundle

EXAMPLES:

```
sage: X = toric_varieties.P2()
sage: V1 = X.sheaves.trivial_bundle(1)
sage: V2 = X.sheaves.trivial_bundle(2)
sage: V2.direct_sum(V1)
Rank 3 bundle on 2-d CPR-Fano toric variety covered by 3 affine patches.

sage: V1 = X.sheaves.trivial_bundle(1)
sage: V2 = X.sheaves.trivial_bundle(2)
sage: V2 == V1 + V1
True
```

```
>>> from sage.all import *
>>> X = toric_varieties.P2()
>>> V1 = X.sheaves.trivial_bundle(Integer(1))
>>> V2 = X.sheaves.trivial_bundle(Integer(2))
>>> V2.direct_sum(V1)
Rank 3 bundle on 2-d CPR-Fano toric variety covered by 3 affine patches.

>>> V1 = X.sheaves.trivial_bundle(Integer(1))
>>> V2 = X.sheaves.trivial_bundle(Integer(2))
>>> V2 == V1 + V1
True
```

dual()

Return the dual bundle.

OUTPUT: the dual bundle as a new Klyachko bundle

EXAMPLES:

```
sage: P1 = toric_varieties.P1()
sage: H = P1.divisor(0)
sage: L = P1.sheaves.line_bundle(H)
sage: L.dual()
Rank 1 bundle on 1-d CPR-Fano toric variety covered by 2 affine patches.
sage: L.dual() == P1.sheaves.line_bundle(-H)
True
```

```
>>> from sage.all import *
>>> P1 = toric_varieties.P1()
>>> H = P1.divisor(Integer(0))
>>> L = P1.sheaves.line_bundle(H)
>>> L.dual()
Rank 1 bundle on 1-d CPR-Fano toric variety covered by 2 affine patches.
>>> L.dual() == P1.sheaves.line_bundle(-H)
True
```

exterior_power(n)

Return the n-th exterior power.

INPUT:

- n – integer

OUTPUT:

The n-th exterior power $\wedge^n_{i=1} V$ of the bundle V as a new Klyachko bundle.

EXAMPLES:

```
sage: X = toric_varieties.P2_123()
sage: TX = X.sheaves.tangent_bundle()
sage: antiK = X.sheaves.line_bundle(-X.K())
sage: TX.exterior_power(2) == antiK
True
sage: TX.wedge(2) == antiK   # alias
True
```

```
>>> from sage.all import *
>>> X = toric_varieties.P2_123()
>>> TX = X.sheaves.tangent_bundle()
>>> antiK = X.sheaves.line_bundle(-X.K())
>>> TX.exterior_power(Integer(2)) == antiK
True
>>> TX.wedge(Integer(2)) == antiK   # alias
True
```

fiber()

Return the generic fiber of the vector bundle.

OUTPUT: a vector space over *base_ring()*

EXAMPLES:

```
sage: T_P2 = toric_varieties.P2().sheaves.tangent_bundle()
sage: T_P2.fiber()
Vector space of dimension 2 over Rational Field
```

```
>>> from sage.all import *
>>> T_P2 = toric_varieties.P2().sheaves.tangent_bundle()
>>> T_P2.fiber()
Vector space of dimension 2 over Rational Field
```

filtration_intersection(*sigma*, *i*)

Return the intersection of the filtered subspaces.

INPUT:

- `sigma` – a cone of the fan of the base toric variety
- `i` – integer; the filtration degree

OUTPUT:

Let the cone be spanned by the rays $\sigma = \langle r_1, \ldots, r_k \rangle$. This method returns the intersection

$$\bigcap_{r \in \{r_1, \ldots, r_k\}} E^r(i)$$

EXAMPLES:

```
sage: X = toric_varieties.P2()
sage: fan = X.fan()
sage: V = X.sheaves.tangent_bundle()
sage: V.filtration_intersection(fan(1)[0], 1)
Vector space of degree 2 and dimension 1 over Rational Field
Basis matrix: [1 0]
sage: V.filtration_intersection(fan(2)[0], 1)
Vector space of degree 2 and dimension 0 over Rational Field
Basis matrix: []
```

```
>>> from sage.all import *
>>> X = toric_varieties.P2()
>>> fan = X.fan()
```

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```
>>> V = X.sheaves.tangent_bundle()
>>> V.filtration_intersection(fan(Integer(1))[Integer(0)], Integer(1))
Vector space of degree 2 and dimension 1 over Rational Field
Basis matrix: [1 0]
>>> V.filtration_intersection(fan(Integer(2))[Integer(0)], Integer(1))
Vector space of degree 2 and dimension 0 over Rational Field
Basis matrix: []
```

get_degree(*ray*, *i*)

Return the vector subspace `E^\alpha(i)`.

- `ray` – integer; a N-lattice point, a one-dimensional cone, or `None` (default). Specifies a ray of the fan of the toric variety, either via its index or its generator.
- `i` – integer; the filtration degree

OUTPUT:

A subspace of the *`fiber()`* vector space. The defining data of a Klyachko bundle.

EXAMPLES:

```
sage: TX = toric_varieties.dP6().sheaves.tangent_bundle()
sage: TX.get_degree(0, 1)
Vector space of degree 2 and dimension 1 over Rational Field
Basis matrix: [0 1]
```

```
>>> from sage.all import *
>>> TX = toric_varieties.dP6().sheaves.tangent_bundle()
>>> TX.get_degree(Integer(0), Integer(1))
Vector space of degree 2 and dimension 1 over Rational Field
Basis matrix: [0 1]
```

get_filtration(*ray=None*)

Return the filtration associated to the `ray`.

INPUT:

- `ray` – integer; a N-lattice point, a one-dimensional cone, or `None` (default). Specifies a ray of the fan of the toric variety, either via its index or its generator.

OUTPUT:

The filtered vector space associated to the given `ray`. If no ray is specified, all filtrations are returned.

EXAMPLES:

```
sage: TX = toric_varieties.dP6().sheaves.tangent_bundle()
sage: TX.get_filtration(0)
QQ^2 >= QQ^1 >= 0
sage: TX.get_filtration([-1, -1])
QQ^2 >= QQ^1 >= 0
sage: TX.get_filtration(TX.variety().fan(1)[0])
QQ^2 >= QQ^1 >= 0
sage: TX.get_filtration()
Filtrations
    N(-1, -1): QQ^2 >= QQ^1 >= 0
```

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```
    N(-1, 0): QQ^2 >= QQ^1 >= 0
    N(0, -1): QQ^2 >= QQ^1 >= 0
     N(0, 1): QQ^2 >= QQ^1 >= 0
     N(1, 0): QQ^2 >= QQ^1 >= 0
     N(1, 1): QQ^2 >= QQ^1 >= 0
```

```
>>> from sage.all import *
>>> TX = toric_varieties.dP6().sheaves.tangent_bundle()
>>> TX.get_filtration(Integer(0))
QQ^2 >= QQ^1 >= 0
>>> TX.get_filtration([-Integer(1), -Integer(1)])
QQ^2 >= QQ^1 >= 0
>>> TX.get_filtration(TX.variety().fan(Integer(1))[Integer(0)])
QQ^2 >= QQ^1 >= 0
>>> TX.get_filtration()
Filtrations
    N(-1, -1): QQ^2 >= QQ^1 >= 0
     N(-1, 0): QQ^2 >= QQ^1 >= 0
     N(0, -1): QQ^2 >= QQ^1 >= 0
      N(0, 1): QQ^2 >= QQ^1 >= 0
      N(1, 0): QQ^2 >= QQ^1 >= 0
      N(1, 1): QQ^2 >= QQ^1 >= 0
```

is_isomorphic(*other*)

Test whether two bundles are isomorphic.

INPUT:

- `other` – anything

OUTPUT: boolean

EXAMPLES:

```
sage: X = toric_varieties.P2()
sage: T_X = X.sheaves.tangent_bundle()
sage: O_X = X.sheaves.trivial_bundle(1)
sage: T_X + O_X == O_X + T_X
False
sage: (T_X + O_X).is_isomorphic(O_X + T_X)
Traceback (most recent call last):
...
NotImplementedError
```

```
>>> from sage.all import *
>>> X = toric_varieties.P2()
>>> T_X = X.sheaves.tangent_bundle()
>>> O_X = X.sheaves.trivial_bundle(Integer(1))
>>> T_X + O_X == O_X + T_X
False
>>> (T_X + O_X).is_isomorphic(O_X + T_X)
Traceback (most recent call last):
...
NotImplementedError
```

random_deformation(*epsilon=None*)

Return a generic torus-equivariant deformation of the bundle.

INPUT:

- `epsilon` – an element of the base ring; scales the random deformation

OUTPUT:

A new Klyachko bundle with randomly perturbed moduli. In particular, the same Chern classes.

EXAMPLES:

```
sage: P1 = toric_varieties.P1()
sage: H = P1.divisor(0)
sage: V = P1.sheaves.line_bundle(H) + P1.sheaves.line_bundle(-H)
sage: V.cohomology(dim=True, weight=(0,))
(1, 0)
sage: Vtilde = V.random_deformation()
sage: Vtilde.cohomology(dim=True, weight=(0,))  # random failure (see #32773)
(1, 0)
```

```
>>> from sage.all import *
>>> P1 = toric_varieties.P1()
>>> H = P1.divisor(Integer(0))
>>> V = P1.sheaves.line_bundle(H) + P1.sheaves.line_bundle(-H)
>>> V.cohomology(dim=True, weight=(Integer(0),))
(1, 0)
>>> Vtilde = V.random_deformation()
>>> Vtilde.cohomology(dim=True, weight=(Integer(0),))  # random failure (see
↪#32773)
(1, 0)
```

rank()

Return the rank of the vector bundle.

OUTPUT: integer

EXAMPLES:

```
sage: T_P2 = toric_varieties.P2().sheaves.tangent_bundle()
sage: T_P2.rank()
2
```

```
>>> from sage.all import *
>>> T_P2 = toric_varieties.P2().sheaves.tangent_bundle()
>>> T_P2.rank()
2
```

symmetric_power(*n*)

Return the n-th symmetric power.

INPUT:

- `n` – integer

OUTPUT: the n-th symmetric power as a new Klyachko bundle

EXAMPLES:

```
sage: P1 = toric_varieties.P1()
sage: H = P1.divisor(0)
sage: L = P1.sheaves.line_bundle(H)
sage: (L + L).symmetric_power(2)
Rank 3 bundle on 1-d CPR-Fano toric variety covered by 2 affine patches.
sage: (L + L).symmetric_power(2) == L*L + L*L + L*L
True
```

```
>>> from sage.all import *
>>> P1 = toric_varieties.P1()
>>> H = P1.divisor(Integer(0))
>>> L = P1.sheaves.line_bundle(H)
>>> (L + L).symmetric_power(Integer(2))
Rank 3 bundle on 1-d CPR-Fano toric variety covered by 2 affine patches.
>>> (L + L).symmetric_power(Integer(2)) == L*L + L*L + L*L
True
```

tensor_product(*other*)

Return the sum of two vector bundles.

INPUT:

- `other` – a Klyachko bundle over the same base

OUTPUT: the tensor product as a new Klyachko bundle

EXAMPLES:

```
sage: X = toric_varieties.P2()
sage: OX = X.sheaves.trivial_bundle(1)
sage: X.sheaves.tangent_bundle().tensor_product(OX)
Rank 2 bundle on 2-d CPR-Fano toric variety covered by 3 affine patches.
sage: OX == OX * OX
True
```

```
>>> from sage.all import *
>>> X = toric_varieties.P2()
>>> OX = X.sheaves.trivial_bundle(Integer(1))
>>> X.sheaves.tangent_bundle().tensor_product(OX)
Rank 2 bundle on 2-d CPR-Fano toric variety covered by 3 affine patches.
>>> OX == OX * OX
True
```

variety()

Return the base toric variety.

OUTPUT: a toric variety

EXAMPLES:

```
sage: X = toric_varieties.P2()
sage: V = X.sheaves.tangent_bundle(); V
Rank 2 bundle on 2-d CPR-Fano toric variety covered by 3 affine patches.
sage: V.variety() is X
True
```

```
>>> from sage.all import *
>>> X = toric_varieties.P2()
>>> V = X.sheaves.tangent_bundle(); V
Rank 2 bundle on 2-d CPR-Fano toric variety covered by 3 affine patches.
>>> V.variety() is X
True
```

wedge(n)

Return the n-th exterior power.

INPUT:

- `n` – integer

OUTPUT:

The n-th exterior power $\wedge^n_{i=1} V$ of the bundle V as a new Klyachko bundle.

EXAMPLES:

```
sage: X = toric_varieties.P2_123()
sage: TX = X.sheaves.tangent_bundle()
sage: antiK = X.sheaves.line_bundle(-X.K())
sage: TX.exterior_power(2) == antiK
True
sage: TX.wedge(2) == antiK   # alias
True
```

```
>>> from sage.all import *
>>> X = toric_varieties.P2_123()
>>> TX = X.sheaves.tangent_bundle()
>>> antiK = X.sheaves.line_bundle(-X.K())
>>> TX.exterior_power(Integer(2)) == antiK
True
>>> TX.wedge(Integer(2)) == antiK   # alias
True
```

sage.schemes.toric.sheaf.klyachko.**is_KlyachkoBundle**(X)

Test whether `X` is a Klyachko bundle.

INPUT:

- `X` – anything

OUTPUT: boolean

EXAMPLES:

```
sage: from sage.schemes.toric.sheaf.klyachko import is_KlyachkoBundle
sage: is_KlyachkoBundle('test')
doctest:warning...
DeprecationWarning: The function is_KlyachkoBundle is deprecated; use
↪'isinstance(..., KlyachkoBundle_class)' instead.
See https://github.com/sagemath/sage/issues/38022 for details.
False
```

```
>>> from sage.all import *
>>> from sage.schemes.toric.sheaf.klyachko import is_KlyachkoBundle
>>> is_KlyachkoBundle('test')
doctest:warning...
DeprecationWarning: The function is_KlyachkoBundle is deprecated; use
↪'isinstance(..., KlyachkoBundle_class)' instead.
See https://github.com/sagemath/sage/issues/38022 for details.
False
```

CHAPTER

SEVENTEEN

CYCLIC COVERS

17.1 Cyclic covers over a finite field

The most interesting feature is computation of Frobenius matrix on Monsky-Washnitzer cohomology and the Frobenius polynomial.

REFERENCES:

- [ABCMT2019]

EXAMPLES:

```
sage: p = 13
sage: x = PolynomialRing(GF(p),"x").gen()
sage: C = CyclicCover(4, x^4 + 1)
sage: C.frobenius_polynomial()
x^6 - 6*x^5 + 3*x^4 + 60*x^3 + 39*x^2 - 1014*x + 2197
sage: R.<t> = PowerSeriesRing(Integers())
sage: C.projective_closure().zeta_series(2,t)
1 + 8*t + 102*t^2 + O(t^3)
sage: C.frobenius_polynomial().reverse()(t)/((1-t)*(1-p*t)) + O(t^5)
1 + 8*t + 102*t^2 + 1384*t^3 + 18089*t^4 + O(t^5)

sage: p = 49999
sage: x = PolynomialRing(GF(p),"x").gen()
sage: CyclicCover(5, x^5 + x).frobenius_polynomial()  # long time
x^12 + 299994*x^10 + 37498500015*x^8 + 2499850002999980*x^6 + 937425002249970000015*x^4
 + 18748125074998500014999994*x^2 + 15623125093747500037499700001
sage: CyclicCover(5, 2*x^5 + x).frobenius_polynomial()  # long time
x^12 + 299994*x^10 + 37498500015*x^8 + 2499850002999980*x^6 + 937425002249970000015*x^4
 + 18748125074998500014999994*x^2 + 15623125093747500037499700001

sage: p = 107
sage: x = PolynomialRing(GF(p),"x").gen()
sage: CyclicCover(2, x^5 + x).frobenius_matrix()
[              O(107^2)       89*107 + O(107^2)               O(107^2)              ␣
↪O(107^2)]
[     89*107 + O(107^2)               O(107^2)               O(107^2)              ␣
↪O(107^2)]
[              O(107^2)               O(107^2)               O(107^2) 105 + 5*107 +␣
↪O(107^2)]
[              O(107^2)               O(107^2) 89 + 53*107 + O(107^2)              ␣
```

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```
↪O(107^2)]
sage: CyclicCover(2, 3*x^5 + x).frobenius_matrix()
[              O(107^2)      14*107 + O(107^2)               O(107^2)              ␣
↪O(107^2)]
[     69*107 + O(107^2)               O(107^2)               O(107^2)              ␣
↪O(107^2)]
[              O(107^2)               O(107^2)               O(107^2) 61 + 58*107 +␣
↪O(107^2)]
[              O(107^2)               O(107^2) 69 + 53*107 + O(107^2)              ␣
↪O(107^2)]
sage: CyclicCover(3, x^3 + x).frobenius_matrix()
[          0           0      O(107)      O(107)]
[          0           0 52 + O(107)      O(107)]
[     O(107) 35 + O(107)           0           0]
[44 + O(107)      O(107)           0           0]
sage: CyclicCover(3, 3*x^3 + x).frobenius_matrix()
[          0           0      O(107)      O(107)]
[          0           0 79 + O(107)      O(107)]
[     O(107) 42 + O(107)           0           0]
[30 + O(107)      O(107)           0           0]
```

```
>>> from sage.all import *
>>> p = Integer(13)
>>> x = PolynomialRing(GF(p),"x").gen()
>>> C = CyclicCover(Integer(4), x**Integer(4) + Integer(1))
>>> C.frobenius_polynomial()
x^6 - 6*x^5 + 3*x^4 + 60*x^3 + 39*x^2 - 1014*x + 2197
>>> R = PowerSeriesRing(Integers(), names=('t',)); (t,) = R._first_ngens(1)
>>> C.projective_closure().zeta_series(Integer(2),t)
1 + 8*t + 102*t^2 + O(t^3)
>>> C.frobenius_polynomial().reverse()(t)/((Integer(1)-t)*(Integer(1)-p*t)) +␣
↪O(t**Integer(5))
1 + 8*t + 102*t^2 + 1384*t^3 + 18089*t^4 + O(t^5)

>>> p = Integer(49999)
>>> x = PolynomialRing(GF(p),"x").gen()
>>> CyclicCover(Integer(5), x**Integer(5) + x).frobenius_polynomial()  # long time
x^12 + 299994*x^10 + 37498500015*x^8 + 2499850002999980*x^6 + 937425002249970000015*x^4
 + 18748125074998500014999994*x^2 + 1562312509374750003749970001
>>> CyclicCover(Integer(5), Integer(2)*x**Integer(5) + x).frobenius_polynomial()  #␣
↪long time
x^12 + 299994*x^10 + 37498500015*x^8 + 2499850002999980*x^6 + 937425002249970000015*x^4
 + 18748125074998500014999994*x^2 + 1562312509374750003749970001

>>> p = Integer(107)
>>> x = PolynomialRing(GF(p),"x").gen()
>>> CyclicCover(Integer(2), x**Integer(5) + x).frobenius_matrix()
[              O(107^2)      89*107 + O(107^2)               O(107^2)              ␣
↪O(107^2)]
[     89*107 + O(107^2)               O(107^2)               O(107^2)              ␣
↪O(107^2)]
[              O(107^2)               O(107^2)               O(107^2) 105 + 5*107 +␣
```

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```
↪O(107^2)]
[              O(107^2)               O(107^2) 89 + 53*107 + O(107^2)              ␣
↪O(107^2)]
>>> CyclicCover(Integer(2), Integer(3)*x**Integer(5) + x).frobenius_matrix()
[              O(107^2)      14*107 + O(107^2)               O(107^2)              ␣
↪O(107^2)]
[     69*107 + O(107^2)               O(107^2)               O(107^2)              ␣
↪O(107^2)]
[              O(107^2)               O(107^2)               O(107^2) 61 + 58*107 +␣
↪O(107^2)]
[              O(107^2)               O(107^2) 69 + 53*107 + O(107^2)              ␣
↪O(107^2)]
>>> CyclicCover(Integer(3), x**Integer(3) + x).frobenius_matrix()
[          0           0      O(107)      O(107)]
[          0           0 52 + O(107)      O(107)]
[     O(107) 35 + O(107)           0           0]
[44 + O(107)      O(107)           0           0]
>>> CyclicCover(Integer(3), Integer(3)*x**Integer(3) + x).frobenius_matrix()
[          0           0      O(107)      O(107)]
[          0           0 79 + O(107)      O(107)]
[     O(107) 42 + O(107)           0           0]
[30 + O(107)      O(107)           0           0]
```

class sage.schemes.cyclic_covers.cyclicover_finite_field.**CyclicCover_finite_field**(*AA*, *r*, *f*, *names=None*, *verbose=0*)

Bases: *CyclicCover_generic*

EXAMPLES:

```
sage: p = 13
sage: x = PolynomialRing(GF(p), "x").gen()
sage: C = CyclicCover(4, x^4 + 1)
sage: C.frobenius_polynomial()
x^6 - 6*x^5 + 3*x^4 + 60*x^3 + 39*x^2 - 1014*x + 2197
sage: R.<t> = PowerSeriesRing(Integers())
sage: C.projective_closure().zeta_series(2,t)
1 + 8*t + 102*t^2 + O(t^3)
sage: C.frobenius_polynomial().reverse()(t)/((1-t)*(1-p*t)) + O(t^5)
1 + 8*t + 102*t^2 + 1384*t^3 + 18089*t^4 + O(t^5)
```

```
>>> from sage.all import *
>>> p = Integer(13)
>>> x = PolynomialRing(GF(p), "x").gen()
>>> C = CyclicCover(Integer(4), x**Integer(4) + Integer(1))
>>> C.frobenius_polynomial()
x^6 - 6*x^5 + 3*x^4 + 60*x^3 + 39*x^2 - 1014*x + 2197
>>> R = PowerSeriesRing(Integers(), names=('t',)); (t,) = R._first_ngens(1)
>>> C.projective_closure().zeta_series(Integer(2),t)
1 + 8*t + 102*t^2 + O(t^3)
```

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```
>>> C.frobenius_polynomial().reverse()(t)/((Integer(1)-t)*(Integer(1)-p*t)) +␣
↪O(t**Integer(5))
1 + 8*t + 102*t^2 + 1384*t^3 + 18089*t^4 + O(t^5)
```

frobenius_matrix(*N=None*)

Compute p-adic Frobenius matrix to precision p^N.

If N not supplied, a default value is selected, which is the minimum needed to recover the charpoly unambiguously.

EXAMPLES:

```
sage: p = 107
sage: x = PolynomialRing(GF(p), "x").gen()
sage: CyclicCover(2, x^5 + x).frobenius_matrix()
[              O(107^2)      89*107 + O(107^2)               O(107^2)        ␣
↪      O(107^2)]
[     89*107 + O(107^2)              O(107^2)               O(107^2)        ␣
↪      O(107^2)]
[              O(107^2)              O(107^2)               O(107^2) 105 +␣
↪5*107 + O(107^2)]
[              O(107^2)              O(107^2) 89 + 53*107 + O(107^2)        ␣
↪      O(107^2)]
sage: CyclicCover(2, 3*x^5 + x).frobenius_matrix()
[              O(107^2)      14*107 + O(107^2)               O(107^2)        ␣
↪      O(107^2)]
[     69*107 + O(107^2)              O(107^2)               O(107^2)        ␣
↪      O(107^2)]
[              O(107^2)              O(107^2)               O(107^2) 61 +␣
↪58*107 + O(107^2)]
[              O(107^2)              O(107^2) 69 + 53*107 + O(107^2)        ␣
↪      O(107^2)]
sage: CyclicCover(3, x^3 + x).frobenius_matrix()
[          0           0      O(107)      O(107)]
[          0           0 52 + O(107)      O(107)]
[     O(107) 35 + O(107)           0           0]
[44 + O(107)      O(107)           0           0]
sage: CyclicCover(3, 3*x^3 + x).frobenius_matrix()
[          0           0      O(107)      O(107)]
[          0           0 79 + O(107)      O(107)]
[     O(107) 42 + O(107)           0           0]
[30 + O(107)      O(107)           0           0]
```

```
>>> from sage.all import *
>>> p = Integer(107)
>>> x = PolynomialRing(GF(p), "x").gen()
>>> CyclicCover(Integer(2), x**Integer(5) + x).frobenius_matrix()
[              O(107^2)      89*107 + O(107^2)               O(107^2)        ␣
↪      O(107^2)]
[     89*107 + O(107^2)              O(107^2)               O(107^2)        ␣
↪      O(107^2)]
[              O(107^2)              O(107^2)               O(107^2) 105 +␣
↪5*107 + O(107^2)]
```

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```
[              O(107^2)               O(107^2) 89 + 53*107 + O(107^2)
↪      O(107^2)]
>>> CyclicCover(Integer(2), Integer(3)*x**Integer(5) + x).frobenius_matrix()
[              O(107^2)      14*107 + O(107^2)               O(107^2)
↪      O(107^2)]
[     69*107 + O(107^2)               O(107^2)               O(107^2)
↪      O(107^2)]
[              O(107^2)               O(107^2)               O(107^2) 61 +
↪58*107 + O(107^2)]
[              O(107^2)               O(107^2) 69 + 53*107 + O(107^2)
↪      O(107^2)]
>>> CyclicCover(Integer(3), x**Integer(3) + x).frobenius_matrix()
[          0           0      O(107)      O(107)]
[          0           0 52 + O(107)      O(107)]
[     O(107) 35 + O(107)           0           0]
[44 + O(107)      O(107)           0           0]
>>> CyclicCover(Integer(3), Integer(3)*x**Integer(3) + x).frobenius_matrix()
[          0           0      O(107)      O(107)]
[          0           0 79 + O(107)      O(107)]
[     O(107) 42 + O(107)           0           0]
[30 + O(107)      O(107)           0           0]
```

frobenius_polynomial()

Return the characteristic polynomial of Frobenius.

EXAMPLES:

Hyperelliptic curves:

```
sage: p = 11
sage: x = PolynomialRing(GF(p), "x").gen()
sage: f = x^7 + 4*x^2 + 10*x + 4
sage: CyclicCover(2, f).frobenius_polynomial() == \
....: HyperellipticCurve(f).frobenius_polynomial()
True
sage: f = 2*x^5 + 4*x^3 + x^2 + 2*x + 1
sage: CyclicCover(2, f).frobenius_polynomial() == \
....: HyperellipticCurve(f).frobenius_polynomial()
True
sage: f = 2*x^6 + 4*x^4 + x^3 + 2*x^2 + x
sage: CyclicCover(2, f).frobenius_polynomial() == \
....: HyperellipticCurve(f).frobenius_polynomial()
True
sage: p = 1117
sage: x = PolynomialRing(GF(p), "x").gen()
sage: f = x^9 + 4*x^2 + 10*x + 4
sage: P1 = CyclicCover(2, f).frobenius_polynomial()
sage: P2 = HyperellipticCurve(f).frobenius_polynomial()
sage: P1 == P2  # long time
True
sage: f = 2*x^5 + 4*x^3 + x^2 + 2*x + 1
sage: CyclicCover(2, f).frobenius_polynomial() == \
....: HyperellipticCurve(f).frobenius_polynomial()
```

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```
True
```

```
>>> from sage.all import *
>>> p = Integer(11)
>>> x = PolynomialRing(GF(p), "x").gen()
>>> f = x**Integer(7) + Integer(4)*x**Integer(2) + Integer(10)*x + Integer(4)
>>> CyclicCover(Integer(2), f).frobenius_polynomial() ==␣
↪HyperellipticCurve(f).frobenius_polynomial()
True
>>> f = Integer(2)*x**Integer(5) + Integer(4)*x**Integer(3) + x**Integer(2) +␣
↪Integer(2)*x + Integer(1)
>>> CyclicCover(Integer(2), f).frobenius_polynomial() ==␣
↪HyperellipticCurve(f).frobenius_polynomial()
True
>>> f = Integer(2)*x**Integer(6) + Integer(4)*x**Integer(4) + x**Integer(3) +␣
↪Integer(2)*x**Integer(2) + x
>>> CyclicCover(Integer(2), f).frobenius_polynomial() ==␣
↪HyperellipticCurve(f).frobenius_polynomial()
True
>>> p = Integer(1117)
>>> x = PolynomialRing(GF(p), "x").gen()
>>> f = x**Integer(9) + Integer(4)*x**Integer(2) + Integer(10)*x + Integer(4)
>>> P1 = CyclicCover(Integer(2), f).frobenius_polynomial()
>>> P2 = HyperellipticCurve(f).frobenius_polynomial()
>>> P1 == P2  # long time
True
>>> f = Integer(2)*x**Integer(5) + Integer(4)*x**Integer(3) + x**Integer(2) +␣
↪Integer(2)*x + Integer(1)
>>> CyclicCover(Integer(2), f).frobenius_polynomial() ==␣
↪HyperellipticCurve(f).frobenius_polynomial()
True
```

Superelliptic curves:

```
sage: p = 11
sage: x = PolynomialRing(GF(p), "x").gen()
sage: CyclicCover(3, x^4 + 4*x^3 + 9*x^2 + 3*x + 1).frobenius_polynomial()
x^6 + 21*x^4 + 231*x^2 + 1331
sage: CyclicCover(4, x^3 + x + 1).frobenius_polynomial()
x^6 + 2*x^5 + 11*x^4 + 121*x^2 + 242*x + 1331
sage: p = 4999
sage: x = PolynomialRing(GF(p),"x").gen()
sage: CyclicCover(4, x^3  - 1).frobenius_polynomial() == \
....: CyclicCover(3, x^4  + 1).frobenius_polynomial()
True
sage: CyclicCover(3, x^4 + 4*x^3 + 9*x^2 + 3*x + 1).frobenius_polynomial()
x^6 + 180*x^5 + 20988*x^4 + 1854349*x^3 + 104919012*x^2 + 4498200180*x +␣
↪124925014999
sage: CyclicCover(4, x^5 + x + 1).frobenius_polynomial()
x^12 - 64*x^11 + 5018*x^10 - 488640*x^9 + 28119583*x^8 - 641791616*x^7
 + 124245485932*x^6 - 3208316288384*x^5 + 702708407289583*x^4 -␣
↪61043359329111360*x^3
```

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```
 + 3133741752599645018*x^2 - 1998000799840015999936*x + 15606259372500374970001

sage: h = PolynomialRing(GF(1129), 'x')([-1] + [0]*(5-1) + [1])
sage: CyclicCover(11, h).frobenius_polynomial()  # long time
x^40 + 7337188909826596*x^30 + 20187877911930897108199045855206*x^20
 + 24687045654725446027864774006541463602997309796*x^10
 + 1132084484963964995160880997358977693203136765026963553258401

sage: h = PolynomialRing(GF(1009^2), 'x')([-1] + [0]*(5-1) + [1])
sage: CyclicCover(3, h).frobenius_polynomial()  # long time
x^8 + 532*x^7 - 2877542*x^6 - 242628176*x^5 + 4390163797795*x^4 -␣
↪247015136050256*x^3
 - 2982540407204025062*x^2 + 561382189105547134612*x +␣
↪1074309286591662654798721
```

```
>>> from sage.all import *
>>> p = Integer(11)
>>> x = PolynomialRing(GF(p), "x").gen()
>>> CyclicCover(Integer(3), x**Integer(4) + Integer(4)*x**Integer(3) +␣
↪Integer(9)*x**Integer(2) + Integer(3)*x + Integer(1)).frobenius_polynomial()
x^6 + 21*x^4 + 231*x^2 + 1331
>>> CyclicCover(Integer(4), x**Integer(3) + x + Integer(1)).frobenius_
↪polynomial()
x^6 + 2*x^5 + 11*x^4 + 121*x^2 + 242*x + 1331
>>> p = Integer(4999)
>>> x = PolynomialRing(GF(p),"x").gen()
>>> CyclicCover(Integer(4), x**Integer(3)  - Integer(1)).frobenius_
↪polynomial() == CyclicCover(Integer(3), x**Integer(4)  + Integer(1)).
↪frobenius_polynomial()
True
>>> CyclicCover(Integer(3), x**Integer(4) + Integer(4)*x**Integer(3) +␣
↪Integer(9)*x**Integer(2) + Integer(3)*x + Integer(1)).frobenius_polynomial()
x^6 + 180*x^5 + 20988*x^4 + 1854349*x^3 + 104919012*x^2 + 4498200180*x +␣
↪124925014999
>>> CyclicCover(Integer(4), x**Integer(5) + x + Integer(1)).frobenius_
↪polynomial()
x^12 - 64*x^11 + 5018*x^10 - 488640*x^9 + 28119583*x^8 - 641791616*x^7
 + 124245485932*x^6 - 3208316288384*x^5 + 702708407289583*x^4 -␣
↪61043359329111360*x^3
 + 3133741752599645018*x^2 - 1998000799840015999936*x + 15606259372500374970001

>>> h = PolynomialRing(GF(Integer(1129)), 'x')([-Integer(1)] +␣
↪[Integer(0)]*(Integer(5)-Integer(1)) + [Integer(1)])
>>> CyclicCover(Integer(11), h).frobenius_polynomial()  # long time
x^40 + 7337188909826596*x^30 + 20187877911930897108199045855206*x^20
 + 24687045654725446027864774006541463602997309796*x^10
 + 1132084484963964995160880997358977693203136765026963553258401

>>> h = PolynomialRing(GF(Integer(1009)**Integer(2)), 'x')([-Integer(1)] +␣
↪[Integer(0)]*(Integer(5)-Integer(1)) + [Integer(1)])
>>> CyclicCover(Integer(3), h).frobenius_polynomial()  # long time
x^8 + 532*x^7 - 2877542*x^6 - 242628176*x^5 + 4390163797795*x^4 -␣
```

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```
↪247015136050256*x^3
 - 2982540407204025062*x^2 + 5613821891055471346l2*x +␣
↪10743092865916626547987 21
```

A non-monic example checking that Issue #29015 is fixed:

```
sage: a = 3
sage: K.<s> = GF(83^3);
sage: R.<x> = PolynomialRing(K)
sage: h = s*x^4 + x^3 + 8
sage: C = CyclicCover(a, h)
sage: C.frobenius_polynomial()
x^6 + 1563486*x^4 + 893980969482*x^2 + 186940255267540403
```

```
>>> from sage.all import *
>>> a = Integer(3)
>>> K = GF(Integer(83)**Integer(3), names=('s',)); (s,) = K._first_ngens(1);
>>> R = PolynomialRing(K, names=('x',)); (x,) = R._first_ngens(1)
>>> h = s*x**Integer(4) + x*Integer(3) + Integer(8)
>>> C = CyclicCover(a, h)
>>> C.frobenius_polynomial()
x^6 + 1563486*x^4 + 893980969482*x^2 + 186940255267540403
```

Non-superelliptic curves:

```
sage: p = 13
sage: x = PolynomialRing(GF(p), "x").gen()
sage: C = CyclicCover(4, x^4 + 1)
sage: C.frobenius_polynomial()
x^6 - 6*x^5 + 3*x^4 + 60*x^3 + 39*x^2 - 1014*x + 2197
sage: R.<t> = PowerSeriesRing(Integers())
sage: C.projective_closure().zeta_series(2, t)
1 + 8*t + 102*t^2 + O(t^3)
sage: C.frobenius_polynomial().reverse()(t)/((1-t)*(1-p*t)) + O(t^5)
1 + 8*t + 102*t^2 + 1384*t^3 + 18089*t^4 + O(t^5)

sage: x = PolynomialRing(GF(11), "x").gen()
sage: CyclicCover(4, x^6 - 11*x^3 + 70*x^2 - x + 961).frobenius_polynomial()
↪# long time
x^14 + 14*x^12 + 287*x^10 + 3025*x^8 + 33275*x^6 + 381997*x^4 + 2254714*x^2 +␣
↪19487171
sage: x = PolynomialRing(GF(4999), "x").gen()
sage: CyclicCover(4, x^6 - 11*x^3 + 70*x^2 - x + 961).frobenius_polynomial()
↪# long time
x^14 - 4*x^13 - 2822*x^12 - 30032*x^11 + 37164411*x^10 - 152369520*x^9
 + 54217349361*x^8 - 1021791160888*x^7 + 271032529455639*x^6 -␣
↪3807714457169520*x^5
 + 4642764601604000589*x^4 - 18754988504199390032*x^3 -␣
↪8809934776794570547178*x^2
 - 624250374900014998800 04*x + 78015690603129374475034999

sage: p = 11
```

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```
sage: x = PolynomialRing(GF(p), "x").gen()
sage: CyclicCover(3, 5*x^3 - 5*x + 13).frobenius_polynomial()
x^2 + 11
sage: CyclicCover(3, x^6 + x^4 - x^3 + 2*x^2 - x - 1).frobenius_polynomial()
x^8 + 32*x^6 + 462*x^4 + 3872*x^2 + 14641
sage: p = 4999
sage: x = PolynomialRing(GF(p), "x").gen()
sage: CyclicCover(3, 5*x^3 - 5*x + 13).frobenius_polynomial()
x^2 - 47*x + 4999
sage: CyclicCover(3, x^6 + x^4 - x^3 + 2*x^2 - x - 1).frobenius_polynomial()
x^8 + 122*x^7 + 4594*x^6 - 639110*x^5 - 82959649*x^4 - 3194910890*x^3
 + 114804064594*x^2 + 152408518298 78*x + 624500149980001

sage: p = 11
sage: x = PolynomialRing(GF(p), "x").gen()
sage: CyclicCover(5, x^5 + x).frobenius_polynomial()  # long time
x^12 + 4*x^11 + 22*x^10 + 108*x^9 + 503*x^8 + 1848*x^7 + 5588*x^6 + 20328*x^5
 + 60863*x^4 + 143748*x^3 + 322102*x^2 + 644204*x + 1771561
sage: CyclicCover(5, 2*x^5 + x).frobenius_polynomial()  # long time
x^12 - 9*x^11 + 42*x^10 - 108*x^9 - 47*x^8 + 1782*x^7 - 8327*x^6 + 19602*x^5
 - 5687*x^4 - 143748*x^3 + 614922*x^2 - 1449459*x + 1771561
sage: p = 49999
sage: x = PolynomialRing(GF(p), "x").gen()
sage: CyclicCover(5, x^5 + x).frobenius_polynomial()  # long time
x^12 + 299994*x^10 + 37498500015*x^8 + 2499850002999980*x^6
 + 937425002249970000 15*x^4 + 187481250749985000 1499994*x^2
 + 156231250937475000 37499700001
sage: CyclicCover(5, 2*x^5 + x).frobenius_polynomial() # long time
x^12 + 299994*x^10 + 37498500015*x^8 + 2499850002999980*x^6
 + 937425002249970000 15*x^4 + 187481250749985000 1499994*x^2
 + 156231250937475000 37499700001
```

```
>>> from sage.all import *
>>> p = Integer(13)
>>> x = PolynomialRing(GF(p), "x").gen()
>>> C = CyclicCover(Integer(4), x**Integer(4) + Integer(1))
>>> C.frobenius_polynomial()
x^6 - 6*x^5 + 3*x^4 + 60*x^3 + 39*x^2 - 1014*x + 2197
>>> R = PowerSeriesRing(Integers(), names=('t',)); (t,) = R._first_ngens(1)
>>> C.projective_closure().zeta_series(Integer(2), t)
1 + 8*t + 102*t^2 + O(t^3)
>>> C.frobenius_polynomial().reverse()(t)/((Integer(1)-t)*(Integer(1)-p*t)) +␣
↪O(t**Integer(5))
1 + 8*t + 102*t^2 + 1384*t^3 + 18089*t^4 + O(t^5)

>>> x = PolynomialRing(GF(Integer(11)), "x").gen()
>>> CyclicCover(Integer(4), x**Integer(6) - Integer(11)*x**Integer(3) +␣
↪Integer(70)*x**Integer(2) - x + Integer(961)).frobenius_polynomial()  #␣
↪long time
x^14 + 14*x^12 + 287*x^10 + 3025*x^8 + 33275*x^6 + 381997*x^4 + 2254714*x^2 +␣
↪19487171
>>> x = PolynomialRing(GF(Integer(4999)), "x").gen()
```

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```
>>> CyclicCover(Integer(4), x**Integer(6) - Integer(11)*x**Integer(3) +␣
↪Integer(70)*x**Integer(2) - x + Integer(961)).frobenius_polynomial()  #␣
↪long time
x^14 - 4*x^13 - 2822*x^12 - 30032*x^11 + 37164411*x^10 - 152369520*x^9
 + 54217349361*x^8 - 1021791160888*x^7 + 2710325294556 39*x^6 -␣
↪3807714457169520*x^5
 + 46427646016040005 89*x^4 - 18754988504199390032*x^3 -␣
↪8809934776794570547178*x^2
 - 624250374900014998800 04*x + 78015690603129374475034999

>>> p = Integer(11)
>>> x = PolynomialRing(GF(p), "x").gen()
>>> CyclicCover(Integer(3), Integer(5)*x**Integer(3) - Integer(5)*x +␣
↪Integer(13)).frobenius_polynomial()
x^2 + 11
>>> CyclicCover(Integer(3), x**Integer(6) + x**Integer(4) - x**Integer(3) +␣
↪Integer(2)*x**Integer(2) - x - Integer(1)).frobenius_polynomial()
x^8 + 32*x^6 + 462*x^4 + 3872*x^2 + 14641
>>> p = Integer(4999)
>>> x = PolynomialRing(GF(p), "x").gen()
>>> CyclicCover(Integer(3), Integer(5)*x**Integer(3) - Integer(5)*x +␣
↪Integer(13)).frobenius_polynomial()
x^2 - 47*x + 4999
>>> CyclicCover(Integer(3), x**Integer(6) + x**Integer(4) - x**Integer(3) +␣
↪Integer(2)*x**Integer(2) - x - Integer(1)).frobenius_polynomial()
x^8 + 122*x^7 + 4594*x^6 - 639110*x^5 - 82959649*x^4 - 3194910890*x^3
 + 114804064594*x^2 + 15240851829878*x + 624500149980001

>>> p = Integer(11)
>>> x = PolynomialRing(GF(p), "x").gen()
>>> CyclicCover(Integer(5), x**Integer(5) + x).frobenius_polynomial()  # long␣
↪time
x^12 + 4*x^11 + 22*x^10 + 108*x^9 + 503*x^8 + 1848*x^7 + 5588*x^6 + 20328*x^5
 + 60863*x^4 + 143748*x^3 + 322102*x^2 + 644204*x + 1771561
>>> CyclicCover(Integer(5), Integer(2)*x**Integer(5) + x).frobenius_
↪polynomial()  # long time
x^12 - 9*x^11 + 42*x^10 - 108*x^9 - 47*x^8 + 1782*x^7 - 8327*x^6 + 19602*x^5
 - 5687*x^4 - 143748*x^3 + 614922*x^2 - 1449459*x + 1771561
>>> p = Integer(49999)
>>> x = PolynomialRing(GF(p), "x").gen()
>>> CyclicCover(Integer(5), x**Integer(5) + x).frobenius_polynomial()  # long␣
↪time
x^12 + 299994*x^10 + 37498500015*x^8 + 2499850002999980*x^6
 + 937425002249970000 15*x^4 + 187481250749985000 1499994*x^2
 + 156231250937475000 37499700001
>>> CyclicCover(Integer(5), Integer(2)*x**Integer(5) + x).frobenius_
↪polynomial() # long time
x^12 + 299994*x^10 + 37498500015*x^8 + 2499850002999980*x^6
 + 937425002249970000 15*x^4 + 187481250749985000 1499994*x^2
 + 156231250937475000 37499700001
```

17.2 Cyclic covers curves over a general ring

EXAMPLES:

```
sage: ZZx.<x> = ZZ[]
sage: C = CyclicCover(5, x^5 + x + 1); C
Cyclic Cover of P^1 over Integer Ring defined by y^5 = x^5 + x + 1
sage: C.genus()
6
sage: D = C.projective_closure(); D
Projective Plane Curve over Integer Ring defined by x0^5 + x0^4*x1 + x1^5 - x2^5
sage: D.change_ring(QQ).genus()
6
sage: C.change_ring(GF(5))
Traceback (most recent call last):
...
ValueError: As the characteristic divides the order of the cover, this model is not␣
↪smooth.

sage: GF7x.<x> = GF(7)[]
sage: C = CyclicCover(3, x^9 + x + 1)
sage: C
Cyclic Cover of P^1 over Finite Field of size 7 defined by y^3 = x^9 + x + 1
sage: C.genus()
7
sage: C.projective_closure()
Traceback (most recent call last):
...
NotImplementedError: Weighted Projective Space is not implemented
```

```
>>> from sage.all import *
>>> ZZx = ZZ['x']; (x,) = ZZx._first_ngens(1)
>>> C = CyclicCover(Integer(5), x**Integer(5) + x + Integer(1)); C
Cyclic Cover of P^1 over Integer Ring defined by y^5 = x^5 + x + 1
>>> C.genus()
6
>>> D = C.projective_closure(); D
Projective Plane Curve over Integer Ring defined by x0^5 + x0^4*x1 + x1^5 - x2^5
>>> D.change_ring(QQ).genus()
6
>>> C.change_ring(GF(Integer(5)))
Traceback (most recent call last):
...
ValueError: As the characteristic divides the order of the cover, this model is not␣
↪smooth.

>>> GF7x = GF(Integer(7))['x']; (x,) = GF7x._first_ngens(1)
>>> C = CyclicCover(Integer(3), x**Integer(9) + x + Integer(1))
>>> C
Cyclic Cover of P^1 over Finite Field of size 7 defined by y^3 = x^9 + x + 1
>>> C.genus()
7
>>> C.projective_closure()
```

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```
Traceback (most recent call last):
...
NotImplementedError: Weighted Projective Space is not implemented
```

class sage.schemes.cyclic_covers.cycliccover_generic.**CyclicCover_generic**(*AA*, *r*, *f*, *names=None*)

Bases: AffinePlaneCurve

Cyclic covers over a general ring.

INPUT:

- A – ambient affine space
- r – degree of the cover
- f – univariate polynomial
- names – (default: ["x","y"]); names for the coordinate functions

base_extend(*R*)

Return this CyclicCover over a new base ring R.

EXAMPLES:

```
sage: ZZx.<x> = ZZ[]
sage: C = CyclicCover(5, x^5 + x + 1)
sage: C.change_ring(GF(5))
Traceback (most recent call last):
...
ValueError: As the characteristic divides the order of the cover,
this model is not smooth.
sage: C.change_ring(GF(3))
Traceback (most recent call last):
...
ValueError: Not a smooth Cyclic Cover of P^1: singularity in the
provided affine patch.
sage: C.change_ring(GF(17))
Cyclic Cover of P^1 over Finite Field of size 17 defined by y^5 = x^5 + x + 1
```

```
>>> from sage.all import *
>>> ZZx = ZZ['x']; (x,) = ZZx._first_ngens(1)
>>> C = CyclicCover(Integer(5), x**Integer(5) + x + Integer(1))
>>> C.change_ring(GF(Integer(5)))
Traceback (most recent call last):
...
ValueError: As the characteristic divides the order of the cover,
this model is not smooth.
>>> C.change_ring(GF(Integer(3)))
Traceback (most recent call last):
...
ValueError: Not a smooth Cyclic Cover of P^1: singularity in the
provided affine patch.
>>> C.change_ring(GF(Integer(17)))
Cyclic Cover of P^1 over Finite Field of size 17 defined by y^5 = x^5 + x + 1
```

change_ring(*R*)

Return this CyclicCover over a new base ring R.

EXAMPLES:

```
sage: ZZx.<x> = ZZ[]
sage: C = CyclicCover(5, x^5 + x + 1)
sage: C.change_ring(GF(5))
Traceback (most recent call last):
...
ValueError: As the characteristic divides the order of the cover,
this model is not smooth.
sage: C.change_ring(GF(3))
Traceback (most recent call last):
...
ValueError: Not a smooth Cyclic Cover of P^1: singularity in the
provided affine patch.
sage: C.change_ring(GF(17))
Cyclic Cover of P^1 over Finite Field of size 17 defined by y^5 = x^5 + x + 1
```

```
>>> from sage.all import *
>>> ZZx = ZZ['x']; (x,) = ZZx._first_ngens(1)
>>> C = CyclicCover(Integer(5), x**Integer(5) + x + Integer(1))
>>> C.change_ring(GF(Integer(5)))
Traceback (most recent call last):
...
ValueError: As the characteristic divides the order of the cover,
this model is not smooth.
>>> C.change_ring(GF(Integer(3)))
Traceback (most recent call last):
...
ValueError: Not a smooth Cyclic Cover of P^1: singularity in the
provided affine patch.
>>> C.change_ring(GF(Integer(17)))
Cyclic Cover of P^1 over Finite Field of size 17 defined by y^5 = x^5 + x + 1
```

cover_polynomial(*K=None*, *var='x'*)

Return the polynomial defining the cyclic cover.

EXAMPLES:

```
sage: ZZx.<x> = ZZ[]; CyclicCover(5, x^5 + x + 1).cover_polynomial()
x^5 + x + 1
```

```
>>> from sage.all import *
>>> ZZx = ZZ['x']; (x,) = ZZx._first_ngens(1); CyclicCover(Integer(5),␣
↪x**Integer(5) + x + Integer(1)).cover_polynomial()
x^5 + x + 1
```

genus()

The geometric genus of the curve.

EXAMPLES:

```
sage: ZZx.<x> = ZZ[]
sage: CyclicCover(5, x^5 + x + 1).genus()
6
sage: CyclicCover(3, x^5 + x + 1).genus()
4
```

```
>>> from sage.all import *
>>> ZZx = ZZ['x']; (x,) = ZZx._first_ngens(1)
>>> CyclicCover(Integer(5), x**Integer(5) + x + Integer(1)).genus()
6
>>> CyclicCover(Integer(3), x**Integer(5) + x + Integer(1)).genus()
4
```

is_singular()

Return if this curve is singular or not.

This just checks that the characteristic of the ring does not divide the order of the cover and that the defining polynomial of the cover is square free.

EXAMPLES:

```
sage: R.<x> = QQ[]
sage: CyclicCover(3, x^5 + x + 1).is_singular()
False
sage: CyclicCover(3, (x^5 + x + 1)^2, check_smooth=False).is_singular()
True
```

```
>>> from sage.all import *
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> CyclicCover(Integer(3), x**Integer(5) + x + Integer(1)).is_singular()
False
>>> CyclicCover(Integer(3), (x**Integer(5) + x + Integer(1))**Integer(2),␣
↪check_smooth=False).is_singular()
True
```

is_smooth()

Return if this curve is smooth or not.

This just checks that the characteristic of the ring does not divide the order of the cover and that the defining polynomial of the cover is square free.

EXAMPLES:

```
sage: R.<x> = QQ[]
sage: CyclicCover(3, x^5 + x + 1).is_smooth()
True
sage: CyclicCover(3, (x^5 + x + 1)^2, check_smooth=False).is_smooth()
False
```

```
>>> from sage.all import *
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> CyclicCover(Integer(3), x**Integer(5) + x + Integer(1)).is_smooth()
True
>>> CyclicCover(Integer(3), (x**Integer(5) + x + Integer(1))**Integer(2),␣
```

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```
↪check_smooth=False).is_smooth()
False
```

order()

The order of the cover.

EXAMPLES:

```
sage: ZZx.<x> = ZZ[]
sage: CyclicCover(5, x^5 + x + 1).order()
5
sage: CyclicCover(3, x^5 + x + 1).order()
3
```

```
>>> from sage.all import *
>>> ZZx = ZZ['x']; (x,) = ZZx._first_ngens(1)
>>> CyclicCover(Integer(5), x**Integer(5) + x + Integer(1)).order()
5
>>> CyclicCover(Integer(3), x**Integer(5) + x + Integer(1)).order()
3
```

projective_closure(***kwds*)

Return the projective closure of this affine curve.

EXAMPLES:

```
sage: GF7x.<x> = GF(7)[]
sage: CyclicCover(3, x^9 + x + 1).projective_closure()
Traceback (most recent call last):
...
NotImplementedError: Weighted Projective Space is not implemented

sage: ZZx.<x> = ZZ[]
sage: CyclicCover(5, x^5 + x + 1).projective_closure()
Projective Plane Curve over Integer Ring defined by x0^5 + x0^4*x1 + x1^5 -␣
↪x2^5
```

```
>>> from sage.all import *
>>> GF7x = GF(Integer(7))['x']; (x,) = GF7x._first_ngens(1)
>>> CyclicCover(Integer(3), x**Integer(9) + x + Integer(1)).projective_
↪closure()
Traceback (most recent call last):
...
NotImplementedError: Weighted Projective Space is not implemented

>>> ZZx = ZZ['x']; (x,) = ZZx._first_ngens(1)
>>> CyclicCover(Integer(5), x**Integer(5) + x + Integer(1)).projective_
↪closure()
Projective Plane Curve over Integer Ring defined by x0^5 + x0^4*x1 + x1^5 -␣
↪x2^5
```

17.3 Computation of the Frobenius polynomial using Newton's identities

sage.schemes.cyclic_covers.charpoly_frobenius.**charpoly_frobenius**(*frob_matrix*, *charpoly_prec*, *p*, *weight*, *a=1*, *known_factor=[1]*)

Return the characteristic polynomial of the given Frobenius matrix.

INPUT:

- `frob_matrix` – a matrix representing the Frobenius matrix up to some precision
- `charpoly_prec` – a vector ai, such that, `frob_matrix.change_ring(ZZ).charpoly()[i]` will be correct mod $p^a i$, this can be easily deduced from the Hodge numbers and knowing the q-adic precision of `frob_matrix`
- `p` – prime p
- `weight` – weight of the motive
- `a` – $p = q^a$
- `known_factor` – the list of coefficients of the known factor

OUTPUT: list of integers corresponding to the characteristic polynomial of the Frobenius action

EXAMPLES:

```
sage: from sage.schemes.cyclic_covers.charpoly_frobenius import charpoly_frobenius
sage: M = Matrix([[O(17), 8 + O(17)], [O(17), 15 + O(17)]])
sage: charpoly_frobenius(M, [2, 1, 1], 17, 1, 1)
[17, 2, 1]

sage: R = Zq(17**2, names=('a',))
sage: M = Matrix(R, [[8*17 + 16*17**2 + O(17**3), 8 + 11*17 + O(17**2)],
....:                [7*17**2 + O(17**3), 15 + 8*17 + O(17**2)]])
sage: charpoly_frobenius(M*M, [3, 2, 2], 17, 1, 2)
[289, 30, 1]

sage: M = Matrix([[8*31 + 8*31**2 + O(31**3), O(31**3), O(31**3), O(31**3)],
....:             [O(31**3), 23*31 + 22*31**2 + O(31**3), O(31**3), O(31**3)],
....:             [O(31**3), O(31**3), 27 + 7*31 + O(31**3), O(31**3)],
....:             [O(31**3), O(31**3), O(31**3), 4 + 23*31 + O(31**3)]])
sage: charpoly_frobenius(M, [4, 3, 2, 2, 2], 31, 1, 1)
[961, 0, 46, 0, 1]

sage: M = Matrix([(4*43^2 + O(43^3), 17*43 + 11*43^2 + O(43^3), O(43^3), O(43^3),␣
↪17 + 37*43 + O(43^3), O(43^3)),
....:             (30*43 + 23*43^2 + O(43^3), 5*43 + O(43^3), O(43^3), O(43^3), 3␣
↪+ 38*43 + O(43^3), O(43^3)),
....:             (O(43^3), O(43^3), 9*43 + 32*43^2 + O(43^3), 13 + 25*43 + O(43^
↪3), O(43^3), 17 + 18*43 + O(43^3)),
....:             (O(43^3), O(43^3), 22*43 + 25*43^2 + O(43^3), 11 + 24*43 + O(43^
↪3), O(43^3), 36 + 5*43 + O(43^3)),
....:             (42*43 + 15*43^2 + O(43^3), 22*43 + 8*43^2 + O(43^3), O(43^3),␣
↪O(43^3), 29 + 4*43 + O(43^3), O(43^3)),
....:             (O(43^3), O(43^3), 6*43 + 19*43^2 + O(43^3), 8 + 24*43 + O(43^
```

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```
↪3), O(43^3), 31 + 42*43 + O(43^3))])
sage: charpoly_frobenius(M, [5, 4, 3, 2, 2, 2, 2], 43, 1, 1)
    [79507, 27735, 6579, 1258, 153, 15, 1]

sage: M = Matrix([(1 + O(4999), O(4999), 0, 0),
....:             (O(4999), 4860 + O(4999), 0, 0),
....:             (0, 0, O(4999), O(4999)),
....:             (0, 0, O(4999), 1 + O(4999))])
sage: charpoly_frobenius(M, [2, 1, 1], 4999, 1, 1, [1, -2, 1])
[4999, 139, 1]
```

```
>>> from sage.all import *
>>> from sage.schemes.cyclic_covers.charpoly_frobenius import charpoly_frobenius
>>> M = Matrix([[O(Integer(17)), Integer(8) + O(Integer(17))], [O(Integer(17)),␣
↪Integer(15) + O(Integer(17))]])
>>> charpoly_frobenius(M, [Integer(2), Integer(1), Integer(1)], Integer(17),␣
↪Integer(1), Integer(1))
[17, 2, 1]

>>> R = Zq(Integer(17)**Integer(2), names=('a',))
>>> M = Matrix(R, [[Integer(8)*Integer(17) + Integer(16)*Integer(17)**Integer(2)␣
↪+ O(Integer(17)**Integer(3)), Integer(8) + Integer(11)*Integer(17) +␣
↪O(Integer(17)**Integer(2))],
...                [Integer(7)*Integer(17)**Integer(2) +␣
↪O(Integer(17)**Integer(3)), Integer(15) + Integer(8)*Integer(17) +␣
↪O(Integer(17)**Integer(2))]])
>>> charpoly_frobenius(M*M, [Integer(3), Integer(2), Integer(2)], Integer(17),␣
↪Integer(1), Integer(2))
[289, 30, 1]

>>> M = Matrix([[Integer(8)*Integer(31) + Integer(8)*Integer(31)**Integer(2) +␣
↪O(Integer(31)**Integer(3)), O(Integer(31)**Integer(3)),␣
↪O(Integer(31)**Integer(3)), O(Integer(31)**Integer(3))],
...             [O(Integer(31)**Integer(3)), Integer(23)*Integer(31) +␣
↪Integer(22)*Integer(31)**Integer(2) + O(Integer(31)**Integer(3)),␣
↪O(Integer(31)**Integer(3)), O(Integer(31)**Integer(3))],
...             [O(Integer(31)**Integer(3)), O(Integer(31)**Integer(3)),␣
↪Integer(27) + Integer(7)*Integer(31) + O(Integer(31)**Integer(3)),␣
↪O(Integer(31)**Integer(3))],
...             [O(Integer(31)**Integer(3)), O(Integer(31)**Integer(3)),␣
↪O(Integer(31)**Integer(3)), Integer(4) + Integer(23)*Integer(31) +␣
↪O(Integer(31)**Integer(3))]])
>>> charpoly_frobenius(M, [Integer(4), Integer(3), Integer(2), Integer(2),␣
↪Integer(2)], Integer(31), Integer(1), Integer(1))
[961, 0, 46, 0, 1]

>>> M = Matrix([(Integer(4)*Integer(43)**Integer(2) + O(Integer(43)**Integer(3)),␣
↪Integer(17)*Integer(43) + Integer(11)*Integer(43)**Integer(2) +␣
↪O(Integer(43)**Integer(3)), O(Integer(43)**Integer(3)),␣
↪O(Integer(43)**Integer(3)), Integer(17) + Integer(37)*Integer(43) +␣
↪O(Integer(43)**Integer(3)), O(Integer(43)**Integer(3))),
...             (Integer(30)*Integer(43) + Integer(23)*Integer(43)**Integer(2) +␣
```

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```
↪O(Integer(43)**Integer(3)), Integer(5)*Integer(43) + O(Integer(43)**Integer(3)),
↪ O(Integer(43)**Integer(3)), O(Integer(43)**Integer(3)), Integer(3) +␣
↪Integer(38)*Integer(43) + O(Integer(43)**Integer(3)),␣
↪O(Integer(43)**Integer(3))),
...              (O(Integer(43)**Integer(3)), O(Integer(43)**Integer(3)),␣
↪Integer(9)*Integer(43) + Integer(32)*Integer(43)**Integer(2) +␣
↪O(Integer(43)**Integer(3)), Integer(13) + Integer(25)*Integer(43) +␣
↪O(Integer(43)**Integer(3)), O(Integer(43)**Integer(3)), Integer(17) +␣
↪Integer(18)*Integer(43) + O(Integer(43)**Integer(3))),
...              (O(Integer(43)**Integer(3)), O(Integer(43)**Integer(3)),␣
↪Integer(22)*Integer(43) + Integer(25)*Integer(43)**Integer(2) +␣
↪O(Integer(43)**Integer(3)), Integer(11) + Integer(24)*Integer(43) +␣
↪O(Integer(43)**Integer(3)), O(Integer(43)**Integer(3)), Integer(36) +␣
↪Integer(5)*Integer(43) + O(Integer(43)**Integer(3))),
...              (Integer(42)*Integer(43) + Integer(15)*Integer(43)**Integer(2) +␣
↪O(Integer(43)**Integer(3)), Integer(22)*Integer(43) +␣
↪Integer(8)*Integer(43)**Integer(2) + O(Integer(43)**Integer(3)),␣
↪O(Integer(43)**Integer(3)), O(Integer(43)**Integer(3)), Integer(29) +␣
↪Integer(4)*Integer(43) + O(Integer(43)**Integer(3)),␣
↪O(Integer(43)**Integer(3))),
...              (O(Integer(43)**Integer(3)), O(Integer(43)**Integer(3)),␣
↪Integer(6)*Integer(43) + Integer(19)*Integer(43)**Integer(2) +␣
↪O(Integer(43)**Integer(3)), Integer(8) + Integer(24)*Integer(43) +␣
↪O(Integer(43)**Integer(3)), O(Integer(43)**Integer(3)), Integer(31) +␣
↪Integer(42)*Integer(43) + O(Integer(43)**Integer(3)))])
>>> charpoly_frobenius(M, [Integer(5), Integer(4), Integer(3), Integer(2),␣
↪Integer(2), Integer(2), Integer(2)], Integer(43), Integer(1), Integer(1))
    [79507, 27735, 6579, 1258, 153, 15, 1]

>>> M = Matrix([(Integer(1) + O(Integer(4999)), O(Integer(4999)), Integer(0),␣
↪Integer(0)),
...              (O(Integer(4999)), Integer(4860) + O(Integer(4999)), Integer(0),␣
↪Integer(0)),
...              (Integer(0), Integer(0), O(Integer(4999)), O(Integer(4999))),
...              (Integer(0), Integer(0), O(Integer(4999)), Integer(1) +␣
↪O(Integer(4999)))])
>>> charpoly_frobenius(M, [Integer(2), Integer(1), Integer(1)], Integer(4999),␣
↪Integer(1), Integer(1), [Integer(1), -Integer(2), Integer(1)])
[4999, 139, 1]
```

17.4 Cyclic cover curve constructor

sage.schemes.cyclic_covers.constructor.**CyclicCover**(*r*, *f*, *names=None*, *check_smooth=True*)

Return the cyclic cover of the projective line given by $y^r = f$, for a univariate polynomial f.

INPUT:

- `r` – the order of the cover
- `f` – univariate polynomial if not given, then it defaults to 0
- `names` – (default: `["x","y"]`) names for the coordinate functions

- `check_squarefree` – boolean (default: `True`); test if the input defines a unramified cover of the projective line

Warning

When setting `check_smooth=False` or using a base ring that is not a field, the output curves are not to be trusted. For example, the output of `is_singular` or `is_smooth` only tests smoothness over the field of fractions.

Note

The words "cyclic cover" are usually used for covers of degree greater than two. We usually refer to smooth double covers of the projective line as "hyperelliptic curves" or "elliptic curves" if the genus is one. We allow such cases in this implementation, but we highly recommend to use the more specific constructors/classes HyperellipticCurve and EllipticCurve for a wider range of tools.

EXAMPLES:

Basic examples:

```
sage: R.<x> = QQ[]
sage: CyclicCover(2, x^5 + x + 1)
Cyclic Cover of P^1 over Rational Field defined by y^2 = x^5 + x + 1
sage: CyclicCover(3, x^5 + x + 1)
Cyclic Cover of P^1 over Rational Field defined by y^3 = x^5 + x + 1
sage: CyclicCover(5, x^5 + x + 1)
Cyclic Cover of P^1 over Rational Field defined by y^5 = x^5 + x + 1
sage: CyclicCover(15, x^9 + x + 1)
Cyclic Cover of P^1 over Rational Field defined by y^15 = x^9 + x + 1

sage: k.<a> = GF(9); R.<x> = k[]                                                #␣
↪needs sage.rings.finite_rings
sage: CyclicCover(5, x^9 + x + 1)                                               #␣
↪needs sage.rings.finite_rings
Cyclic Cover of P^1 over Finite Field in a of size 3^2
 defined by y^5 = x^9 + x + 1
sage: CyclicCover(15, x^9 + x + 1)                                              #␣
↪needs sage.rings.finite_rings
Traceback (most recent call last):
...
ValueError: As the characteristic divides the order of the cover,
this model is not smooth.
```

```
>>> from sage.all import *
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> CyclicCover(Integer(2), x**Integer(5) + x + Integer(1))
Cyclic Cover of P^1 over Rational Field defined by y^2 = x^5 + x + 1
>>> CyclicCover(Integer(3), x**Integer(5) + x + Integer(1))
Cyclic Cover of P^1 over Rational Field defined by y^3 = x^5 + x + 1
>>> CyclicCover(Integer(5), x**Integer(5) + x + Integer(1))
Cyclic Cover of P^1 over Rational Field defined by y^5 = x^5 + x + 1
```

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```
>>> CyclicCover(Integer(15), x**Integer(9) + x + Integer(1))
Cyclic Cover of P^1 over Rational Field defined by y^15 = x^9 + x + 1

>>> k = GF(Integer(9), names=('a',)); (a,) = k._first_ngens(1); R = k['x']; (x,)␣
↪= R._first_ngens(1)# needs sage.rings.finite_rings
>>> CyclicCover(Integer(5), x**Integer(9) + x + Integer(1))                    ␣
↪                          # needs sage.rings.finite_rings
Cyclic Cover of P^1 over Finite Field in a of size 3^2
 defined by y^5 = x^9 + x + 1
>>> CyclicCover(Integer(15), x**Integer(9) + x + Integer(1))                   ␣
↪                          # needs sage.rings.finite_rings
Traceback (most recent call last):
...
ValueError: As the characteristic divides the order of the cover,
this model is not smooth.
```

We can change the names of the variables in the output:

```
sage: k.<a> = GF(9); R.<x> = k[]                                               #␣
↪needs sage.rings.finite_rings
sage: CyclicCover(5, x^9 + x + 1, names=["A","B"])                             #␣
↪needs sage.rings.finite_rings
Cyclic Cover of P^1 over Finite Field in a of size 3^2
 defined by B^5 = A^9 + A + 1
```

```
>>> from sage.all import *
>>> k = GF(Integer(9), names=('a',)); (a,) = k._first_ngens(1); R = k['x']; (x,)␣
↪= R._first_ngens(1)# needs sage.rings.finite_rings
>>> CyclicCover(Integer(5), x**Integer(9) + x + Integer(1), names=["A","B"])   ␣
↪                          # needs sage.rings.finite_rings
Cyclic Cover of P^1 over Finite Field in a of size 3^2
 defined by B^5 = A^9 + A + 1
```

Double roots:

```
sage: P.<x> = GF(7)[]
sage: CyclicCover(2, (x^3-x+2)^2*(x^6-1))
Traceback (most recent call last):
...
ValueError: Not a smooth Cyclic Cover of P^1: singularity in the provided affine␣
↪patch.

sage: CyclicCover(2, (x^3-x+2)^2*(x^6-1), check_smooth=False)                  #␣
↪needs sage.rings.finite_rings
Cyclic Cover of P^1 over Finite Field of size 7
 defined by y^2 = x^12 - 2*x^10 - 3*x^9 + x^8 + 3*x^7 + 3*x^6
                  + 2*x^4 + 3*x^3 - x^2 - 3*x + 3
```

```
>>> from sage.all import *
>>> P = GF(Integer(7))['x']; (x,) = P._first_ngens(1)
>>> CyclicCover(Integer(2), (x**Integer(3)-
↪x+Integer(2))**Integer(2)*(x**Integer(6)-Integer(1)))
```

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```
Traceback (most recent call last):
...
ValueError: Not a smooth Cyclic Cover of P^1: singularity in the provided affine␣
↪patch.

>>> CyclicCover(Integer(2), (x**Integer(3)-
↪x+Integer(2))**Integer(2)*(x**Integer(6)-Integer(1)), check_smooth=False)      ␣
↪            # needs sage.rings.finite_rings
Cyclic Cover of P^1 over Finite Field of size 7
 defined by y^2 = x^12 - 2*x^10 - 3*x^9 + x^8 + 3*x^7 + 3*x^6
                  + 2*x^4 + 3*x^3 - x^2 - 3*x + 3
```

Input with integer coefficients creates objects with the integers as base ring, but only checks smoothness over $\mathbf{Q}$, not over Spec($\mathbf{Z}$). In other words, it is checked that the discriminant is nonzero, but it is not checked whether the discriminant is a unit in $\mathbf{Z}^*$:

```
sage: R.<x> = ZZ[]
sage: CyclicCover(5, (x^3-x+2)*(x^6-1))
Cyclic Cover of P^1 over Integer Ring defined by y^5 = x^9 - x^7 + 2*x^6 - x^3 +␣
↪x - 2
```

```
>>> from sage.all import *
>>> R = ZZ['x']; (x,) = R._first_ngens(1)
>>> CyclicCover(Integer(5), (x**Integer(3)-x+Integer(2))*(x**Integer(6)-
↪Integer(1)))
Cyclic Cover of P^1 over Integer Ring defined by y^5 = x^9 - x^7 + 2*x^6 - x^3 +␣
↪x - 2
```

CHAPTER

EIGHTEEN

BERKOVICH ANALYTIC SPACE

18.1 Elements of Berkovich space.

Berkovich_Element is an abstract parent class for elements of any Berkovich space.

Berkovich_Element_Cp_Affine and *Berkovich_Element_Cp_Projective* implement elements of Berkovich space over $\mathbf{C}_p$ and $P^1(\mathbf{C}_p)$. Elements are determined by specific data and fall into one of the four following types:

- Type I points are represented by a center.
- Type II points are represented by a center and a rational power of p.
- Type III points are represented by a center and a nonnegative real radius.
- Type IV points are represented by a finite list of centers and a finite list of nonnegative radii.

For an exposition of Berkovich space over $\mathbf{C}_p$, see Chapter 6 of [Ben2019]. For a more involved exposition, see Chapter 1 and 2 of [BR2010].

AUTHORS:

- Alexander Galarraga (2020-06-22): initial implementation

class sage.schemes.berkovich.berkovich_cp_element.**Berkovich_Element**

Bases: Element

The parent class for any element of a Berkovich space.

class sage.schemes.berkovich.berkovich_cp_element.**Berkovich_Element_Cp**(*parent*, *center*, *radius=None*, *power=None*, *prec=20*, *space_type=None*, *error_check=True*)

Bases: *Berkovich_Element*

The abstract parent class for any element of Berkovich space over $\mathbf{C}_p$.

This class should never be instantiated, instead use *Berkovich_Element_Cp_Affine* or *Berkovich_Element_Cp_Projective*.

EXAMPLES:

```
sage: B = Berkovich_Cp_Affine(3)
sage: B(2)
Type I point centered at 2 + O(3^20)
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Affine(Integer(3))
>>> B(Integer(2))
Type I point centered at 2 + O(3^20)
```

```
sage: B(0, 1)
Type II point centered at 0 of radius 3^0
```

```
>>> from sage.all import *
>>> B(Integer(0), Integer(1))
Type II point centered at 0 of radius 3^0
```

Hsia_kernel(*other*, *basepoint*)

The Hsia kernel of this point and `other`, with basepoint `basepoint`.

The Hsia kernel with arbitrary basepoint is a generalization of the Hsia kernel at infinity.

INPUT:

- `other` – a point of the same Berkovich space as this point
- `basepoint` – a point of the same Berkovich space as this point

OUTPUT: a finite or infinite real number

EXAMPLES:

```
sage: B = Berkovich_Cp_Projective(3)
sage: Q1 = B(2, 9)
sage: Q2 = B(1/27, 1/27)
sage: Q3 = B(1, 1/3)
sage: Q1.Hsia_kernel(Q2, Q3)
0.111111111111111
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Projective(Integer(3))
>>> Q1 = B(Integer(2), Integer(9))
>>> Q2 = B(Integer(1)/Integer(27), Integer(1)/Integer(27))
>>> Q3 = B(Integer(1), Integer(1)/Integer(3))
>>> Q1.Hsia_kernel(Q2, Q3)
0.111111111111111
```

```
sage: B = Berkovich_Cp_Projective(3)
sage: Q1 = B(2, 9)
sage: Q2 = B(1/2)
sage: Q3 = B(1/2)
sage: Q1.Hsia_kernel(Q2, Q3)
+infinity
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Projective(Integer(3))
>>> Q1 = B(Integer(2), Integer(9))
>>> Q2 = B(Integer(1)/Integer(2))
>>> Q3 = B(Integer(1)/Integer(2))
```

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```
>>> Q1.Hsia_kernel(Q2, Q3)
+infinity
```

Hsia_kernel_infinity(*other*)

Return the Hsia kernel at infinity of this point with `other`.

The Hsia kernel at infinity is the natural extension of the absolute value on $\mathbf{C}_p$ to Berkovich space.

INPUT:

- `other` – a point of the same Berkovich space as this point

OUTPUT: a real number

EXAMPLES:

```
sage: B = Berkovich_Cp_Affine(Qp(3))
sage: Q1 = B(1/4, 4)
sage: Q2 = B(1/4, 6)
sage: Q1.Hsia_kernel_infinity(Q2)
6.00000000000000
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Affine(Qp(Integer(3)))
>>> Q1 = B(Integer(1)/Integer(4), Integer(4))
>>> Q2 = B(Integer(1)/Integer(4), Integer(6))
>>> Q1.Hsia_kernel_infinity(Q2)
6.00000000000000
```

```
sage: # needs sage.rings.number_field
sage: R.<x> = QQ[]
sage: A.<a> = NumberField(x^3 + 20)
sage: ideal = A.ideal(-1/2*a^2 + a - 3)
sage: B = Berkovich_Cp_Projective(A, ideal)
sage: Q1 = B(4)
sage: Q2 = B(0, 1.5)
sage: Q1.Hsia_kernel_infinity(Q2)
1.50000000000000
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> A = NumberField(x**Integer(3) + Integer(20), names=('a',)); (a,) = A._
↪first_ngens(1)
>>> ideal = A.ideal(-Integer(1)/Integer(2)*a**Integer(2) + a - Integer(3))
>>> B = Berkovich_Cp_Projective(A, ideal)
>>> Q1 = B(Integer(4))
>>> Q2 = B(Integer(0), RealNumber('1.5'))
>>> Q1.Hsia_kernel_infinity(Q2)
1.50000000000000
```

big_metric(*other*)

Return the path distance metric distance between this point and `other`.

Also referred to as the hyperbolic metric, or the big metric.

On the set of type II, III and IV points, the path distance metric is a metric. Following Baker and Rumely, we extend the path distance metric to type I points x, y by $\rho(x, x) = 0$ and $\rho(x, y) = \infty$. See [BR2010].

INPUT:

- `other` – a point of the same Berkovich space as this point

OUTPUT: a finite or infinite real number

EXAMPLES:

```
sage: B = Berkovich_Cp_Affine(3)
sage: Q1 = B(1/4, 4)
sage: Q2 = B(1/4, 6)
sage: Q1.path_distance_metric(Q2)
0.369070246428542
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Affine(Integer(3))
>>> Q1 = B(Integer(1)/Integer(4), Integer(4))
>>> Q2 = B(Integer(1)/Integer(4), Integer(6))
>>> Q1.path_distance_metric(Q2)
0.369070246428542
```

```
sage: Q3 = B(1)
sage: Q3.path_distance_metric(Q1)
+infinity
```

```
>>> from sage.all import *
>>> Q3 = B(Integer(1))
>>> Q3.path_distance_metric(Q1)
+infinity
```

```
sage: Q3.path_distance_metric(Q3)
0
```

```
>>> from sage.all import *
>>> Q3.path_distance_metric(Q3)
0
```

center()

Return the center of the corresponding disk (or sequence of disks) in $\mathbf{C}_p$.

OUTPUT: an element of the `base` of the parent Berkovich space

EXAMPLES:

```
sage: B = Berkovich_Cp_Affine(3)
sage: B(3, 1).center()
3 + O(3^21)
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Affine(Integer(3))
>>> B(Integer(3), Integer(1)).center()
3 + O(3^21)
```

```
sage: C = Berkovich_Cp_Projective(3)
sage: C(3, 1).center()
(3 + O(3^21) : 1 + O(3^20))
```

```
>>> from sage.all import *
>>> C = Berkovich_Cp_Projective(Integer(3))
>>> C(Integer(3), Integer(1)).center()
(3 + O(3^21) : 1 + O(3^20))
```

```
sage: # needs sage.rings.number_field
sage: R.<x> = QQ[]
sage: A.<a> = NumberField(x^3 + 20)
sage: ideal = A.ideal(-1/2*a^2 + a - 3)
sage: B = Berkovich_Cp_Projective(A, ideal)
sage: B(a^2 + 4).center()
(a^2 + 4 : 1)
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> A = NumberField(x**Integer(3) + Integer(20), names=('a',)); (a,) = A._
↪first_ngens(1)
>>> ideal = A.ideal(-Integer(1)/Integer(2)*a**Integer(2) + a - Integer(3))
>>> B = Berkovich_Cp_Projective(A, ideal)
>>> B(a**Integer(2) + Integer(4)).center()
(a^2 + 4 : 1)
```

center_function()

Return the function defining the centers of disks in the approximation.

Not defined unless this point is a type IV point created by using a univariate function to compute centers.

OUTPUT: a univariate function

EXAMPLES:

```
sage: B = Berkovich_Cp_Projective(5)
sage: L.<t> = PolynomialRing(Qp(5))
sage: T = FractionField(L)
sage: f = T(1/t)
sage: R.<x> = RR[]
sage: Y = FractionField(R)
sage: g = (40*pi)/x                                                    #␣
↪needs sage.symbolic
sage: Q1 = B(f, g)                                                     #␣
↪needs sage.symbolic
sage: Q1.center_function()                                             #␣
↪needs sage.symbolic
(1 + O(5^20))/((1 + O(5^20))*t)
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Projective(Integer(5))
>>> L = PolynomialRing(Qp(Integer(5)), names=('t',)); (t,) = L._first_ngens(1)
```

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```
>>> T = FractionField(L)
>>> f = T(Integer(1)/t)
>>> R = RR['x']; (x,) = R._first_ngens(1)
>>> Y = FractionField(R)
>>> g = (Integer(40)*pi)/x
↪     # needs sage.symbolic
>>> Q1 = B(f, g)
↪needs sage.symbolic
>>> Q1.center_function()
↪needs sage.symbolic
(1 + O(5^20))/((1 + O(5^20))*t)
```

diameter(*basepoint=+Infinity*)

Generalized diameter function on Berkovich space.

If the basepoint is infinity, the diameter is equal to the limit of the radii of the corresponding disks in $\mathbf{C}_p$.

If the basepoint is not infinity, the diameter is the Hsia kernel of this point with itself at basepoint `basepoint`.

INPUT:

- `basepoint` – (default: `Infinity`) a point of the same Berkovich space as this point

OUTPUT: a real number

EXAMPLES:

```
sage: B = Berkovich_Cp_Affine(3)
sage: Q1 = B(3)
sage: Q1.diameter()
0
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Affine(Integer(3))
>>> Q1 = B(Integer(3))
>>> Q1.diameter()
0
```

```
sage: Q2 = B(1/2, 9)
sage: Q2.diameter()
9.00000000000000
```

```
>>> from sage.all import *
>>> Q2 = B(Integer(1)/Integer(2), Integer(9))
>>> Q2.diameter()
9.00000000000000
```

The diameter of a type IV point is the limit of the radii:

```
sage: R.<x> = PolynomialRing(Qp(3))
sage: f = R(2)
sage: S.<y> = PolynomialRing(RR)
sage: S = FractionField(S)
sage: g = (y+1)/y
```

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```
sage: B(f,g).diameter()
1.0
```

```
>>> from sage.all import *
>>> R = PolynomialRing(Qp(Integer(3)), names=('x',)); (x,) = R._first_ngens(1)
>>> f = R(Integer(2))
>>> S = PolynomialRing(RR, names=('y',)); (y,) = S._first_ngens(1)
>>> S = FractionField(S)
>>> g = (y+Integer(1))/y
>>> B(f,g).diameter()
1.0
```

```
sage: B = Berkovich_Cp_Affine(3)
sage: Q1 = B(1/81, 1)
sage: Q2 = B(1/3)
sage: Q1.diameter(Q2)
0.00137174211248285
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Affine(Integer(3))
>>> Q1 = B(Integer(1)/Integer(81), Integer(1))
>>> Q2 = B(Integer(1)/Integer(3))
>>> Q1.diameter(Q2)
0.00137174211248285
```

```
sage: Q2.diameter(Q2)
+infinity
```

```
>>> from sage.all import *
>>> Q2.diameter(Q2)
+infinity
```

hyperbolic_metric(*other*)

Return the path distance metric distance between this point and `other`.

Also referred to as the hyperbolic metric, or the big metric.

On the set of type II, III and IV points, the path distance metric is a metric. Following Baker and Rumely, we extend the path distance metric to type I points x, y by $\rho(x, x) = 0$ and $\rho(x, y) = \infty$. See [BR2010].

INPUT:

- `other` – a point of the same Berkovich space as this point

OUTPUT: a finite or infinite real number

EXAMPLES:

```
sage: B = Berkovich_Cp_Affine(3)
sage: Q1 = B(1/4, 4)
sage: Q2 = B(1/4, 6)
sage: Q1.path_distance_metric(Q2)
0.369070246428542
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Affine(Integer(3))
>>> Q1 = B(Integer(1)/Integer(4), Integer(4))
>>> Q2 = B(Integer(1)/Integer(4), Integer(6))
>>> Q1.path_distance_metric(Q2)
0.369070246428542
```

```
sage: Q3 = B(1)
sage: Q3.path_distance_metric(Q1)
+infinity
```

```
>>> from sage.all import *
>>> Q3 = B(Integer(1))
>>> Q3.path_distance_metric(Q1)
+infinity
```

```
sage: Q3.path_distance_metric(Q3)
0
```

```
>>> from sage.all import *
>>> Q3.path_distance_metric(Q3)
0
```

ideal()

The ideal which defines an embedding of the `base_ring` into $\mathbf{C}_p$.

If this Berkovich space is backed by a p-adic field, then an embedding is already specified, and this returns `None`.

EXAMPLES:

```
sage: B = Berkovich_Cp_Projective(QQ, 3)
sage: B(0).ideal()
3

::

sage: B = Berkovich_Cp_Projective(3)
sage: B(0).ideal()
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Projective(QQ, Integer(3))
>>> B(Integer(0)).ideal()
3

::

>>> B = Berkovich_Cp_Projective(Integer(3))
>>> B(Integer(0)).ideal()
```

path_distance_metric(*other*)

Return the path distance metric distance between this point and `other`.

Also referred to as the hyperbolic metric, or the big metric.

On the set of type II, III and IV points, the path distance metric is a metric. Following Baker and Rumely, we extend the path distance metric to type I points x, y by $\rho(x, x) = 0$ and $\rho(x, y) = \infty$. See [BR2010].

INPUT:

- `other` – a point of the same Berkovich space as this point

OUTPUT: a finite or infinite real number

EXAMPLES:

```
sage: B = Berkovich_Cp_Affine(3)
sage: Q1 = B(1/4, 4)
sage: Q2 = B(1/4, 6)
sage: Q1.path_distance_metric(Q2)
0.369070246428542
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Affine(Integer(3))
>>> Q1 = B(Integer(1)/Integer(4), Integer(4))
>>> Q2 = B(Integer(1)/Integer(4), Integer(6))
>>> Q1.path_distance_metric(Q2)
0.369070246428542
```

```
sage: Q3 = B(1)
sage: Q3.path_distance_metric(Q1)
+infinity
```

```
>>> from sage.all import *
>>> Q3 = B(Integer(1))
>>> Q3.path_distance_metric(Q1)
+infinity
```

```
sage: Q3.path_distance_metric(Q3)
0
```

```
>>> from sage.all import *
>>> Q3.path_distance_metric(Q3)
0
```

potential_kernel(*other*, *basepoint*)

The potential kernel of this point with `other`, with basepoint `basepoint`.

The potential kernel is the hyperbolic distance between `basepoint` and the join of this point with `other` relative to `basepoint`.

INPUT:

- `other` – a point of the same Berkovich space as this point
- `basepoint` – a point of the same Berkovich space as this point

OUTPUT: a finite or infinite real number

EXAMPLES:

```
sage: B = Berkovich_Cp_Projective(3)
sage: Q1 = B(27, 1)
sage: Q2 = B(1/3, 2)
sage: Q3 = B(1/9, 1/2)
sage: Q3.potential_kernel(Q1, Q2)
0.369070246428543
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Projective(Integer(3))
>>> Q1 = B(Integer(27), Integer(1))
>>> Q2 = B(Integer(1)/Integer(3), Integer(2))
>>> Q3 = B(Integer(1)/Integer(9), Integer(1)/Integer(2))
>>> Q3.potential_kernel(Q1, Q2)
0.369070246428543
```

```
sage: B = Berkovich_Cp_Affine(3)
sage: Q1 = B(27, 1)
sage: Q2 = B(1/3, 2)
sage: Q3 = B(1/9, 1/2)
sage: Q3.potential_kernel(Q1, Q2)
0.369070246428543
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Affine(Integer(3))
>>> Q1 = B(Integer(27), Integer(1))
>>> Q2 = B(Integer(1)/Integer(3), Integer(2))
>>> Q3 = B(Integer(1)/Integer(9), Integer(1)/Integer(2))
>>> Q3.potential_kernel(Q1, Q2)
0.369070246428543
```

power()

The power of p such that $p^{\text{power}} = \text{radius}$.

For type II points, always in $\mathbf{Q}$. For type III points, a real number. Not defined for type I or IV points.

OUTPUT:

- A rational for type II points.
- A real number for type III points.

EXAMPLES:

```
sage: B = Berkovich_Cp_Affine(3)
sage: Q1 = B(1, 9)
sage: Q1.power()
2
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Affine(Integer(3))
>>> Q1 = B(Integer(1), Integer(9))
>>> Q1.power()
2
```

```
sage: Q2 = B(1, 4)
sage: Q2.power()
1.26185950714291
```

```
>>> from sage.all import *
>>> Q2 = B(Integer(1), Integer(4))
>>> Q2.power()
1.26185950714291
```

prec()

Return the precision of a type IV point.

This integer is the number of disks used in the approximation of the type IV point. Not defined for type I, II, or III points.

OUTPUT: integer

EXAMPLES:

```
sage: B = Berkovich_Cp_Affine(Qp(3))
sage: d = B([2, 2, 2], [1.761, 1.123, 1.112])
sage: d.precision()
3
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Affine(Qp(Integer(3)))
>>> d = B([Integer(2), Integer(2), Integer(2)], [RealNumber('1.761'),␣
↪RealNumber('1.123'), RealNumber('1.112')])
>>> d.precision()
3
```

precision()

Return the precision of a type IV point.

This integer is the number of disks used in the approximation of the type IV point. Not defined for type I, II, or III points.

OUTPUT: integer

EXAMPLES:

```
sage: B = Berkovich_Cp_Affine(Qp(3))
sage: d = B([2, 2, 2], [1.761, 1.123, 1.112])
sage: d.precision()
3
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Affine(Qp(Integer(3)))
>>> d = B([Integer(2), Integer(2), Integer(2)], [RealNumber('1.761'),␣
↪RealNumber('1.123'), RealNumber('1.112')])
>>> d.precision()
3
```

prime()

The residue characteristic of the parent.

OUTPUT: a prime integer

EXAMPLES:

```
sage: B = Berkovich_Cp_Affine(3)
sage: B(1).prime()
3
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Affine(Integer(3))
>>> B(Integer(1)).prime()
3
```

radius()

Radius of the corresponding disk (or sequence of disks) in $\mathbf{C}_p$.

OUTPUT:

- A nonnegative real number for type I, II, or III points.
- A list of nonnegative real numbers for type IV points.

EXAMPLES:

```
sage: B = Berkovich_Cp_Affine(3)
sage: Q1 = B(1, 2/5)
sage: Q1.radius()
0.400000000000000
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Affine(Integer(3))
>>> Q1 = B(Integer(1), Integer(2)/Integer(5))
>>> Q1.radius()
0.400000000000000
```

```
sage: d = B([2, 2, 2], [1.761, 1.123, 1.112])
sage: d.radius()
[1.76100000000000, 1.12300000000000, 1.11200000000000]
```

```
>>> from sage.all import *
>>> d = B([Integer(2), Integer(2), Integer(2)], [RealNumber('1.761'),␣
↪RealNumber('1.123'), RealNumber('1.112')])
>>> d.radius()
[1.76100000000000, 1.12300000000000, 1.11200000000000]
```

radius_function()

Return the function defining the radii of disks in the approximation.

Not defined unless this point is a type IV point created by using a univariate function to compute radii.

OUTPUT: a univariate function

EXAMPLES:

```
sage: B = Berkovich_Cp_Projective(5)
sage: L.<t> = PolynomialRing(Qp(5))
```

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```
sage: T = FractionField(L)
sage: f = T(1/t)
sage: R.<x> = RR[]
sage: Y = FractionField(R)
sage: g = (40*pi)/x                                                    #␣
↪needs sage.symbolic
sage: Q1 = B(f, g)                                                     #␣
↪needs sage.symbolic
sage: Q1.radius_function()                                             #␣
↪needs sage.symbolic
40.0000000000000*pi/x
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Projective(Integer(5))
>>> L = PolynomialRing(Qp(Integer(5)), names=('t',)); (t,) = L._first_ngens(1)
>>> T = FractionField(L)
>>> f = T(Integer(1)/t)
>>> R = RR['x']; (x,) = R._first_ngens(1)
>>> Y = FractionField(R)
>>> g = (Integer(40)*pi)/x                                                 ␣
↪     # needs sage.symbolic
>>> Q1 = B(f, g)                                                        #␣
↪needs sage.symbolic
>>> Q1.radius_function()                                                #␣
↪needs sage.symbolic
40.0000000000000*pi/x
```

small_metric(*other*)

Return the small metric distance between this point and `other`.

The small metric is an extension of twice the spherical distance on $P^1(\mathbf{C}_p)$.

INPUT:

- `other` – a point of the same Berkovich space as this point

OUTPUT: a real number

EXAMPLES:

```
sage: B = Berkovich_Cp_Affine(3)
sage: Q1 = B(1/4, 4)
sage: Q2 = B(1/4, 6)
sage: Q1.small_metric(Q2)
0.0833333333333333
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Affine(Integer(3))
>>> Q1 = B(Integer(1)/Integer(4), Integer(4))
>>> Q2 = B(Integer(1)/Integer(4), Integer(6))
>>> Q1.small_metric(Q2)
0.0833333333333333
```

```
sage: B = Berkovich_Cp_Projective(QQ, 5)
sage: Q1 = B(0, 1)
sage: Q2 = B(99)
sage: Q1.small_metric(Q2)
1.00000000000000
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Projective(QQ, Integer(5))
>>> Q1 = B(Integer(0), Integer(1))
>>> Q2 = B(Integer(99))
>>> Q1.small_metric(Q2)
1.00000000000000
```

```
sage: Q3 = B(1/4, 4)
sage: Q3.small_metric(Q2)
1.75000000000000
```

```
>>> from sage.all import *
>>> Q3 = B(Integer(1)/Integer(4), Integer(4))
>>> Q3.small_metric(Q2)
1.75000000000000
```

```
sage: Q2.small_metric(Q3)
1.75000000000000
```

```
>>> from sage.all import *
>>> Q2.small_metric(Q3)
1.75000000000000
```

spherical_kernel(*other*)

The spherical kernel of this point with `other`.

The spherical kernel is one possible extension of the spherical distance on $P^1(\mathbf{C}_p)$ to the projective Berkovich line. See [BR2010] for details.

INPUT:

- `other` – a point of the same Berkovich space as this point

OUTPUT: a real number

EXAMPLES:

```
sage: B = Berkovich_Cp_Projective(3)
sage: Q1 = B(2, 2)
sage: Q2 = B(1/9, 1)
sage: Q1.spherical_kernel(Q2)
0.500000000000000
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Projective(Integer(3))
>>> Q1 = B(Integer(2), Integer(2))
>>> Q2 = B(Integer(1)/Integer(9), Integer(1))
```

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```
>>> Q1.spherical_kernel(Q2)
0.500000000000000
```

```
sage: Q3 = B(2)
sage: Q3.spherical_kernel(Q3)
0
```

```
>>> from sage.all import *
>>> Q3 = B(Integer(2))
>>> Q3.spherical_kernel(Q3)
0
```

type_of_point()

Return the type of this point of Berkovich space over $\mathbf{C}_p$.

OUTPUT: integer between 1 and 4 inclusive

EXAMPLES:

```
sage: B = Berkovich_Cp_Affine(3)
sage: B(1).type_of_point()
1
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Affine(Integer(3))
>>> B(Integer(1)).type_of_point()
1
```

```
sage: B(0, 1).type_of_point()
2
```

```
>>> from sage.all import *
>>> B(Integer(0), Integer(1)).type_of_point()
2
```

class sage.schemes.berkovich.berkovich_cp_element.**Berkovich_Element_Cp_Affine**(*parent*, *center*, *radius=None*, *power=None*, *prec=20*, *error_check=True*)

Bases: *Berkovich_Element_Cp*

Element class of the Berkovich affine line over $\mathbf{C}_p$.

Elements are categorized into four types, represented by specific data:

- Type I points are represented by a center in the `base` of the parent Berkovich space, which is $\mathbf{Q}_p$, a finite extension of $\mathbf{Q}_p$, or a number field.
- Type II points are represented by a center in the `base` of the parent Berkovich space, and a rational power of p.
- Type III points are represented by a center in the `base` of the parent Berkovich space, and a radius, a real number in $[0, \infty)$.

- Type IV points are represented by a finite list of centers in the `base` of the parent Berkovich space and a finite list of radii in $[0, \infty)$. Type IV points can be created from univariate functions, allowing for arbitrary precision.

INPUT:

- `center` – for type I, II, and III points, the center of the corresponding disk in $\mathbf{C}_p$. If the parent Berkovich space was created using a number field K, then `center` must be an element of K. Otherwise, `center` must be an element of a p-adic field. For type IV points, can be a list of centers used to approximate the point or a univariate function that computes the centers (computation starts at 1).
- `radius` – (optional) For type I, II, and III points, the radius of the corresponding disk in `Cp`. Must coerce into the real numbers. For type IV points, can be a list of radii used to approximate the point or a univariate function that computes the radii (computation starts at 1).
- `power` – (optional) Rational number. Used for constructing type II points; specifies the power of `p` such that p^{power} = radius
- `prec` – (default: 20) the number of disks to be used to approximate a type IV point
- `error_check` – boolean (default: `True`); if error checking should be run on input. If input is correctly formatted, can be set to `False` for better performance. WARNING: with error check set to `False`, any error in the input will lead to incorrect results.

EXAMPLES:

Type I points can be created by specifying the corresponding point of `Cp`:

```
sage: B = Berkovich_Cp_Affine(Qp(3))
sage: B(4)
Type I point centered at 1 + 3 + O(3^20)
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Affine(Qp(Integer(3)))
>>> B(Integer(4))
Type I point centered at 1 + 3 + O(3^20)
```

The center of a point can be an element of a finite extension of `Qp`:

```
sage: A.<t> = Qq(27)
sage: B(1 + t)
Type I point centered at (t + 1) + O(3^20)
```

```
>>> from sage.all import *
>>> A = Qq(Integer(27), names=('t',)); (t,) = A._first_ngens(1)
>>> B(Integer(1) + t)
Type I point centered at (t + 1) + O(3^20)
```

Type II and III points can be created by specifying a center and a radius:

```
sage: B(2, 3**(1/2))                                                    #␣
↪needs sage.symbolic
Type II point centered at 2 + O(3^20) of radius 3^1/2
```

```
>>> from sage.all import *
>>> B(Integer(2), Integer(3)**(Integer(1)/Integer(2)))                  ␣
```

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```
↪                                  # needs sage.symbolic
Type II point centered at 2 + O(3^20) of radius 3^1/2
```

```
sage: B(2, 1.6)
Type III point centered at 2 + O(3^20) of radius 1.60000000000000
```

```
>>> from sage.all import *
>>> B(Integer(2), RealNumber('1.6'))
Type III point centered at 2 + O(3^20) of radius 1.60000000000000
```

Some type II points may be mistaken for type III points:

```
sage: B(3, 3**0.5)                          # not tested
Type III point centered at 3 + O(3^21) of radius 1.73205080756888
```

```
>>> from sage.all import *
>>> B(Integer(3), Integer(3)**RealNumber('0.5'))                          # not tested
Type III point centered at 3 + O(3^21) of radius 1.73205080756888
```

To avoid these errors, specify the power instead of the radius:

```
sage: B(3, power=RR(1/100000))
Type II point centered at 3 + O(3^21) of radius 3^1/100000
```

```
>>> from sage.all import *
>>> B(Integer(3), power=RR(Integer(1)/Integer(100000)))
Type II point centered at 3 + O(3^21) of radius 3^1/100000
```

Type IV points can be constructed in a number of ways, the first being from a list of centers and radii used to approximate the point:

```
sage: B([Qp(3)(2), Qp(3)(2), Qp(3)(2)], [1.761, 1.123, 1.112])
Type IV point of precision 3, approximated by disks centered at
[2 + O(3^20), 2 + O(3^20)] ... with radii [1.76100000000000, 1.12300000000000] ...
```

```
>>> from sage.all import *
>>> B([Qp(Integer(3))(Integer(2)), Qp(Integer(3))(Integer(2)),␣
↪Qp(Integer(3))(Integer(2))], [RealNumber('1.761'), RealNumber('1.123'),␣
↪RealNumber('1.112')])
Type IV point of precision 3, approximated by disks centered at
[2 + O(3^20), 2 + O(3^20)] ... with radii [1.76100000000000, 1.12300000000000] ...
```

Type IV points can be constructed from univariate functions, with arbitrary precision:

```
sage: A.<t> = Qq(27)
sage: R.<x> = PolynomialRing(A)
sage: f = (1 + t)^2*x
sage: S.<y> = PolynomialRing(RR)
sage: S = FractionField(S)
sage: g = (y + 1)/y
sage: d = B(f, g, prec=100); d
```

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```
Type IV point of precision 100 with centers given by
((t^2 + 2*t + 1) + O(3^20))*x and radii given by (y + 1.00000000000000)/y
```

```
>>> from sage.all import *
>>> A = Qq(Integer(27), names=('t',)); (t,) = A._first_ngens(1)
>>> R = PolynomialRing(A, names=('x',)); (x,) = R._first_ngens(1)
>>> f = (Integer(1) + t)**Integer(2)*x
>>> S = PolynomialRing(RR, names=('y',)); (y,) = S._first_ngens(1)
>>> S = FractionField(S)
>>> g = (y + Integer(1))/y
>>> d = B(f, g, prec=Integer(100)); d
Type IV point of precision 100 with centers given by
((t^2 + 2*t + 1) + O(3^20))*x and radii given by (y + 1.00000000000000)/y
```

For increased performance, `error_check` can be set to `False`. WARNING: with error check set to `False`, any error in the input will lead to incorrect results:

```
sage: B(f, g, prec=100, error_check=False)
Type IV point of precision 100 with centers given by
((t^2 + 2*t + 1) + O(3^20))*x and radii given by (y + 1.00000000000000)/y
```

```
>>> from sage.all import *
>>> B(f, g, prec=Integer(100), error_check=False)
Type IV point of precision 100 with centers given by
((t^2 + 2*t + 1) + O(3^20))*x and radii given by (y + 1.00000000000000)/y
```

When creating a Berkovich space backed by a number field, points can be created similarly:

```
sage: # needs sage.rings.number_field
sage: R.<x> = QQ[]
sage: A.<a> = NumberField(x^3 + 20)
sage: ideal = A.prime_above(3)
sage: B = Berkovich_Cp_Projective(A, ideal)
sage: Q1 = B(a); Q1
Type I point centered at (a : 1)
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> A = NumberField(x**Integer(3) + Integer(20), names=('a',)); (a,) = A._first_
↪ngens(1)
>>> ideal = A.prime_above(Integer(3))
>>> B = Berkovich_Cp_Projective(A, ideal)
>>> Q1 = B(a); Q1
Type I point centered at (a : 1)
```

```
sage: B(a + 1, 3)                                                    #␣
↪needs sage.rings.number_field
Type II point centered at (a + 1 : 1) of radius 3^1
```

```
>>> from sage.all import *
>>> B(a + Integer(1), Integer(3))
↪              # needs sage.rings.number_field
Type II point centered at (a + 1 : 1) of radius 3^1
```

as_projective_point()

Return the corresponding point of projective Berkovich space.

We identify affine Berkovich space with the subset $P^1_{\text{Berk}}(C_p) - \{(1:0)\}$.

EXAMPLES:

```
sage: B = Berkovich_Cp_Affine(5)
sage: B(5).as_projective_point()
Type I point centered at (5 + O(5^21) : 1 + O(5^20))
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Affine(Integer(5))
>>> B(Integer(5)).as_projective_point()
Type I point centered at (5 + O(5^21) : 1 + O(5^20))
```

```
sage: B(0, 1).as_projective_point()
Type II point centered at (0 : 1 + O(5^20)) of radius 5^0
```

```
>>> from sage.all import *
>>> B(Integer(0), Integer(1)).as_projective_point()
Type II point centered at (0 : 1 + O(5^20)) of radius 5^0
```

```
sage: L.<t> = PolynomialRing(Qp(5))
sage: T = FractionField(L)
sage: f = T(1/t)
sage: R.<x> = RR[]
sage: Y = FractionField(R)
sage: g = (40*pi)/x                                                    #␣
↪needs sage.symbolic
sage: Q2 = B(f, g)                                                     #␣
↪needs sage.symbolic
sage: Q2.as_projective_point()                                         #␣
↪needs sage.symbolic
Type IV point of precision 20 with centers given by (1 + O(5^20))/((1 + O(5^
↪20))*t)
and radii given by 40.0000000000000*pi/x
```

```
>>> from sage.all import *
>>> L = PolynomialRing(Qp(Integer(5)), names=('t',)); (t,) = L._first_ngens(1)
>>> T = FractionField(L)
>>> f = T(Integer(1)/t)
>>> R = RR['x']; (x,) = R._first_ngens(1)
>>> Y = FractionField(R)
>>> g = (Integer(40)*pi)/x                                                 ␣
↪     # needs sage.symbolic
>>> Q2 = B(f, g)                                                        #␣
```

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```
↪needs sage.symbolic
>>> Q2.as_projective_point()                                                #␣
↪needs sage.symbolic
Type IV point of precision 20 with centers given by (1 + O(5^20))/((1 + O(5^
↪20))*t)
and radii given by 40.0000000000000*pi/x
```

contained_in_interval(*start*, *end*)

Check if this point is an element of the interval [`start`, `end`].

INPUT:

- `start` – a point of the same Berkovich space as this point
- `end` – a point of the same Berkovich space as this point

OUTPUT:

- `True` if this point is an element of [`start`, `end`].
- `False` otherwise.

EXAMPLES:

```
sage: B = Berkovich_Cp_Projective((3))
sage: Q1 = B(2, 1)
sage: Q2 = B(2, 4)
sage: Q3 = B(1/3)
sage: Q2.contained_in_interval(Q1, Q3.join(Q1))
False
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Projective((Integer(3)))
>>> Q1 = B(Integer(2), Integer(1))
>>> Q2 = B(Integer(2), Integer(4))
>>> Q3 = B(Integer(1)/Integer(3))
>>> Q2.contained_in_interval(Q1, Q3.join(Q1))
False
```

```
sage: Q4 = B(1/81, 1)
sage: Q2.contained_in_interval(Q1, Q4.join(Q1))
True
```

```
>>> from sage.all import *
>>> Q4 = B(Integer(1)/Integer(81), Integer(1))
>>> Q2.contained_in_interval(Q1, Q4.join(Q1))
True
```

gt(*other*)

Return `True` if this point is strictly greater than `other` in the standard partial order.

Roughly, the partial order corresponds to containment of the corresponding disks in $\mathbf{C}_p$.

For example, let x and y be points of type II or III. If x has center c_1 and radius r_1 and y has center c_2 and radius r_2, $x < y$ if and only if $D(c_1, r_1)$ is a subset of $D(c_2, r_2)$ in $\mathbf{C}_p$.

INPUT:

- `other` – a point of the same Berkovich space as this point

OUTPUT:

- `True` – if this point is greater than `other` in the standard partial order
- `False` – otherwise

EXAMPLES:

```
sage: B = Berkovich_Cp_Affine(QQ, 3)
sage: Q1 = B(5, 3)
sage: Q2 = B(5, 1)
sage: Q1.gt(Q2)
True
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Affine(QQ, Integer(3))
>>> Q1 = B(Integer(5), Integer(3))
>>> Q2 = B(Integer(5), Integer(1))
>>> Q1.gt(Q2)
True
```

```
sage: Q3 = B(1/27)
sage: Q1.gt(Q3)
False
```

```
>>> from sage.all import *
>>> Q3 = B(Integer(1)/Integer(27))
>>> Q1.gt(Q3)
False
```

involution_map()

Return the image of this point under the involution map.

The involution map is the extension of the map `z |-> 1/z` on $\mathbf{C}_p$ to Berkovich space.

For affine Berkovich space, not defined for the type I point centered at 0.

If zero is contained in every disk approximating a type IV point, then the image under the involution map is not defined. To avoid this error, increase precision.

OUTPUT: a point of the same Berkovich space

EXAMPLES:

The involution map is 1/z on type I points:

```
sage: B = Berkovich_Cp_Affine(3)
sage: Q1 = B(1/2)
sage: Q1.involution_map()
Type I point centered at 2 + O(3^20)
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Affine(Integer(3))
>>> Q1 = B(Integer(1)/Integer(2))
>>> Q1.involution_map()
Type I point centered at 2 + O(3^20)
```

```
sage: Q2 = B(0, 1/3)
sage: Q2.involution_map()
Type II point centered at 0 of radius 3^1
```

```
>>> from sage.all import *
>>> Q2 = B(Integer(0), Integer(1)/Integer(3))
>>> Q2.involution_map()
Type II point centered at 0 of radius 3^1
```

```
sage: Q3 = B(1/3, 1/3)
sage: Q3.involution_map()
Type II point centered at 3 + O(3^21) of radius 3^-3
```

```
>>> from sage.all import *
>>> Q3 = B(Integer(1)/Integer(3), Integer(1)/Integer(3))
>>> Q3.involution_map()
Type II point centered at 3 + O(3^21) of radius 3^-3
```

join(*other*, *basepoint=+Infinity*)

Compute the join of this point and `other` with respect to `basepoint`.

The join is first point that lies on the intersection of the path from this point to `basepoint` and the path from `other` to `basepoint`.

INPUT:

- `other` – a point of the same Berkovich space as this point
- `basepoint` – (default: `Infinity`) a point of the same Berkovich space as this point or `Infinity`

OUTPUT: a point of the same Berkovich space

EXAMPLES:

```
sage: B = Berkovich_Cp_Affine(3)
sage: Q1 = B(2, 1)
sage: Q2 = B(2, 2)
sage: Q1.join(Q2)
Type III point centered at 2 + O(3^20) of radius 2.00000000000000
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Affine(Integer(3))
>>> Q1 = B(Integer(2), Integer(1))
>>> Q2 = B(Integer(2), Integer(2))
>>> Q1.join(Q2)
Type III point centered at 2 + O(3^20) of radius 2.00000000000000
```

```
sage: Q3 = B(5)
sage: Q3.join(Q1)
Type II point centered at 2 + 3 + O(3^20) of radius 3^0
```

```
>>> from sage.all import *
>>> Q3 = B(Integer(5))
```

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```
>>> Q3.join(Q1)
Type II point centered at 2 + 3 + O(3^20) of radius 3^0
```

```
sage: Q3.join(Q1, basepoint=Q2)
Type II point centered at 2 + O(3^20) of radius 3^0
```

```
>>> from sage.all import *
>>> Q3.join(Q1, basepoint=Q2)
Type II point centered at 2 + O(3^20) of radius 3^0
```

lt(*other*)

Return `True` if this point is strictly less than `other` in the standard partial order.

Roughly, the partial order corresponds to containment of the corresponding disks in `Cp`.

For example, let x and y be points of type II or III. If x has center c_1 and radius r_1 and y has center c_2 and radius r_2, $x < y$ if and only if $D(c_1, r_1)$ is a subset of $D(c_2, r_2)$ in $\mathbf{C}_p$.

INPUT:

- `other` – a point of the same Berkovich space as this point

OUTPUT:

- `True` – if this point is less than `other` in the standard partial order
- `False` – otherwise

EXAMPLES:

```
sage: B = Berkovich_Cp_Projective(3)
sage: Q1 = B(5, 0.5)
sage: Q2 = B(5, 1)
sage: Q1.lt(Q2)
True
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Projective(Integer(3))
>>> Q1 = B(Integer(5), RealNumber('0.5'))
>>> Q2 = B(Integer(5), Integer(1))
>>> Q1.lt(Q2)
True
```

```
sage: Q3 = B(1)
sage: Q1.lt(Q3)
False
```

```
>>> from sage.all import *
>>> Q3 = B(Integer(1))
>>> Q1.lt(Q3)
False
```

class sage.schemes.berkovich.berkovich_cp_element.**Berkovich_Element_Cp_Projective**(*parent*, *center*, *radius=None*, *power=None*, *prec=20*, *error_check=True*)

Bases: *Berkovich_Element_Cp*

Element class of the Berkovich projective line over $\mathbf{C}_p$.

Elements are categorized into four types, represented by specific data:

- Type I points are represented by a center in the `base` of the parent Berkovich space, which is projective space of dimension 1 over either $\mathbf{Q}_p$, a finite extension of $\mathbf{Q}_p$, or a number field.
- Type II points are represented by a center in the `base` of the parent Berkovich space, and a rational power of p.
- Type III points are represented by a center in the `base` of the parent Berkovich space, and by a radius, a real number, in $[0, \infty)$.
- Type IV points are represented by a finite list of centers in the `base` of the parent Berkovich space and a finite list of radii in $[0, \infty)$.

The projective Berkovich line is viewed as the one-point compactification of the affine Berkovich line. The projective Berkovich line therefore contains every point of the affine Berkovich line, along with a type I point centered at infinity.

INPUT:

- `center` – for type I, II, and III points, the center of the corresponding disk in $P^1(\mathbf{C}_p)$. If the parent Berkovich space was created using a number field K, then `center` can be an element of $P^1(K)$. Otherwise, `center` must be an element of a projective space of dimension 1 over a p-adic field. For type IV points, can be a list of centers used to approximate the point or a univariate function that computes the centers (computation starts at 1).
- `radius` – (optional) For type I, II, and III points, the radius of the corresponding disk in $\mathbf{C}_p$. Must coerce into the real numbers. For type IV points, can be a list of radii used to approximate the point or a univariate function that computes the radii (computation starts at 1).
- `power` – (optional) Rational number. Used for constructing type II points; specifies the power of `p` such that p^{power} = radius
- `prec` – (default: 20) the number of disks to be used to approximate a type IV point
- `error_check` – boolean (default: `True`); if error checking should be run on input. If input is correctly formatted, can be set to `False` for better performance. WARNING: with error check set to `False`, any error in the input will lead to incorrect results.

EXAMPLES:

Type I points can be created by specifying the corresponding point of $P^1(\mathbf{C}_p)$:

```
sage: S = ProjectiveSpace(Qp(5), 1)
sage: P = Berkovich_Cp_Projective(S); P
Projective Berkovich line over Cp(5) of precision 20
```

```
>>> from sage.all import *
>>> S = ProjectiveSpace(Qp(Integer(5)), Integer(1))
>>> P = Berkovich_Cp_Projective(S); P
Projective Berkovich line over Cp(5) of precision 20
```

```
sage: a = S(0, 1)
sage: Q1 = P(a); Q1
Type I point centered at (0 : 1 + O(5^20))
```

```
>>> from sage.all import *
>>> a = S(Integer(0), Integer(1))
>>> Q1 = P(a); Q1
Type I point centered at (0 : 1 + O(5^20))
```

```
sage: Q2 = P((1,0)); Q2
Type I point centered at (1 + O(5^20) : 0)
```

```
>>> from sage.all import *
>>> Q2 = P((Integer(1),Integer(0))); Q2
Type I point centered at (1 + O(5^20) : 0)
```

Type II and III points can be created by specifying a center and a radius:

```
sage: Q3 = P((0,5), 5**(3/2)); Q3                                                #␣
↪needs sage.symbolic
Type II point centered at (0 : 1 + O(5^20)) of radius 5^3/2
```

```
>>> from sage.all import *
>>> Q3 = P((Integer(0),Integer(5)), Integer(5)**(Integer(3)/Integer(2))); Q3     ␣
↪                                          # needs sage.symbolic
Type II point centered at (0 : 1 + O(5^20)) of radius 5^3/2
```

```
sage: Q4 = P(0, 3**(3/2)); Q4                                                    #␣
↪needs sage.symbolic
Type III point centered at (0 : 1 + O(5^20)) of radius 5.19615242270663
```

```
>>> from sage.all import *
>>> Q4 = P(Integer(0), Integer(3)**(Integer(3)/Integer(2))); Q4                  ␣
↪                                    # needs sage.symbolic
Type III point centered at (0 : 1 + O(5^20)) of radius 5.19615242270663
```

Type IV points can be created from lists of centers and radii:

```
sage: b = S((3,2))  # create centers
sage: c = S((4,3))
sage: d = S((2,3))
sage: L = [b, c, d]
sage: R = [1.761, 1.123, 1.112]
sage: Q5 = P(L, R); Q5
Type IV point of precision 3, approximated by disks centered at
[(4 + 2*5 + 2*5^2 + 2*5^3 + 2*5^4 + 2*5^5 + 2*5^6 + 2*5^7 + 2*5^8 + 2*5^9 + 2*5^
```

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```
↪10 +
 2*5^11 + 2*5^12 + 2*5^13 + 2*5^14 + 2*5^15 + 2*5^16 + 2*5^17 + 2*5^18 + 2*5^19 +␣
↪O(5^20) :
 1 + O(5^20)), (3 + 3*5 + 5^2 + 3*5^3 + 5^4 + 3*5^5 + 5^6 + 3*5^7 + 5^8 + 3*5^9 +
 5^10 + 3*5^11 + 5^12 + 3*5^13 + 5^14 + 3*5^15 + 5^16 + 3*5^17 + 5^18 + 3*5^19 +␣
↪O(5^20) :
 1 + O(5^20))] ... with radii [1.76100000000000, 1.12300000000000] ...
```

```
>>> from sage.all import *
>>> b = S((Integer(3),Integer(2)))  # create centers
>>> c = S((Integer(4),Integer(3)))
>>> d = S((Integer(2),Integer(3)))
>>> L = [b, c, d]
>>> R = [RealNumber('1.761'), RealNumber('1.123'), RealNumber('1.112')]
>>> Q5 = P(L, R); Q5
Type IV point of precision 3, approximated by disks centered at
[(4 + 2*5 + 2*5^2 + 2*5^3 + 2*5^4 + 2*5^5 + 2*5^6 + 2*5^7 + 2*5^8 + 2*5^9 + 2*5^
↪10 +
 2*5^11 + 2*5^12 + 2*5^13 + 2*5^14 + 2*5^15 + 2*5^16 + 2*5^17 + 2*5^18 + 2*5^19 +␣
↪O(5^20) :
 1 + O(5^20)), (3 + 3*5 + 5^2 + 3*5^3 + 5^4 + 3*5^5 + 5^6 + 3*5^7 + 5^8 + 3*5^9 +
 5^10 + 3*5^11 + 5^12 + 3*5^13 + 5^14 + 3*5^15 + 5^16 + 3*5^17 + 5^18 + 3*5^19 +␣
↪O(5^20) :
 1 + O(5^20))] ... with radii [1.76100000000000, 1.12300000000000] ...
```

Type IV points can also be created from univariate functions. Since the centers of the sequence of disks can not be the point at infinity in $P^1(\mathbf{C}_p)$, only functions into $\mathbf{C}_p$ are supported:

```
sage: L.<t> = PolynomialRing(Qp(5))
sage: T = FractionField(L)
sage: f = T(1/t)
sage: R.<x> = RR[]
sage: Y = FractionField(R)
sage: g = (40*pi)/x                                                          #␣
↪needs sage.symbolic
sage: Q6 = P(f, g); Q6                                                       #␣
↪needs sage.symbolic
Type IV point of precision 20 with centers given by (1 + O(5^20))/((1 + O(5^
↪20))*t)
 and radii given by 40.0000000000000*pi/x
```

```
>>> from sage.all import *
>>> L = PolynomialRing(Qp(Integer(5)), names=('t',)); (t,) = L._first_ngens(1)
>>> T = FractionField(L)
>>> f = T(Integer(1)/t)
>>> R = RR['x']; (x,) = R._first_ngens(1)
>>> Y = FractionField(R)
>>> g = (Integer(40)*pi)/x                                                   ␣
↪     # needs sage.symbolic
>>> Q6 = P(f, g); Q6                                                       #␣
↪needs sage.symbolic
Type IV point of precision 20 with centers given by (1 + O(5^20))/((1 + O(5^
```

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```
↪20))*t)
 and radii given by 40.0000000000000*pi/x
```

as_affine_point()

Return the corresponding affine point after dehomogenizing at infinity.

OUTPUT: a point of affine Berkovich space

EXAMPLES:

```
sage: B = Berkovich_Cp_Projective(5)
sage: B(5).as_affine_point()
Type I point centered at 5 + O(5^21)
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Projective(Integer(5))
>>> B(Integer(5)).as_affine_point()
Type I point centered at 5 + O(5^21)
```

```
sage: Q = B(0, 1).as_affine_point(); Q
Type II point centered at 0 of radius 5^0
sage: Q.parent()
Affine Berkovich line over Cp(5) of precision 20
```

```
>>> from sage.all import *
>>> Q = B(Integer(0), Integer(1)).as_affine_point(); Q
Type II point centered at 0 of radius 5^0
>>> Q.parent()
Affine Berkovich line over Cp(5) of precision 20
```

```
sage: L.<t> = PolynomialRing(Qp(5))
sage: T = FractionField(L)
sage: f = T(1/t)
sage: R.<x> = RR[]
sage: Y = FractionField(R)
sage: g = (40*pi)/x                                                    #␣
↪needs sage.symbolic
sage: Q2 = B(f, g)                                                     #␣
↪needs sage.symbolic
sage: Q2.as_affine_point()                                             #␣
↪needs sage.symbolic
Type IV point of precision 20 with centers given by (1 + O(5^20))/((1 + O(5^
↪20))*t)
and radii given by 40.0000000000000*pi/x
```

```
>>> from sage.all import *
>>> L = PolynomialRing(Qp(Integer(5)), names=('t',)); (t,) = L._first_ngens(1)
>>> T = FractionField(L)
>>> f = T(Integer(1)/t)
>>> R = RR['x']; (x,) = R._first_ngens(1)
>>> Y = FractionField(R)
>>> g = (Integer(40)*pi)/x                                             ␣
```

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```
↪      # needs sage.symbolic
>>> Q2 = B(f, g)                                                    #␣
↪needs sage.symbolic
>>> Q2.as_affine_point()                                            #␣
↪needs sage.symbolic
Type IV point of precision 20 with centers given by (1 + O(5^20))/((1 + O(5^
↪20))*t)
and radii given by 40.0000000000000*pi/x
```

contained_in_interval(*start*, *end*)

Check if this point is an element of the interval [`start`, `end`].

INPUT:

- `start` – a point of the same Berkovich space as this point
- `end` – a point of the same Berkovich space as this point

OUTPUT:

- `True` if this point is an element of [`start`, `end`].
- `False` otherwise.

EXAMPLES:

```
sage: B = Berkovich_Cp_Projective(3)
sage: Q1 = B(2, 1)
sage: Q2 = B(2, 4)
sage: Q3 = B(1/3)
sage: Q2.contained_in_interval(Q1, Q3.join(Q1))
False
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Projective(Integer(3))
>>> Q1 = B(Integer(2), Integer(1))
>>> Q2 = B(Integer(2), Integer(4))
>>> Q3 = B(Integer(1)/Integer(3))
>>> Q2.contained_in_interval(Q1, Q3.join(Q1))
False
```

```
sage: Q4 = B(1/81, 1)
sage: Q2.contained_in_interval(Q1, Q4.join(Q1))
True
```

```
>>> from sage.all import *
>>> Q4 = B(Integer(1)/Integer(81), Integer(1))
>>> Q2.contained_in_interval(Q1, Q4.join(Q1))
True
```

gt(*other*)

Return `True` if this point is strictly greater than `other` in the standard partial order.

Roughly, the partial order corresponds to containment of the corresponding disks in $\mathbf{C}_p$.

For example, let x and y be points of type II or III. If x has center c_1 and radius r_1 and y has center c_2 and radius r_2, $x < y$ if and only if $D(c_1, r_1)$ is a subset of $D(c_2, r_2)$ in $\mathbf{C}_p$.

INPUT:

- `other` – a point of the same Berkovich space as this point

OUTPUT:

- `True` – if this point is greater than `other` in the standard partial order
- `False` – otherwise

EXAMPLES:

```
sage: B = Berkovich_Cp_Projective(QQ, 3)
sage: Q1 = B(5, 3)
sage: Q2 = B(5, 1)
sage: Q1.gt(Q2)
True
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Projective(QQ, Integer(3))
>>> Q1 = B(Integer(5), Integer(3))
>>> Q2 = B(Integer(5), Integer(1))
>>> Q1.gt(Q2)
True
```

```
sage: Q3 = B(1/27)
sage: Q1.gt(Q3)
False
```

```
>>> from sage.all import *
>>> Q3 = B(Integer(1)/Integer(27))
>>> Q1.gt(Q3)
False
```

involution_map()

Return the image of this point under the involution map.

The involution map is the extension of the map `z |-> 1/z` on $P^1(\mathbf{C}_p)$ to Berkovich space.

If zero is contained in every disk approximating a type IV point, then the image under the involution map is not defined. To avoid this error, increase precision.

OUTPUT: a point of the same Berkovich space

EXAMPLES:

The involution map is 1/z on type I points:

```
sage: B = Berkovich_Cp_Projective(3)
sage: Q1 = B(1/2)
sage: Q1.involution_map()
Type I point centered at (2 + O(3^20) : 1 + O(3^20))
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Projective(Integer(3))
>>> Q1 = B(Integer(1)/Integer(2))
>>> Q1.involution_map()
Type I point centered at (2 + O(3^20) : 1 + O(3^20))
```

```
sage: Q2 = B(0, 1/3)
sage: Q2.involution_map()
Type II point centered at (0 : 1 + O(3^20)) of radius 3^1
```

```
>>> from sage.all import *
>>> Q2 = B(Integer(0), Integer(1)/Integer(3))
>>> Q2.involution_map()
Type II point centered at (0 : 1 + O(3^20)) of radius 3^1
```

```
sage: Q3 = B(1/3, 1/3)
sage: Q3.involution_map()
Type II point centered at (3 + O(3^21) : 1 + O(3^20)) of radius 3^-3
```

```
>>> from sage.all import *
>>> Q3 = B(Integer(1)/Integer(3), Integer(1)/Integer(3))
>>> Q3.involution_map()
Type II point centered at (3 + O(3^21) : 1 + O(3^20)) of radius 3^-3
```

join(*other*, *basepoint=+Infinity*)

Compute the join of this point and `other`, with respect to `basepoint`.

The join is first point that lies on the intersection of the path from this point to `basepoint` and the path from `other` to `basepoint`.

INPUT:

- `other` – a point of the same Berkovich space as this point
- `basepoint` – (default: `Infinity`) a point of the same Berkovich space as this point, or `Infinity`

OUTPUT: a point of the same Berkovich space

EXAMPLES:

```
sage: B = Berkovich_Cp_Projective(3)
sage: Q1 = B(2, 1)
sage: Q2 = B(2, 2)
sage: Q1.join(Q2)
Type III point centered at (2 + O(3^20) : 1 + O(3^20)) of radius 2.
↪00000000000000
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Projective(Integer(3))
>>> Q1 = B(Integer(2), Integer(1))
>>> Q2 = B(Integer(2), Integer(2))
>>> Q1.join(Q2)
Type III point centered at (2 + O(3^20) : 1 + O(3^20)) of radius 2.
↪00000000000000
```

```
sage: Q3 = B(5)
sage: Q3.join(Q1)
Type II point centered at (2 + 3 + O(3^20) : 1 + O(3^20)) of radius 3^0
```

```
>>> from sage.all import *
>>> Q3 = B(Integer(5))
>>> Q3.join(Q1)
Type II point centered at (2 + 3 + O(3^20) : 1 + O(3^20)) of radius 3^0
```

```
sage: Q3.join(Q1, basepoint=Q2)
Type II point centered at (2 + O(3^20) : 1 + O(3^20)) of radius 3^0
```

```
>>> from sage.all import *
>>> Q3.join(Q1, basepoint=Q2)
Type II point centered at (2 + O(3^20) : 1 + O(3^20)) of radius 3^0
```

lt(*other*)

Return `True` if this point is strictly less than `other` in the standard partial order.

Roughly, the partial order corresponds to containment of the corresponding disks in $\mathbf{C}_p$.

For example, let x and y be points of type II or III. If x has center c_1 and radius r_1 and y has center c_2 and radius r_2, $x < y$ if and only if $D(c_1, r_1)$ is a subset of $D(c_2, r_2)$ in $\mathbf{C}_p$.

INPUT:

- `other` – a point of the same Berkovich space as this point

OUTPUT:

- `True` – if this point is less than `other` in the standard partial order
- `False` – otherwise

EXAMPLES:

```
sage: B = Berkovich_Cp_Projective(3)
sage: Q1 = B(5, 0.5)
sage: Q2 = B(5, 1)
sage: Q1.lt(Q2)
True
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Projective(Integer(3))
>>> Q1 = B(Integer(5), RealNumber('0.5'))
>>> Q2 = B(Integer(5), Integer(1))
>>> Q1.lt(Q2)
True
```

```
sage: Q3 = B(1)
sage: Q1.lt(Q3)
False
```

```
>>> from sage.all import *
>>> Q3 = B(Integer(1))
```

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```
>>> Q1.lt(Q3)
False
```

18.2 Berkovich Space over $\mathbf{C}_p$

The Berkovich affine line is the set of seminorms on $\mathbf{C}_p[x]$, with the weakest topology that makes the map $|\cdot| \to |f|$ continuous for all $f \in \mathbf{C}_p[x]$. The Berkovich projective line is the one-point compactification of the Berkovich affine line.

The two main classes are *Berkovich_Cp_Affine* and *Berkovich_Cp_Projective*, which implement the affine and projective lines, respectively.

Berkovich_Cp_Affine and *Berkovich_Cp_Projective* take as input one of the following: the prime p, a finite extension of $\mathbf{Q}_p$, or a number field and a place.

For an exposition of Berkovich space over $\mathbf{C}_p$, see Chapter 6 of [Ben2019]. For a more involved exposition, see Chapter 1 and 2 of [BR2010].

AUTHORS:

- Alexander Galarraga (2020-06-22): initial implementation

class sage.schemes.berkovich.berkovich_space.**Berkovich**

Bases: UniqueRepresentation, Parent

The parent class for any Berkovich space

class sage.schemes.berkovich.berkovich_space.**Berkovich_Cp**

Bases: *Berkovich*

Abstract parent class for Berkovich space over Cp.

ideal()

The ideal which defines an embedding of the base_ring into $\mathbf{C}_p$.

If this Berkovich space is backed by a p-adic field, then an embedding is already specified, and this returns None.

OUTPUT:

- An ideal of a base_ring if base_ring is a number field.
- A prime of $\mathbf{Q}$ if base_ring is $\mathbf{Q}$.
- None if base_ring is a p-adic field.

EXAMPLES:

```
sage: # needs sage.rings.number_field
sage: R.<z> = QQ[]
sage: A.<a> = NumberField(z^2 + 1)
sage: ideal = A.prime_above(5)
sage: B = Berkovich_Cp_Projective(A, ideal)
sage: B.ideal()
Fractional ideal (2*a - 1)
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = QQ['z']; (z,) = R._first_ngens(1)
>>> A = NumberField(z**Integer(2) + Integer(1), names=('a',)); (a,) = A._
↪first_ngens(1)
>>> ideal = A.prime_above(Integer(5))
>>> B = Berkovich_Cp_Projective(A, ideal)
>>> B.ideal()
Fractional ideal (2*a - 1)
```

```
sage: B = Berkovich_Cp_Projective(QQ, 3)
sage: B.ideal()
3
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Projective(QQ, Integer(3))
>>> B.ideal()
3
```

```
sage: B = Berkovich_Cp_Projective(Qp(3))
sage: B.ideal() is None
True
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Projective(Qp(Integer(3)))
>>> B.ideal() is None
True
```

is_number_field_base()

Return `True` if this Berkovich space is backed by a number field.

OUTPUT:

- `True` if this Berkovich space was created with a number field.
- `False` otherwise.

EXAMPLES:

```
sage: B = Berkovich_Cp_Affine(Qp(3))
sage: B.is_number_field_base()
False
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Affine(Qp(Integer(3)))
>>> B.is_number_field_base()
False
```

```
sage: B = Berkovich_Cp_Affine(QQ, 3)
sage: B.is_number_field_base()
True
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Affine(QQ, Integer(3))
>>> B.is_number_field_base()
True
```

is_padic_base()

Return `True` if this Berkovich space is backed by a p-adic field.

OUTPUT:

- `True` if this Berkovich space was created with a p-adic field.
- `False` otherwise.

EXAMPLES:

```
sage: B = Berkovich_Cp_Affine(Qp(3))
sage: B.is_padic_base()
True
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Affine(Qp(Integer(3)))
>>> B.is_padic_base()
True
```

```
sage: B = Berkovich_Cp_Affine(QQ, 3)
sage: B.is_padic_base()
False
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Affine(QQ, Integer(3))
>>> B.is_padic_base()
False
```

prime()

The residue characteristic of the `base`.

EXAMPLES:

```
sage: B = Berkovich_Cp_Projective(3)
sage: B.prime()
3
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Projective(Integer(3))
>>> B.prime()
3
```

```
sage: # needs sage.rings.number_field
sage: R.<x> = QQ[]
sage: A.<a> = NumberField(x^3 + 20)
sage: ideal = A.ideal(-1/2*a^2 + a - 3)
sage: B = Berkovich_Cp_Affine(A, ideal)
```

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```
sage: B.residue_characteristic()
7
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> A = NumberField(x**Integer(3) + Integer(20), names=('a',)); (a,) = A._
↪first_ngens(1)
>>> ideal = A.ideal(-Integer(1)/Integer(2)*a**Integer(2) + a - Integer(3))
>>> B = Berkovich_Cp_Affine(A, ideal)
>>> B.residue_characteristic()
7
```

residue_characteristic()

The residue characteristic of the `base`.

EXAMPLES:

```
sage: B = Berkovich_Cp_Projective(3)
sage: B.prime()
3
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Projective(Integer(3))
>>> B.prime()
3
```

```
sage: # needs sage.rings.number_field
sage: R.<x> = QQ[]
sage: A.<a> = NumberField(x^3 + 20)
sage: ideal = A.ideal(-1/2*a^2 + a - 3)
sage: B = Berkovich_Cp_Affine(A, ideal)
sage: B.residue_characteristic()
7
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> A = NumberField(x**Integer(3) + Integer(20), names=('a',)); (a,) = A._
↪first_ngens(1)
>>> ideal = A.ideal(-Integer(1)/Integer(2)*a**Integer(2) + a - Integer(3))
>>> B = Berkovich_Cp_Affine(A, ideal)
>>> B.residue_characteristic()
7
```

class sage.schemes.berkovich.berkovich_space.**Berkovich_Cp_Affine**(*base*, *ideal=None*)

Bases: *Berkovich_Cp*

The Berkovich affine line over $\mathbf{C}_p$.

The Berkovich affine line is the set of seminorms on $\mathbf{C}_p[x]$, with the weakest topology such that the map $|\cdot| \to |f|$ is continuous for all $f \in \mathbf{C}_p[x]$.

We can represent the Berkovich affine line in two separate ways: either using a p-adic field to represent elements or using a number field to represent elements while storing an ideal of the ring of integers of the number field, which specifies an embedding of the number field into $\mathbf{C}_p$. See the examples.

INPUT:

- `base` – three cases:
  - a prime number p. Centers of elements are then represented as points of $\mathbf{Q}_p$.
  - $\mathbf{Q}_p$ or a finite extension of $\mathbf{Q}_p$. Centers of elements are then represented as points of `base`.
  - A number field K. Centers of elements are then represented as points of K.
- `ideal` – (optional) a prime ideal of `base`. Must be specified if a number field is passed to `base`, otherwise it is ignored.

EXAMPLES:

```
sage: B = Berkovich_Cp_Affine(3); B
Affine Berkovich line over Cp(3) of precision 20
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Affine(Integer(3)); B
Affine Berkovich line over Cp(3) of precision 20
```

We can create elements:

```
sage: B(-2)
Type I point centered at 1 + 2*3 + 2*3^2 + 2*3^3 + 2*3^4 + 2*3^5
+ 2*3^6 + 2*3^7 + 2*3^8 + 2*3^9 + 2*3^10 + 2*3^11 + 2*3^12 + 2*3^13
+ 2*3^14 + 2*3^15 + 2*3^16 + 2*3^17 + 2*3^18 + 2*3^19 + O(3^20)
```

```
>>> from sage.all import *
>>> B(-Integer(2))
Type I point centered at 1 + 2*3 + 2*3^2 + 2*3^3 + 2*3^4 + 2*3^5
+ 2*3^6 + 2*3^7 + 2*3^8 + 2*3^9 + 2*3^10 + 2*3^11 + 2*3^12 + 2*3^13
+ 2*3^14 + 2*3^15 + 2*3^16 + 2*3^17 + 2*3^18 + 2*3^19 + O(3^20)
```

```
sage: B(1, 2)
Type III point centered at 1 + O(3^20) of radius 2.00000000000000
```

```
>>> from sage.all import *
>>> B(Integer(1), Integer(2))
Type III point centered at 1 + O(3^20) of radius 2.00000000000000
```

For details on element creation, see the documentation of *Berkovich_Element_Cp_Affine*. Initializing by passing in $\mathbf{Q}_p$ looks the same:

```
sage: B = Berkovich_Cp_Affine(Qp(3)); B
Affine Berkovich line over Cp(3) of precision 20
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Affine(Qp(Integer(3))); B
Affine Berkovich line over Cp(3) of precision 20
```

However, this method allows for more control over behind-the-scenes conversion:

```
sage: B = Berkovich_Cp_Affine(Qp(3, 1)); B
Affine Berkovich line over Cp(3) of precision 1

sage: B(1/2)
Type I point centered at 2 + O(3)
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Affine(Qp(Integer(3), Integer(1))); B
Affine Berkovich line over Cp(3) of precision 1

>>> B(Integer(1)/Integer(2))
Type I point centered at 2 + O(3)
```

Note that this point has very low precision, as `B` was initialized with a p-adic field of capped-relative precision one. For high precision, pass in a high precision p-adic field:

```
sage: B = Berkovich_Cp_Affine(Qp(3, 1000)); B
Affine Berkovich line over Cp(3) of precision 1000
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Affine(Qp(Integer(3), Integer(1000))); B
Affine Berkovich line over Cp(3) of precision 1000
```

Points of Berkovich space can be created from points of extensions of $\mathbf{Q}_p$:

```
sage: B = Berkovich_Cp_Affine(3)
sage: A.<a> = Qp(3).extension(x^3 - 3)
sage: B(a)
Type I point centered at a + O(a^61)
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Affine(Integer(3))
>>> A = Qp(Integer(3)).extension(x**Integer(3) - Integer(3), names=('a',)); (a,)␣
↪= A._first_ngens(1)
>>> B(a)
Type I point centered at a + O(a^61)
```

For exact computation, a number field can be used:

```
sage: R.<x> = QQ[]
sage: A.<a> = NumberField(x^3 + 20)                                    #␣
↪needs sage.rings.number_field
sage: ideal = A.prime_above(3)                                         #␣
↪needs sage.rings.number_field
sage: B = Berkovich_Cp_Affine(A, ideal); B                             #␣
↪needs sage.rings.number_field
Affine Berkovich line over Cp(3), with base
 Number Field in a with defining polynomial x^3 + 20
```

```
>>> from sage.all import *
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> A = NumberField(x**Integer(3) + Integer(20), names=('a',)); (a,) = A._first_
```

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```
↪ngens(1)# needs sage.rings.number_field
>>> ideal = A.prime_above(Integer(3))                                    ␣
↪     # needs sage.rings.number_field
>>> B = Berkovich_Cp_Affine(A, ideal); B                                 #␣
↪needs sage.rings.number_field
Affine Berkovich line over Cp(3), with base
 Number Field in a with defining polynomial x^3 + 20
```

Number fields have a major advantage of exact computation.

Number fields also have added functionality. Arbitrary extensions of $\mathbf{Q}$ are supported, while there is currently limited functionality for extensions of $\mathbf{Q}_p$. As seen above, constructing a Berkovich space backed by a number field requires specifying an ideal of the ring of integers of the number field. Specifying the ideal uniquely specifies an embedding of the number field into $\mathbf{C}_p$.

Unlike in the case where Berkovich space is backed by a p-adic field, any point of a Berkovich space backed by a number field must be centered at a point of that number field:

```
sage: # needs sage.rings.number_field
sage: R.<x> = QQ[]
sage: A.<a> = NumberField(x^3 + 20)
sage: ideal = A.prime_above(3)
sage: B = Berkovich_Cp_Affine(A, ideal)
sage: C.<c> = NumberField(x^2 + 1)
sage: B(c)
Traceback (most recent call last):
...
ValueError: could not convert c to Number Field in a
with defining polynomial x^3 + 20
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> A = NumberField(x**Integer(3) + Integer(20), names=('a',)); (a,) = A._first_
↪ngens(1)
>>> ideal = A.prime_above(Integer(3))
>>> B = Berkovich_Cp_Affine(A, ideal)
>>> C = NumberField(x**Integer(2) + Integer(1), names=('c',)); (c,) = C._first_
↪ngens(1)
>>> B(c)
Traceback (most recent call last):
...
ValueError: could not convert c to Number Field in a
with defining polynomial x^3 + 20
```

Element

alias of *Berkovich_Element_Cp_Affine*

class sage.schemes.berkovich.berkovich_space.**Berkovich_Cp_Projective**(*base*, *ideal=None*)

Bases: *Berkovich_Cp*

The Berkovich projective line over $\mathbf{C}_p$.

The Berkovich projective line is the one-point compactification of the Berkovich affine line.

We can represent the Berkovich projective line in two separate ways: either using a p-adic field to represent elements or using a number field to represent elements while storing an ideal of the ring of integers of the number field, which specifies an embedding of the number field into $\mathbf{C}_p$. See the examples.

INPUT:

- `base` – three cases:
  - a prime number p. Centers of elements are then represented as points of projective space of dimension 1 over $\mathbf{Q}_p$.
  - $\mathbf{Q}_p$ or a finite extension of $\mathbf{Q}_p$. Centers of elements are then represented as points of projective space of dimension 1 over `base`.
  - A number field K. Centers of elements are then represented as points of projective space of dimension 1 over `base`.
- `ideal` – (optional) a prime ideal of `base`. Must be specified if a number field is passed to `base`, otherwise it is ignored.

EXAMPLES:

```
sage: B = Berkovich_Cp_Projective(3); B
Projective Berkovich line over Cp(3) of precision 20
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Projective(Integer(3)); B
Projective Berkovich line over Cp(3) of precision 20
```

Elements can be constructed:

```
sage: B(1/2)
Type I point centered at (2 + 3 + 3^2 + 3^3 + 3^4 + 3^5
+ 3^6 + 3^7 + 3^8 + 3^9 + 3^10 + 3^11 + 3^12 + 3^13 + 3^14
+ 3^15 + 3^16 + 3^17 + 3^18 + 3^19 + O(3^20) : 1 + O(3^20))
```

```
>>> from sage.all import *
>>> B(Integer(1)/Integer(2))
Type I point centered at (2 + 3 + 3^2 + 3^3 + 3^4 + 3^5
+ 3^6 + 3^7 + 3^8 + 3^9 + 3^10 + 3^11 + 3^12 + 3^13 + 3^14
+ 3^15 + 3^16 + 3^17 + 3^18 + 3^19 + O(3^20) : 1 + O(3^20))
```

```
sage: B(2, 1)
Type II point centered at (2 + O(3^20) : 1 + O(3^20)) of radius 3^0
```

```
>>> from sage.all import *
>>> B(Integer(2), Integer(1))
Type II point centered at (2 + O(3^20) : 1 + O(3^20)) of radius 3^0
```

For details about element construction, see the documentation of *Berkovich_Element_Cp_Projective*. Initializing a Berkovich projective line by passing in a p-adic space looks the same:

```
sage: B = Berkovich_Cp_Projective(Qp(3)); B
Projective Berkovich line over Cp(3) of precision 20
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Projective(Qp(Integer(3))); B
Projective Berkovich line over Cp(3) of precision 20
```

However, this method allows for more control over behind-the-scenes conversion:

```
sage: S = Qp(3, 1)
sage: B = Berkovich_Cp_Projective(S); B
Projective Berkovich line over Cp(3) of precision 1

sage: Q1 = B(1/2); Q1
Type I point centered at (2 + O(3) : 1 + O(3))
```

```
>>> from sage.all import *
>>> S = Qp(Integer(3), Integer(1))
>>> B = Berkovich_Cp_Projective(S); B
Projective Berkovich line over Cp(3) of precision 1

>>> Q1 = B(Integer(1)/Integer(2)); Q1
Type I point centered at (2 + O(3) : 1 + O(3))
```

Note that this point has very low precision, as S has low precision cap. Berkovich space can also be created over a number field, as long as an ideal is specified:

```
sage: R.<x> = QQ[]
sage: A.<a> = NumberField(x^2 + 1)                                              #␣
↪needs sage.rings.number_field
sage: ideal = A.prime_above(2)                                                  #␣
↪needs sage.rings.number_field
sage: B = Berkovich_Cp_Projective(A, ideal); B                                  #␣
↪needs sage.rings.number_field
Projective Berkovich line over Cp(2), with base
 Number Field in a with defining polynomial x^2 + 1
```

```
>>> from sage.all import *
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> A = NumberField(x**Integer(2) + Integer(1), names=('a',)); (a,) = A._first_
↪ngens(1)# needs sage.rings.number_field
>>> ideal = A.prime_above(Integer(2))                                           ␣
↪     # needs sage.rings.number_field
>>> B = Berkovich_Cp_Projective(A, ideal); B                                  #␣
↪needs sage.rings.number_field
Projective Berkovich line over Cp(2), with base
 Number Field in a with defining polynomial x^2 + 1
```

Number fields have the benefit that computation is exact, but lack support for all of $\mathbf{C}_p$.

Number fields also have the advantage of added functionality, as arbitrary extensions of $\mathbf{Q}$ can be constructed while there is currently limited functionality for extensions of $\mathbf{Q}_p$. As seen above, constructing a Berkovich space backed by a number field requires specifying an ideal of the ring of integers of the number field. Specifying the ideal uniquely specifies an embedding of the number field into $\mathbf{C}_p$.

Unlike in the case where Berkovich space is backed by a p-adic field, any point of a Berkovich space backed by a number field must be centered at a point of that number field:

```
sage: # needs sage.rings.number_field
sage: R.<x> = QQ[]
sage: A.<a> = NumberField(x^3 + 20)
sage: ideal = A.prime_above(3)
sage: B = Berkovich_Cp_Projective(A, ideal)
sage: C.<c> = NumberField(x^2 + 1)
sage: B(c)
Traceback (most recent call last):
...
TypeError: could not convert c to Projective Space
of dimension 1 over Number Field in a with defining polynomial x^3 + 20
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> A = NumberField(x**Integer(3) + Integer(20), names=('a',)); (a,) = A._first_
↪ngens(1)
>>> ideal = A.prime_above(Integer(3))
>>> B = Berkovich_Cp_Projective(A, ideal)
>>> C = NumberField(x**Integer(2) + Integer(1), names=('c',)); (c,) = C._first_
↪ngens(1)
>>> B(c)
Traceback (most recent call last):
...
TypeError: could not convert c to Projective Space
of dimension 1 over Number Field in a with defining polynomial x^3 + 20
```

Element

alias of *Berkovich_Element_Cp_Projective*

base_ring()

The base ring of this Berkovich Space.

OUTPUT: a field

EXAMPLES:

```
sage: B = Berkovich_Cp_Projective(3)
sage: B.base_ring()
3-adic Field with capped relative precision 20
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Projective(Integer(3))
>>> B.base_ring()
3-adic Field with capped relative precision 20
```

```
sage: C = Berkovich_Cp_Projective(ProjectiveSpace(Qp(3, 1), 1))
sage: C.base_ring()
3-adic Field with capped relative precision 1
```

```
>>> from sage.all import *
>>> C = Berkovich_Cp_Projective(ProjectiveSpace(Qp(Integer(3), Integer(1)),␣
↪Integer(1)))
```

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```
>>> C.base_ring()
3-adic Field with capped relative precision 1
```

```
sage: # needs sage.rings.number_field
sage: R.<x> = QQ[]
sage: A.<a> = NumberField(x^3 + 20)
sage: ideal = A.prime_above(3)
sage: D = Berkovich_Cp_Projective(A, ideal)
sage: D.base_ring()
Number Field in a with defining polynomial x^3 + 20
```

```
>>> from sage.all import *
>>> # needs sage.rings.number_field
>>> R = QQ['x']; (x,) = R._first_ngens(1)
>>> A = NumberField(x**Integer(3) + Integer(20), names=('a',)); (a,) = A._
↪first_ngens(1)
>>> ideal = A.prime_above(Integer(3))
>>> D = Berkovich_Cp_Projective(A, ideal)
>>> D.base_ring()
Number Field in a with defining polynomial x^3 + 20
```

sage.schemes.berkovich.berkovich_space.**is_Berkovich**(*space*)

Check if `space` is a Berkovich space.

OUTPUT:

- `True` if `space` is a Berkovich space.
- `False` otherwise.

EXAMPLES:

```
sage: B = Berkovich_Cp_Projective(3)
sage: from sage.schemes.berkovich.berkovich_space import is_Berkovich
sage: is_Berkovich(B)
doctest:warning...
DeprecationWarning: The function is_Berkovich is deprecated; use 'isinstance(...,␣
↪Berkovich)' instead.
See https://github.com/sagemath/sage/issues/38022 for details.
True
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Projective(Integer(3))
>>> from sage.schemes.berkovich.berkovich_space import is_Berkovich
>>> is_Berkovich(B)
doctest:warning...
DeprecationWarning: The function is_Berkovich is deprecated; use 'isinstance(...,␣
↪Berkovich)' instead.
See https://github.com/sagemath/sage/issues/38022 for details.
True
```

sage.schemes.berkovich.berkovich_space.**is_Berkovich_Cp**(*space*)

Check if `space` is a Berkovich space over `Cp`.

OUTPUT:

- `True` if `space` is a Berkovich space over `Cp`.
- `False` otherwise.

EXAMPLES:

```
sage: B = Berkovich_Cp_Projective(3)
sage: from sage.schemes.berkovich.berkovich_space import is_Berkovich_Cp
sage: is_Berkovich_Cp(B)
doctest:warning...
DeprecationWarning: The function is_Berkovich_Cp is deprecated; use 'isinstance(..
↪., Berkovich_Cp)' instead.
See https://github.com/sagemath/sage/issues/38022 for details.
True
```

```
>>> from sage.all import *
>>> B = Berkovich_Cp_Projective(Integer(3))
>>> from sage.schemes.berkovich.berkovich_space import is_Berkovich_Cp
>>> is_Berkovich_Cp(B)
doctest:warning...
DeprecationWarning: The function is_Berkovich_Cp is deprecated; use 'isinstance(..
↪., Berkovich_Cp)' instead.
See https://github.com/sagemath/sage/issues/38022 for details.
True
```

CHAPTER

NINETEEN

INDICES AND TABLES

- Index
- Module Index
- Search Page

PYTHON MODULE INDEX

S

sage.schemes.affine.affine_homset, 187
sage.schemes.affine.affine_morphism, 134
sage.schemes.affine.affine_point, 162
sage.schemes.affine.affine_rational_point, 182
sage.schemes.affine.affine_space, 119
sage.schemes.affine.affine_subscheme, 169
sage.schemes.berkovich.berkovich_cp_element, 703
sage.schemes.berkovich.berkovich_space, 734
sage.schemes.cyclic_covers.charpoly_frobenius, 696
sage.schemes.cyclic_covers.constructor, 698
sage.schemes.cyclic_covers.cycliccover_finite_field, 681
sage.schemes.cyclic_covers.cyclic_cover_generic, 691
sage.schemes.generic.algebraic_scheme, 33
sage.schemes.generic.ambient_space, 27
sage.schemes.generic.divisor, 109
sage.schemes.generic.divisor_group, 115
sage.schemes.generic.glue, 23
sage.schemes.generic.homset, 75
sage.schemes.generic.hypersurface, 71
sage.schemes.generic.morphism, 83
sage.schemes.generic.point, 25
sage.schemes.generic.scheme, 5
sage.schemes.generic.spec, 21
sage.schemes.overview, 1
sage.schemes.product_projective.homset, 367
sage.schemes.product_projective.morphism, 373
sage.schemes.product_projective.point, 377
sage.schemes.product_projective.rational_point, 394
sage.schemes.product_projective.space, 353
sage.schemes.product_projective.subscheme, 385
sage.schemes.projective.projective_homset, 341
sage.schemes.projective.projective_morphism, 234
sage.schemes.projective.projective_point, 286
sage.schemes.projective.projective_rational_point, 334
sage.schemes.projective.projective_space, 195
sage.schemes.projective.projective_subscheme, 306
sage.schemes.toric.chow_group, 540
sage.schemes.toric.divisor, 504
sage.schemes.toric.divisor_class, 539
sage.schemes.toric.fano_variety, 457
sage.schemes.toric.homset, 634
sage.schemes.toric.ideal, 559
sage.schemes.toric.library, 485
sage.schemes.toric.morphism, 564
sage.schemes.toric.points, 642
sage.schemes.toric.sheaf.constructor, 656
sage.schemes.toric.sheaf.klyachko, 661
sage.schemes.toric.toric_subscheme, 598
sage.schemes.toric.variety, 401
sage.schemes.toric.weierstrass, 612
sage.schemes.toric.weierstrass_covering, 623
sage.schemes.toric.weierstrass_higher, 632

INDEX

A

A() (*sage.schemes.toric.ideal.ToricIdeal method*), 562
A() (*sage.schemes.toric.library.ToricVarietyFactory method*), 485
A1() (*sage.schemes.toric.library.ToricVarietyFactory method*), 486
A2() (*sage.schemes.toric.library.ToricVarietyFactory method*), 486
A2_Z2() (*sage.schemes.toric.library.ToricVarietyFactory method*), 487
add_variables() (*in module sage.schemes.toric.fano_variety*), 483
affine_algebraic_patch() (*sage.schemes.toric.toric_subscheme.AlgebraicScheme_subscheme_toric method*), 601
affine_algebraic_patch() (*sage.schemes.toric.variety.ToricVariety_field method*), 425
affine_open() (*sage.schemes.generic.point.SchemeTopologicalPoint_affine_open method*), 25
affine_patch() (*sage.schemes.product_projective.space.ProductProjectiveSpaces_ring method*), 359
affine_patch() (*sage.schemes.product_projective.subscheme.AlgebraicScheme_subscheme_product_projective method*), 385
affine_patch() (*sage.schemes.projective.projective_space.ProjectiveSpace_ring method*), 207
affine_patch() (*sage.schemes.projective.projective_subscheme.AlgebraicScheme_subscheme_projective method*), 307
affine_patch() (*sage.schemes.toric.toric_subscheme.AlgebraicScheme_subscheme_toric method*), 603
affine_patch() (*sage.schemes.toric.variety.ToricVariety_field method*), 426
AffineHypersurface (*class in sage.schemes.generic.hypersurface*), 71
AffineScheme (*class in sage.schemes.generic.scheme*), 5
AffineSpace() (*in module sage.schemes.affine.affine_space*), 119
AffineSpace_field (*class in sage.schemes.affine.affine_space*), 120
AffineSpace_finite_field (*class in sage.schemes.affine.affine_space*), 124
AffineSpace_generic (*class in sage.schemes.affine.affine_space*), 124
AffineToricVariety() (*in module sage.schemes.toric.variety*), 409
AlgebraicScheme (*class in sage.schemes.generic.algebraic_scheme*), 35
AlgebraicScheme_quasi (*class in sage.schemes.generic.algebraic_scheme*), 42
AlgebraicScheme_subscheme (*class in sage.schemes.generic.algebraic_scheme*), 45
AlgebraicScheme_subscheme_affine (*class in sage.schemes.affine.affine_subscheme*), 169
AlgebraicScheme_subscheme_affine_field (*class in sage.schemes.affine.affine_subscheme*), 180
AlgebraicScheme_subscheme_affine_toric (*class in sage.schemes.toric.toric_subscheme*), 598
AlgebraicScheme_subscheme_product_projective (*class in sage.schemes.product_projective.subscheme*), 385
AlgebraicScheme_subscheme_projective (*class in sage.schemes.projective.projective_subscheme*), 306
AlgebraicScheme_subscheme_projective_field (*class in sage.schemes.projective.projective_subscheme*), 329
AlgebraicScheme_subscheme_toric (*class in sage.schemes.toric.toric_subscheme*), 601
ambient_space() (*sage.schemes.generic.algebraic_scheme.AlgebraicScheme method*), 35
ambient_space() (*sage.schemes.generic.ambient_space.AmbientSpace method*), 27
AmbientSpace (*class in sage.schemes.generic.ambient_space*), 27
anticanonical_hypersurface() (*sage.schemes.toric.fano_variety.CPRFanoToricVariety_field method*), 470
AnticanonicalHypersurface (*class in sage.schemes.toric.fano_variety*), 459
as_affine_point() (*sage.schemes.berkovich.berkovich_cp_element.Berkovich_Element_Cp_Projective*

method), 729
as_dynamical_system() (*sage.schemes.affine.affine_morphism.SchemeMorphism_polynomial_affine_space method*), 135
as_dynamical_system() (*sage.schemes.product_projective.morphism.ProductProjectiveSpaces_morphism_ring method*), 373
as_dynamical_system() (*sage.schemes.projective.projective_morphism.SchemeMorphism_polynomial_projective_space method*), 238
as_fan_morphism() (*sage.schemes.toric.morphism.SchemeMorphism_polynomial_toric_variety method*), 597
as_polynomial_map() (*sage.schemes.toric.morphism.SchemeMorphism_fan_fiber_component_toric_variety method*), 574
as_polynomial_map() (*sage.schemes.toric.morphism.SchemeMorphism_fan_toric_variety method*), 579
as_polynomial_map() (*sage.schemes.toric.morphism.SchemeMorphism_orbit_closure_toric_variety method*), 595
as_projective_point() (*sage.schemes.berkovich.berkovich_cp_element.Berkovich_Element_Cp_Affine method*), 721
as_subscheme() (*sage.schemes.affine.affine_point.SchemeMorphism_point_affine_field method*), 165
as_subscheme() (*sage.schemes.projective.projective_point.SchemeMorphism_point_projective_field method*), 287
Aut_dimension() (*sage.schemes.toric.variety.ToricVariety_field method*), 416

B

base_cone() (*sage.schemes.toric.morphism.SchemeMorphism_fan_fiber_component_toric_variety method*), 576
base_extend() (*sage.schemes.cyclic_covers.cyclic_cover_generic.CyclicCover_generic method*), 692
base_extend() (*sage.schemes.generic.algebraic_scheme.AlgebraicScheme_subscheme method*), 47
base_extend() (*sage.schemes.generic.ambient_space.AmbientSpace method*), 27
base_extend() (*sage.schemes.generic.divisor_group.DivisorGroup_generic method*), 115
base_extend() (*sage.schemes.generic.scheme.AffineScheme method*), 5
base_extend() (*sage.schemes.generic.scheme.Scheme method*), 8
base_extend() (*sage.schemes.projective.projective_homset.SchemeHomset_points_abelian_variety_field method*), 341
base_extend() (*sage.schemes.toric.divisor.ToricDivisorGroup method*), 511
base_indeterminacy_locus() (*sage.schemes.projective.projective_morphism.SchemeMorphism_polynomial_projective_space_field method*), 260
base_morphism() (*sage.schemes.generic.scheme.Scheme method*), 9
base_ring() (*sage.schemes.berkovich.berkovich_space.Berkovich_Cp_Projective method*), 743
base_ring() (*sage.schemes.generic.morphism.SchemeMorphism method*), 84
base_ring() (*sage.schemes.generic.scheme.Scheme method*), 10
base_ring() (*sage.schemes.toric.sheaf.klyachko.KlyachkoBundle_class method*), 669
base_scheme() (*sage.schemes.generic.scheme.Scheme method*), 10
BCdlOG() (*sage.schemes.toric.library.ToricVarietyFactory method*), 488
BCdlOG_base() (*sage.schemes.toric.library.ToricVarietyFactory method*), 488
Berkovich (*class in sage.schemes.berkovich.berkovich_space*), 734
Berkovich_Cp (*class in sage.schemes.berkovich.berkovich_space*), 734
Berkovich_Cp_Affine (*class in sage.schemes.berkovich.berkovich_space*), 737
Berkovich_Cp_Projective (*class in sage.schemes.berkovich.berkovich_space*), 740
Berkovich_Element (*class in sage.schemes.berkovich.berkovich_cp_element*), 703
Berkovich_Element_Cp (*class in sage.schemes.berkovich.berkovich_cp_element*), 703
Berkovich_Element_Cp_Affine (*class in sage.schemes.berkovich.berkovich_cp_element*), 717
Berkovich_Element_Cp_Projective (*class in sage.schemes.berkovich.berkovich_cp_element*), 725
big_metric() (*sage.schemes.berkovich.berkovich_cp_element.Berkovich_Element_Cp method*), 705
Bundle() (*in module sage.schemes.toric.sheaf.klyachko*), 662

C

c() (*sage.schemes.toric.variety.ToricVariety_field method*), 427
cardinality() (*sage.schemes.generic.homset.SchemeHomset_points method*), 79
cardinality() (*sage.schemes.toric.homset.SchemeHomset_points_subscheme_toric_field method*), 636
cardinality() (*sage.schemes.toric.homset.SchemeHomset_points_toric_field method*), 639
cardinality() (*sage.schemes.toric.points.FiniteFieldPointEnumerator method*), 642
cardinality() (*sage.schemes.toric.points.FiniteFieldSubschemePointEnumerator method*), 647
cartesian_product() (*sage.schemes.projective.projective_space.ProjectiveSpace_ring method*), 208
cartesian_product() (*sage.schemes.toric.fano_variety.CPRFanoToricVariety_field method*), 473
cartesian_product() (*sage.schemes.toric.variety.ToricVariety_field method*), 427
category() (*sage.schemes.generic.morphism.SchemeMorphism method*), 85
category_for() (*sage.schemes.generic.morphism.SchemeMorphism method*), 86
center() (*sage.schemes.berkovich.berkovich_cp_element.Berkovich_Element_Cp method*), 706
center_function() (*sage.schemes.berkovich.berkovich_cp_element.Berkovich_Element_Cp method*), 707
ch() (*sage.schemes.toric.divisor.ToricDivisor_generic method*), 516
ch() (*sage.schemes.toric.variety.ToricVariety_field method*), 428
change_ring() (*sage.schemes.affine.affine_space.AffineSpace_generic method*), 126
change_ring() (*sage.schemes.cyclic_covers.cyclic_cover_generic.CyclicCover_generic method*), 692
change_ring() (*sage.schemes.generic.algebraic_scheme.AlgebraicScheme_subscheme method*), 48
change_ring() (*sage.schemes.generic.ambient_space.AmbientSpace method*), 28
change_ring() (*sage.schemes.generic.morphism.SchemeMorphism_point method*), 89
change_ring() (*sage.schemes.generic.morphism.SchemeMorphism_polynomial method*), 96
change_ring() (*sage.schemes.product_projective.point.ProductProjectiveSpaces_point_ring method*), 380
change_ring() (*sage.schemes.product_projective.space.ProductProjectiveSpaces_ring method*), 360
change_ring() (*sage.schemes.projective.projective_space.ProjectiveSpace_ring method*), 209
change_ring() (*sage.schemes.toric.fano_variety.CPRFanoToricVariety_field method*), 474
change_ring() (*sage.schemes.toric.variety.ToricVariety_field method*), 429
charpoly_frobenius() (*in module sage.schemes.cyclic_covers.charpoly_frobenius*), 696
chebyshev_polynomial() (*sage.schemes.affine.affine_space.AffineSpace_generic method*), 126
chebyshev_polynomial() (*sage.schemes.projective.projective_space.ProjectiveSpace_ring method*), 209
Chern_character() (*sage.schemes.toric.divisor.ToricDivisor_generic method*), 513
Chern_character() (*sage.schemes.toric.variety.ToricVariety_field method*), 417
Chern_class() (*sage.schemes.toric.variety.ToricVariety_field method*), 417
chi() (*sage.schemes.toric.variety.ToricVariety_field method*), 430
Chow_cycle() (*sage.schemes.toric.divisor.ToricDivisor_generic method*), 514
Chow_form() (*sage.schemes.projective.projective_subscheme.AlgebraicScheme_subscheme_projective_field method*), 329
Chow_group() (*sage.schemes.toric.variety.ToricVariety_field method*), 418
ChowCycle (*class in sage.schemes.toric.chow_group*), 542
ChowGroup_class (*class in sage.schemes.toric.chow_group*), 549
ChowGroup_degree_class (*class in sage.schemes.toric.chow_group*), 555
ChowGroupFactory (*class in sage.schemes.toric.chow_group*), 548
clear_denominators() (*sage.schemes.projective.projective_point.SchemeMorphism_point_projective_field method*), 287
codimension() (*sage.schemes.generic.algebraic_scheme.AlgebraicScheme_subscheme method*), 53
codomain() (*sage.schemes.generic.morphism.SchemeMorphism method*), 86
coefficient() (*sage.schemes.generic.divisor.Divisor_curve method*), 111
coefficient() (*sage.schemes.toric.divisor.ToricDivisor_generic method*), 516
cohomology() (*sage.schemes.toric.divisor.ToricDivisor_generic method*), 517
cohomology() (*sage.schemes.toric.sheaf.klyachko.KlyachkoBundle_class method*), 669
cohomology_basis() (*sage.schemes.toric.variety.Toric-*

Variety_field method), 430
cohomology_class() (*sage.schemes.toric.chow_group.ChowCycle method*), 543
cohomology_class() (*sage.schemes.toric.divisor.ToricDivisor_generic method*), 520
cohomology_class() (*sage.schemes.toric.fano_variety.NefCompleteIntersection method*), 481
cohomology_complex() (*sage.schemes.toric.sheaf.klyachko.KlyachkoBundle_class method*), 670
cohomology_ring() (*sage.schemes.toric.variety.ToricVariety_field method*), 431
cohomology_support() (*sage.schemes.toric.divisor.ToricDivisor_generic method*), 521
CohomologyClass (*class in sage.schemes.toric.variety*), 410
CohomologyRing (*class in sage.schemes.toric.variety*), 412
complement() (*sage.schemes.generic.algebraic_scheme.AlgebraicScheme_subscheme method*), 53
components() (*sage.schemes.product_projective.space.ProductProjectiveSpaces_ring method*), 360
cone_iter() (*sage.schemes.toric.points.NaiveFinitePointEnumerator method*), 652
cone_points_iter() (*sage.schemes.toric.points.FiniteFieldPointEnumerator method*), 643
Conifold() (*sage.schemes.toric.library.ToricVarietyFactory method*), 489
contained_in_interval() (*sage.schemes.berkovich.berkovich_cp_element.Berkovich_Element_Cp_Affine method*), 722
contained_in_interval() (*sage.schemes.berkovich.berkovich_cp_element.Berkovich_Element_Cp_Projective method*), 730
coordinate_iter() (*sage.schemes.toric.points.NaiveFinitePointEnumerator method*), 653
coordinate_point_to_coordinate() (*sage.schemes.toric.fano_variety.CPRFanoToricVariety_field method*), 475
coordinate_points() (*sage.schemes.toric.fano_variety.CPRFanoToricVariety_field method*), 476
coordinate_ring() (*sage.schemes.affine.affine_space.AffineSpace_generic method*), 129
coordinate_ring() (*sage.schemes.generic.algebraic_scheme.AlgebraicScheme method*), 36
coordinate_ring() (*sage.schemes.generic.morphism.SchemeMorphism_polynomial method*), 101
coordinate_ring() (*sage.schemes.generic.scheme.AffineScheme method*), 6
coordinate_ring() (*sage.schemes.generic.scheme.Scheme method*), 10
coordinate_ring() (*sage.schemes.projective.projective_space.ProjectiveSpace_ring method*), 212
coordinate_ring() (*sage.schemes.toric.variety.ToricVariety_field method*), 432
coordinate_vector() (*sage.schemes.toric.chow_group.ChowGroup_class method*), 550
cotangent_bundle() (*sage.schemes.toric.sheaf.constructor.SheafLibrary method*), 658
CotangentBundle() (*in module sage.schemes.toric.sheaf.constructor*), 656
count_points() (*sage.schemes.generic.scheme.Scheme method*), 11
count_points() (*sage.schemes.toric.chow_group.ChowCycle method*), 545
count_points() (*sage.schemes.toric.variety.ToricVariety_field method*), 432
cover_polynomial() (*sage.schemes.cyclic_covers.cycliccover_generic.CyclicCover_generic method*), 693
CPRFanoToricVariety() (*in module sage.schemes.toric.fano_variety*), 460
CPRFanoToricVariety_field (*class in sage.schemes.toric.fano_variety*), 468
create_key_and_extra_args() (*sage.schemes.generic.homset.SchemeHomsetFactory method*), 76
create_key_and_extra_args() (*sage.schemes.toric.chow_group.ChowGroupFactory method*), 548
create_object() (*sage.schemes.generic.homset.SchemeHomsetFactory method*), 77
create_object() (*sage.schemes.toric.chow_group.ChowGroupFactory method*), 549
Cube_deformation() (*sage.schemes.toric.library.ToricVarietyFactory method*), 489
Cube_face_fan() (*sage.schemes.toric.library.ToricVarietyFactory method*), 490
Cube_nonpolyhedral() (*sage.schemes.toric.library.ToricVarietyFactory method*), 491
Cube_sublattice() (*sage.schemes.toric.library.ToricVarietyFactory method*), 492
curve() (*sage.schemes.affine.affine_space.AffineSpace_field method*), 120
curve() (*sage.schemes.projective.projective_space.ProjectiveSpace_field method*), 199
CurvePointToIdeal() (*in module sage.schemes.generic.divisor*), 110
CyclicCover() (*in module sage.schemes.cyclic_covers.constructor*), 698
CyclicCover_finite_field (*class in*

sage.schemes.cyclic_covers.cyclicover_finite_field), 683
CyclicCover_generic (*class in sage.schemes.cyclic_covers.cyclicover_generic*), 692

D

defining_cone() (*sage.schemes.toric.morphism.SchemeMorphism_fan_fiber_component_toric_variety method*), 576
defining_cone() (*sage.schemes.toric.morphism.SchemeMorphism_orbit_closure_toric_variety method*), 595
defining_ideal() (*sage.schemes.generic.algebraic_scheme.AlgebraicScheme_subscheme method*), 55
defining_polynomial() (*sage.schemes.generic.hypersurface.AffineHypersurface method*), 71
defining_polynomial() (*sage.schemes.generic.hypersurface.ProjectiveHypersurface method*), 72
defining_polynomials() (*sage.schemes.generic.algebraic_scheme.AlgebraicScheme_subscheme method*), 55
defining_polynomials() (*sage.schemes.generic.ambient_space.AmbientSpace method*), 28
defining_polynomials() (*sage.schemes.generic.morphism.SchemeMorphism_polynomial method*), 102
deg() (*sage.schemes.toric.variety.CohomologyClass method*), 410
degree() (*sage.schemes.affine.affine_morphism.SchemeMorphism_polynomial_affine_space method*), 136
degree() (*sage.schemes.projective.projective_morphism.SchemeMorphism_polynomial_projective_space method*), 240
degree() (*sage.schemes.projective.projective_morphism.SchemeMorphism_polynomial_projective_subscheme_field method*), 276
degree() (*sage.schemes.projective.projective_subscheme.AlgebraicScheme_subscheme_projective method*), 309
degree() (*sage.schemes.toric.chow_group.ChowCycle method*), 546
degree() (*sage.schemes.toric.chow_group.ChowGroup_class method*), 550
dehomogenize() (*sage.schemes.product_projective.point.ProductProjectiveSpaces_point_ring method*), 380
dehomogenize() (*sage.schemes.projective.projective_morphism.SchemeMorphism_polynomial_projective_space method*), 241
dehomogenize() (*sage.schemes.projective.projective_point.SchemeMorphism_point_projective_ring method*), 292
Delta() (*sage.schemes.toric.fano_variety.CPRFanoToricVariety_field method*), 469
Delta_polar() (*sage.schemes.toric.fano_variety.CPRFanoToricVariety_field method*), 469
Demazure_roots() (*sage.schemes.toric.variety.ToricVariety_field method*), 418
diameter() (*sage.schemes.berkovich.berkovich_cp_element.Berkovich_Element_Cp method*), 708
dimension() (*sage.schemes.affine.affine_subscheme.AlgebraicScheme_subscheme_affine method*), 169
dimension() (*sage.schemes.generic.ambient_space.AmbientSpace method*), 29
dimension() (*sage.schemes.generic.scheme.AffineScheme method*), 6
dimension() (*sage.schemes.generic.scheme.Scheme method*), 12
dimension() (*sage.schemes.product_projective.space.ProductProjectiveSpaces_ring method*), 361
dimension() (*sage.schemes.product_projective.subscheme.AlgebraicScheme_subscheme_product_projective method*), 386
dimension() (*sage.schemes.projective.projective_subscheme.AlgebraicScheme_subscheme_projective method*), 310
dimension() (*sage.schemes.toric.toric_subscheme.AlgebraicScheme_subscheme_affine_toric method*), 598
dimension() (*sage.schemes.toric.toric_subscheme.AlgebraicScheme_subscheme_toric method*), 604
dimension_absolute() (*sage.schemes.generic.ambient_space.AmbientSpace method*), 29
dimension_absolute() (*sage.schemes.generic.scheme.AffineScheme method*), 6
dimension_absolute() (*sage.schemes.generic.scheme.Scheme method*), 12
dimension_absolute() (*sage.schemes.product_projective.space.ProductProjectiveSpaces_ring method*), 361
dimension_absolute_components() (*sage.schemes.product_projective.space.ProductProjectiveSpaces_ring method*), 361
dimension_components() (*sage.schemes.product_projective.space.ProductProjectiveSpaces_ring method*), 362
dimension_relative() (*sage.schemes.generic.ambient_space.AmbientSpace method*), 30
dimension_relative() (*sage.schemes.generic.scheme.AffineScheme method*), 7

dimension_relative() (*sage.schemes.generic.scheme.Scheme method*), 13
dimension_relative() (*sage.schemes.product_projective.space.ProductProjectiveSpaces_ring method*), 362
dimension_relative_components() (*sage.schemes.product_projective.space.ProductProjectiveSpaces_ring method*), 362
dimension_singularities() (*sage.schemes.toric.variety.ToricVariety_field method*), 433
direct_sum() (*sage.schemes.toric.sheaf.klyachko.KlyachkoBundle_class method*), 671
Discriminant() (*in module sage.schemes.toric.weierstrass*), 614
divisor() (*sage.schemes.toric.sheaf.constructor.SheafLibrary method*), 659
divisor() (*sage.schemes.toric.variety.ToricVariety_field method*), 433
divisor_class() (*sage.schemes.toric.divisor.ToricDivisor_generic method*), 521
Divisor_curve (*class in sage.schemes.generic.divisor*), 110
Divisor_generic (*class in sage.schemes.generic.divisor*), 112
divisor_group() (*sage.schemes.toric.variety.ToricVariety_field method*), 434
DivisorGroup() (*in module sage.schemes.generic.divisor_group*), 115
DivisorGroup_curve (*class in sage.schemes.generic.divisor_group*), 115
DivisorGroup_generic (*class in sage.schemes.generic.divisor_group*), 115
domain() (*sage.schemes.generic.morphism.SchemeMorphism method*), 86
dP6() (*sage.schemes.toric.library.ToricVarietyFactory method*), 500
dP6xdP6() (*sage.schemes.toric.library.ToricVarietyFactory method*), 501
dP7() (*sage.schemes.toric.library.ToricVarietyFactory method*), 502
dP8() (*sage.schemes.toric.library.ToricVarietyFactory method*), 502
dual() (*sage.schemes.projective.projective_subscheme.AlgebraicScheme_subscheme_projective method*), 311
dual() (*sage.schemes.toric.sheaf.klyachko.KlyachkoBundle_class method*), 672

E

E_degree() (*sage.schemes.toric.sheaf.klyachko.KlyachkoBundle_class method*), 664
E_intersection() (*sage.schemes.toric.sheaf.klyachko.KlyachkoBundle_class method*), 665
E_quotient() (*sage.schemes.toric.sheaf.klyachko.KlyachkoBundle_class method*), 666
E_quotient_projection() (*sage.schemes.toric.sheaf.klyachko.KlyachkoBundle_class method*), 667
Element (*sage.schemes.berkovich.berkovich_space.Berkovich_Cp_Affine attribute*), 740
Element (*sage.schemes.berkovich.berkovich_space.Berkovich_Cp_Projective attribute*), 743
Element (*sage.schemes.generic.homset.SchemeHomset_generic attribute*), 78
Element (*sage.schemes.generic.scheme.AffineScheme attribute*), 5
Element (*sage.schemes.toric.chow_group.ChowGroup_class attribute*), 550
Element (*sage.schemes.toric.divisor.ToricDivisorGroup attribute*), 511
Element (*sage.schemes.toric.divisor.ToricRationalDivisorClassGroup attribute*), 537
Element (*sage.schemes.toric.divisor.ToricRationalDivisorClassGroup_basis_lattice attribute*), 538
embedding_center() (*sage.schemes.generic.algebraic_scheme.AlgebraicScheme method*), 36
embedding_morphism() (*sage.schemes.generic.algebraic_scheme.AlgebraicScheme method*), 37
embedding_morphism() (*sage.schemes.toric.variety.ToricVariety_field method*), 435
embedding_of_affine_open() (*sage.schemes.generic.point.SchemeTopologicalPoint_affine_open method*), 25
enum_affine_finite_field() (*in module sage.schemes.affine.affine_rational_point*), 183
enum_affine_number_field() (*in module sage.schemes.affine.affine_rational_point*), 184
enum_affine_rational_field() (*in module sage.schemes.affine.affine_rational_point*), 185
enum_product_projective_finite_field() (*in module sage.schemes.product_projective.rational_point*), 395
enum_product_projective_number_field() (*in module sage.schemes.product_projective.rational_point*), 396
enum_product_projective_rational_field() (*in module sage.schemes.product_projective.rational_point*), 397
enum_projective_finite_field() (*in module sage.schemes.projective.projective_rational_point*), 335
enum_projective_number_field() (*in module sage.schemes.projective.projective_ratio-*

nal_point), 336
enum_projective_rational_field() (*in module sage.schemes.projective.projective_rational_point*), 338
Euler_number() (*sage.schemes.toric.variety.ToricVariety_field method*), 420
exp() (*sage.schemes.toric.points.FiniteFieldPointEnumerator method*), 644
exp() (*sage.schemes.toric.variety.CohomologyClass method*), 411
extended_codomain() (*sage.schemes.generic.homset.SchemeHomset_points method*), 80
exterior_power() (*sage.schemes.toric.sheaf.klyachko.KlyachkoBundle_class method*), 672

F

factor() (*sage.schemes.toric.morphism.SchemeMorphism_fan_toric_variety method*), 580
fan() (*sage.schemes.toric.toric_subscheme.AlgebraicScheme_subscheme_toric method*), 605
fan() (*sage.schemes.toric.variety.ToricVariety_field method*), 436
fan_morphism() (*sage.schemes.toric.morphism.SchemeMorphism_fan_toric_variety method*), 582
fiber() (*sage.schemes.toric.sheaf.klyachko.KlyachkoBundle_class method*), 673
fiber_component() (*sage.schemes.toric.morphism.SchemeMorphism_fan_toric_variety_dominant method*), 588
fiber_dimension() (*sage.schemes.toric.morphism.SchemeMorphism_fan_toric_variety_dominant method*), 589
fiber_generic() (*sage.schemes.toric.morphism.SchemeMorphism_fan_toric_variety_dominant method*), 591
fiber_graph() (*sage.schemes.toric.morphism.SchemeMorphism_fan_toric_variety_dominant method*), 592
filtration_intersection() (*sage.schemes.toric.sheaf.klyachko.KlyachkoBundle_class method*), 673
FiniteFieldPointEnumerator (*class in sage.schemes.toric.points*), 642
FiniteFieldSubschemePointEnumerator (*class in sage.schemes.toric.points*), 647
frobenius_matrix() (*sage.schemes.cyclic_covers.cycliccover_finite_field.CyclicCover_finite_field method*), 684
frobenius_polynomial() (*sage.schemes.cyclic_covers.cycliccover_finite_field.CyclicCover_finite_field method*), 685
function_value() (*sage.schemes.toric.divisor.ToricDivisor_generic method*), 522

G

gen() (*sage.schemes.generic.ambient_space.AmbientSpace method*), 30
gen() (*sage.schemes.toric.chow_group.ChowGroup_degree_class method*), 556
gen() (*sage.schemes.toric.divisor.ToricDivisorGroup method*), 511
gen() (*sage.schemes.toric.variety.CohomologyRing method*), 413
gens() (*sage.schemes.generic.ambient_space.AmbientSpace method*), 30
gens() (*sage.schemes.toric.chow_group.ChowGroup_class method*), 554
gens() (*sage.schemes.toric.chow_group.ChowGroup_degree_class method*), 556
gens() (*sage.schemes.toric.divisor.ToricDivisorGroup method*), 512
gens() (*sage.schemes.toric.variety.CohomologyRing method*), 413
genus() (*sage.schemes.cyclic_covers.cyclic_cover_generic.CyclicCover_generic method*), 693
get_degree() (*sage.schemes.toric.sheaf.klyachko.KlyachkoBundle_class method*), 674
get_filtration() (*sage.schemes.toric.sheaf.klyachko.KlyachkoBundle_class method*), 674
global_height() (*sage.schemes.affine.affine_morphism.SchemeMorphism_polynomial_affine_space method*), 137
global_height() (*sage.schemes.affine.affine_point.SchemeMorphism_point_affine method*), 163
global_height() (*sage.schemes.product_projective.morphism.ProductProjectiveSpaces_morphism_ring method*), 374
global_height() (*sage.schemes.product_projective.point.ProductProjectiveSpaces_point_ring method*), 381
global_height() (*sage.schemes.projective.projective_morphism.SchemeMorphism_polynomial_projective_space method*), 245
global_height() (*sage.schemes.projective.projective_point.SchemeMorphism_point_projective_ring method*), 293
global_height() (*sage.schemes.projective.projective_subscheme.AlgebraicScheme_subscheme_projective_field method*), 331
glue_along_domains() (*sage.schemes.generic.morphism.SchemeMorphism method*), 86
GluedScheme (*class in sage.schemes.generic.glue*), 23
gluing_maps() (*sage.schemes.generic.glue.GluedScheme method*), 24
graph() (*sage.schemes.projective.projective_morphism.SchemeMorphism_polynomial_projective_subscheme_field method*), 277

gt() (*sage.schemes.berkovich.berkovich_cp_element.Berkovich_Element_Cp_Affine method*), 722
gt() (*sage.schemes.berkovich.berkovich_cp_element.Berkovich_Element_Cp_Projective method*), 730

H

hom() (*sage.schemes.generic.scheme.AffineScheme method*), 7
hom() (*sage.schemes.generic.scheme.Scheme method*), 13
homogeneous_coordinates() (*sage.schemes.toric.points.FiniteFieldSubschemePointEnumerator method*), 648
homogenize() (*sage.schemes.affine.affine_morphism.SchemeMorphism_polynomial_affine_space method*), 139
homogenize() (*sage.schemes.affine.affine_point.SchemeMorphism_point_affine method*), 164
Hsia_kernel() (*sage.schemes.berkovich.berkovich_cp_element.Berkovich_Element_Cp method*), 704
Hsia_kernel_infinity() (*sage.schemes.berkovich.berkovich_cp_element.Berkovich_Element_Cp method*), 705
hyperbolic_metric() (*sage.schemes.berkovich.berkovich_cp_element.Berkovich_Element_Cp method*), 709
hyperplane_transformation_matrix() (*sage.schemes.projective.projective_space.ProjectiveSpace_ring method*), 213

I

ideal() (*sage.schemes.berkovich.berkovich_cp_element.Berkovich_Element_Cp method*), 710
ideal() (*sage.schemes.berkovich.berkovich_space.Berkovich_Cp method*), 734
identity() (*sage.schemes.affine.affine_homset.SchemeHomset_polynomial_affine_space method*), 193
identity() (*sage.schemes.projective.projective_homset.SchemeHomset_polynomial_projective_space method*), 351
identity_morphism() (*sage.schemes.generic.algebraic_scheme.AlgebraicScheme method*), 40
identity_morphism() (*sage.schemes.generic.ambient_space.AmbientSpace method*), 31
identity_morphism() (*sage.schemes.generic.scheme.Scheme method*), 14
image() (*sage.schemes.affine.affine_morphism.SchemeMorphism_polynomial_affine_space_field method*), 148
image() (*sage.schemes.affine.affine_morphism.SchemeMorphism_polynomial_affine_subscheme_field method*), 156
image() (*sage.schemes.projective.projective_morphism.SchemeMorphism_polynomial_projective_space_field method*), 262
image() (*sage.schemes.projective.projective_morphism.SchemeMorphism_polynomial_projective_subscheme_field method*), 278
indeterminacy_locus() (*sage.schemes.affine.affine_morphism.SchemeMorphism_polynomial_affine_space_field method*), 149
indeterminacy_locus() (*sage.schemes.affine.affine_morphism.SchemeMorphism_polynomial_affine_subscheme_field method*), 157
indeterminacy_locus() (*sage.schemes.projective.projective_morphism.SchemeMorphism_polynomial_projective_space_field method*), 264
indeterminacy_locus() (*sage.schemes.projective.projective_morphism.SchemeMorphism_polynomial_projective_subscheme_field method*), 279
indeterminacy_points() (*sage.schemes.affine.affine_morphism.SchemeMorphism_polynomial_affine_space_field method*), 150
indeterminacy_points() (*sage.schemes.projective.projective_morphism.SchemeMorphism_polynomial_projective_space_field method*), 265
InfinitePointEnumerator (*class in sage.schemes.toric.points*), 651
inhomogeneous_equations() (*sage.schemes.toric.points.FiniteFieldSubschemePointEnumerator method*), 649
inject_coefficients() (*sage.schemes.toric.variety.ToricVariety_field method*), 436
integrate() (*sage.schemes.toric.variety.ToricVariety_field method*), 437
intersection() (*sage.schemes.generic.algebraic_scheme.AlgebraicScheme_subscheme method*), 56
intersection_multiplicity() (*sage.schemes.affine.affine_point.SchemeMorphism_point_affine_field method*), 166
intersection_multiplicity() (*sage.schemes.affine.affine_subscheme.AlgebraicScheme_subscheme_affine method*), 170
intersection_multiplicity() (*sage.schemes.product_projective.point.ProductProjectiveSpaces_point_field method*), 378
intersection_multiplicity() (*sage.schemes.product_projective.subscheme.AlgebraicScheme_subscheme_product_projective method*), 388
intersection_multiplicity() (*sage.schemes.pro-*

jective.projective_point.SchemeMorphism_point_projective_field method), 289
intersection_multiplicity() (*sage.schemes.projective.projective_subscheme.AlgebraicScheme_subscheme_projective method*), 313
intersection_with_divisor() (*sage.schemes.toric.chow_group.ChowCycle method*), 547
involution_map() (*sage.schemes.berkovich.berkovich_cp_element.Berkovich_Element_Cp_Affine method*), 723
involution_map() (*sage.schemes.berkovich.berkovich_cp_element.Berkovich_Element_Cp_Projective method*), 731
irreducible_components() (*sage.schemes.generic.algebraic_scheme.AlgebraicScheme_subscheme method*), 56
is_affine() (*sage.schemes.toric.variety.ToricVariety_field method*), 439
is_AffineScheme() (*in module sage.schemes.generic.scheme*), 19
is_AffineSpace() (*in module sage.schemes.affine.affine_space*), 133
is_AlgebraicScheme() (*in module sage.schemes.generic.algebraic_scheme*), 69
is_AmbientSpace() (*in module sage.schemes.generic.ambient_space*), 32
is_ample() (*sage.schemes.toric.divisor.ToricDivisor_generic method*), 524
is_Berkovich() (*in module sage.schemes.berkovich.berkovich_space*), 744
is_Berkovich_Cp() (*in module sage.schemes.berkovich.berkovich_space*), 744
is_birational() (*sage.schemes.toric.morphism.SchemeMorphism_fan_toric_variety method*), 583
is_bundle() (*sage.schemes.toric.morphism.SchemeMorphism_fan_toric_variety method*), 583
is_Cartier() (*sage.schemes.toric.divisor.ToricDivisor_generic method*), 522
is_ChowCycle() (*in module sage.schemes.toric.chow_group*), 557
is_ChowGroup() (*in module sage.schemes.toric.chow_group*), 558
is_CohomologyClass() (*in module sage.schemes.toric.variety*), 452
is_complete() (*sage.schemes.toric.variety.ToricVariety_field method*), 439
is_CPRFanoToricVariety() (*in module sage.schemes.toric.fano_variety*), 484
is_Divisor() (*in module sage.schemes.generic.divisor*), 112
is_DivisorGroup() (*in module sage.schemes.generic.divisor_group*), 116
is_dominant() (*sage.schemes.toric.morphism.SchemeMorphism_fan_toric_variety method*), 584
is_endomorphism() (*sage.schemes.generic.morphism.SchemeMorphism method*), 88
is_fibration() (*sage.schemes.toric.morphism.SchemeMorphism_fan_toric_variety method*), 584
is_finite() (*sage.schemes.toric.homset.SchemeHomset_points_toric_base method*), 637
is_homogeneous() (*sage.schemes.toric.variety.ToricVariety_field method*), 440
is_Hypersurface() (*in module sage.schemes.generic.hypersurface*), 73
is_injective() (*sage.schemes.toric.morphism.SchemeMorphism_fan_toric_variety method*), 585
is_integral() (*sage.schemes.toric.divisor.ToricDivisor_generic method*), 526
is_irreducible() (*sage.schemes.generic.algebraic_scheme.AlgebraicScheme_subscheme method*), 58
is_isomorphic() (*sage.schemes.toric.sheaf.klyachko.KlyachkoBundle_class method*), 675
is_isomorphic() (*sage.schemes.toric.variety.ToricVariety_field method*), 441
is_KlyachkoBundle() (*in module sage.schemes.toric.sheaf.klyachko*), 678
is_linearly_independent() (*sage.schemes.projective.projective_space.ProjectiveSpace_ring method*), 217
is_morphism() (*sage.schemes.affine.affine_morphism.SchemeMorphism_polynomial_affine_subscheme_field method*), 159
is_morphism() (*sage.schemes.product_projective.morphism.ProductProjectiveSpaces_morphism_ring method*), 375
is_morphism() (*sage.schemes.projective.projective_morphism.SchemeMorphism_polynomial_projective_space method*), 248
is_morphism() (*sage.schemes.projective.projective_morphism.SchemeMorphism_polynomial_projective_subscheme_field method*), 281
is_nef() (*sage.schemes.toric.divisor.ToricDivisor_generic method*), 527
is_noetherian() (*sage.schemes.generic.scheme.AffineScheme method*), 8
is_nondegenerate() (*sage.schemes.toric.toric_subscheme.AlgebraicScheme_subscheme_toric method*), 605
is_number_field_base() (*sage.schemes.berkovich.berkovich_space.Berkovich_Cp method*), 735

is_orbifold() (*sage.schemes.toric.variety.ToricVariety_field method*), 442
is_padic_base() (*sage.schemes.berkovich.berkovich_space.Berkovich_Cp method*), 736
is_preperiodic() (*sage.schemes.projective.projective_point.SchemeMorphism_point_projective_ring method*), 295
is_ProductProjectiveSpaces() (*in module sage.schemes.product_projective.space*), 367
is_projective() (*sage.schemes.generic.algebraic_scheme.AlgebraicScheme method*), 41
is_projective() (*sage.schemes.generic.ambient_space.AmbientSpace method*), 31
is_projective() (*sage.schemes.projective.projective_space.ProjectiveSpace_ring method*), 219
is_ProjectiveSpace() (*in module sage.schemes.projective.projective_space*), 233
is_QQ_Cartier() (*sage.schemes.toric.divisor.ToricDivisor_generic method*), 523
is_QQ_Weil() (*sage.schemes.toric.divisor.ToricDivisor_generic method*), 523
is_Scheme() (*in module sage.schemes.generic.scheme*), 19
is_SchemeHomset() (*in module sage.schemes.generic.homset*), 81
is_SchemeMorphism() (*in module sage.schemes.generic.morphism*), 108
is_SchemeTopologicalPoint() (*in module sage.schemes.generic.point*), 26
is_schon() (*sage.schemes.toric.toric_subscheme.AlgebraicScheme_subscheme_toric method*), 608
is_singular() (*sage.schemes.cyclic_covers.cyclic_cover_generic.CyclicCover_generic method*), 694
is_smooth() (*sage.schemes.affine.affine_subscheme.AlgebraicScheme_subscheme_affine method*), 173
is_smooth() (*sage.schemes.cyclic_covers.cyclic_cover_generic.CyclicCover_generic method*), 694
is_smooth() (*sage.schemes.product_projective.subscheme.AlgebraicScheme_subscheme_product_projective method*), 390
is_smooth() (*sage.schemes.projective.projective_subscheme.AlgebraicScheme_subscheme_projective method*), 315
is_smooth() (*sage.schemes.toric.toric_subscheme.AlgebraicScheme_subscheme_affine_toric method*), 599
is_smooth() (*sage.schemes.toric.toric_subscheme.AlgebraicScheme_subscheme_toric method*), 608
is_smooth() (*sage.schemes.toric.variety.ToricVariety_field method*), 442
is_surjective() (*sage.schemes.toric.morphism.SchemeMorphism_fan_toric_variety method*), 585
is_toric_divisor() (*in module sage.schemes.toric.divisor*), 538
is_ToricRationalDivisorClass() (*in module sage.schemes.toric.divisor_class*), 539
is_ToricVariety() (*in module sage.schemes.toric.variety*), 453
is_Weil() (*sage.schemes.toric.divisor.ToricDivisor_generic method*), 524

J

j_invariant() (*in module sage.schemes.toric.weierstrass*), 622
jacobian() (*sage.schemes.affine.affine_morphism.SchemeMorphism_polynomial_affine_space method*), 143
Jacobian() (*sage.schemes.generic.algebraic_scheme.AlgebraicScheme_subscheme method*), 46
Jacobian_matrix() (*sage.schemes.generic.algebraic_scheme.AlgebraicScheme_subscheme method*), 47
join() (*sage.schemes.berkovich.berkovich_cp_element.Berkovich_Element_Cp_Affine method*), 724
join() (*sage.schemes.berkovich.berkovich_cp_element.Berkovich_Element_Cp_Projective method*), 732

K

K() (*sage.schemes.toric.variety.ToricVariety_field method*), 420
Kaehler_cone() (*sage.schemes.toric.variety.ToricVariety_field method*), 421
ker() (*sage.schemes.toric.ideal.ToricIdeal method*), 563
Klyachko() (*sage.schemes.toric.sheaf.constructor.SheafLibrary method*), 658
KlyachkoBundle_class (*class in sage.schemes.toric.sheaf.klyachko*), 663
Kodaira_map() (*sage.schemes.toric.divisor.ToricDivisor_generic method*), 515

L

Lattes_map() (*sage.schemes.projective.projective_space.ProjectiveSpace_ring method*), 206
lift() (*sage.schemes.toric.divisor_class.ToricRationalDivisorClass method*), 539
line_bundle() (*sage.schemes.toric.sheaf.constructor.SheafLibrary method*), 659
line_through() (*sage.schemes.affine.affine_space.AffineSpace_field method*), 120
line_through() (*sage.schemes.projective.projective_space.ProjectiveSpace_field method*), 199

linear_equivalence_ideal() (*sage.schemes.toric.variety.ToricVariety_field method*), 443
LineBundle() (*in module sage.schemes.toric.sheaf.constructor*), 657
list() (*sage.schemes.generic.homset.SchemeHomset_points method*), 80
local_height() (*sage.schemes.affine.affine_morphism.SchemeMorphism_polynomial_affine_space method*), 145
local_height() (*sage.schemes.product_projective.morphism.ProductProjectiveSpaces_morphism_ring method*), 376
local_height() (*sage.schemes.product_projective.point.ProductProjectiveSpaces_point_ring method*), 383
local_height() (*sage.schemes.projective.projective_morphism.SchemeMorphism_polynomial_projective_space method*), 250
local_height() (*sage.schemes.projective.projective_point.SchemeMorphism_point_projective_ring method*), 300
local_height() (*sage.schemes.projective.projective_subscheme.AlgebraicScheme_subscheme_projective_field method*), 332
local_height_arch() (*sage.schemes.affine.affine_morphism.SchemeMorphism_polynomial_affine_space method*), 146
local_height_arch() (*sage.schemes.projective.projective_morphism.SchemeMorphism_polynomial_projective_space method*), 251
local_height_arch() (*sage.schemes.projective.projective_point.SchemeMorphism_point_projective_ring method*), 301
local_height_arch() (*sage.schemes.projective.projective_subscheme.AlgebraicScheme_subscheme_projective_field method*), 333
log() (*sage.schemes.toric.points.FiniteFieldPointEnumerator method*), 644
lt() (*sage.schemes.berkovich.berkovich_cp_element.Berkovich_Element_Cp_Affine method*), 725
lt() (*sage.schemes.berkovich.berkovich_cp_element.Berkovich_Element_Cp_Projective method*), 733

M

m() (*sage.schemes.toric.divisor.ToricDivisor_generic method*), 528
module
    sage.schemes.affine.affine_homset, 187
    sage.schemes.affine.affine_morphism, 134
    sage.schemes.affine.affine_point, 162
    sage.schemes.affine.affine_rational_point, 182
    sage.schemes.affine.affine_space, 119
    sage.schemes.affine.affine_subscheme, 169
    sage.schemes.berkovich.berkovich_cp_element, 703
    sage.schemes.berkovich.berkovich_space, 734
    sage.schemes.cyclic_covers.charpoly_frobenius, 696
    sage.schemes.cyclic_covers.constructor, 698
    sage.schemes.cyclic_covers.cyclic_cover_finite_field, 681
    sage.schemes.cyclic_covers.cyclic_cover_generic, 691
    sage.schemes.generic.algebraic_scheme, 33
    sage.schemes.generic.ambient_space, 27
    sage.schemes.generic.divisor, 109
    sage.schemes.generic.divisor_group, 115
    sage.schemes.generic.glue, 23
    sage.schemes.generic.homset, 75
    sage.schemes.generic.hypersurface, 71
    sage.schemes.generic.morphism, 83
    sage.schemes.generic.point, 25
    sage.schemes.generic.scheme, 5
    sage.schemes.generic.spec, 21
    sage.schemes.overview, 1
    sage.schemes.product_projective.homset, 367
    sage.schemes.product_projective.morphism, 373
    sage.schemes.product_projective.point, 377
    sage.schemes.product_projective.rational_point, 394
    sage.schemes.product_projective.space, 353
    sage.schemes.product_projective.subscheme, 385
    sage.schemes.projective.projective_homset, 341
    sage.schemes.projective.projective_morphism, 234
    sage.schemes.projective.projective_point, 286
    sage.schemes.projective.projective_rational_point, 334
    sage.schemes.projective.projective_space, 195
    sage.schemes.projective.projective_subscheme, 306

sage.schemes.toric.chow_group, 540
sage.schemes.toric.divisor, 504
sage.schemes.toric.divisor_class, 539
sage.schemes.toric.fano_variety, 457
sage.schemes.toric.homset, 634
sage.schemes.toric.ideal, 559
sage.schemes.toric.library, 485
sage.schemes.toric.morphism, 564
sage.schemes.toric.points, 642
sage.schemes.toric.sheaf.constructor, 656
sage.schemes.toric.sheaf.klyachko, 661
sage.schemes.toric.toric_subscheme, 598
sage.schemes.toric.variety, 401
sage.schemes.toric.weierstrass, 612
sage.schemes.toric.weierstrass_covering, 623
sage.schemes.toric.weierstrass_higher, 632
module() (*sage.schemes.toric.chow_group.ChowGroup_degree_class method*), 556
monomial() (*sage.schemes.toric.divisor.ToricDivisor_generic method*), 530
Mori_cone() (*sage.schemes.toric.variety.ToricVariety_field method*), 421
move_away_from() (*sage.schemes.toric.divisor.ToricDivisor_generic method*), 530
multiplicative_generator() (*sage.schemes.toric.points.FiniteFieldPointEnumerator method*), 645
multiplicative_group_order() (*sage.schemes.toric.points.FiniteFieldPointEnumerator method*), 646
multiplicity() (*sage.schemes.affine.affine_point.SchemeMorphism_point_affine_field method*), 167
multiplicity() (*sage.schemes.affine.affine_subscheme.AlgebraicScheme_subscheme_affine method*), 174
multiplicity() (*sage.schemes.product_projective.point.ProductProjectiveSpaces_point_field method*), 378
multiplicity() (*sage.schemes.product_projective.subscheme.AlgebraicScheme_subscheme_product_projective method*), 390
multiplicity() (*sage.schemes.projective.projective_point.SchemeMorphism_point_projective_field method*), 290
multiplicity() (*sage.schemes.projective.projective_subscheme.AlgebraicScheme_subscheme_projective method*), 316
multiplier() (*sage.schemes.projective.projective_point.SchemeMorphism_point_projective_ring method*), 302

N

NaiveFinitePointEnumerator (*class in sage.schemes.toric.points*), 651
NaiveSubschemePointEnumerator (*class in sage.schemes.toric.points*), 656
natural_map() (*sage.schemes.generic.homset.SchemeHomset_generic method*), 78
nef_complete_intersection() (*sage.schemes.toric.fano_variety.CPRFanoToricVariety_field method*), 477
nef_partition() (*sage.schemes.toric.fano_variety.NefCompleteIntersection method*), 482
NefCompleteIntersection (*class in sage.schemes.toric.fano_variety*), 481
neighborhood() (*sage.schemes.projective.projective_subscheme.AlgebraicScheme_subscheme_projective method*), 317
neighborhood() (*sage.schemes.toric.toric_subscheme.AlgebraicScheme_subscheme_toric method*), 610
Newton_polygon_embedded() (*in module sage.schemes.toric.weierstrass*), 615
Newton_polytope_vars_coeffs() (*in module sage.schemes.toric.weierstrass*), 616
ngens() (*sage.schemes.affine.affine_space.AffineSpace_generic method*), 129
ngens() (*sage.schemes.generic.algebraic_scheme.AlgebraicScheme method*), 42
ngens() (*sage.schemes.generic.ambient_space.AmbientSpace method*), 32
ngens() (*sage.schemes.product_projective.space.ProductProjectiveSpaces_ring method*), 363
ngens() (*sage.schemes.projective.projective_space.ProjectiveSpace_ring method*), 219
ngens() (*sage.schemes.toric.chow_group.ChowGroup_degree_class method*), 557
ngens() (*sage.schemes.toric.divisor.ToricDivisorGroup method*), 512
normalize_coordinates() (*sage.schemes.product_projective.point.ProductProjectiveSpaces_point_ring method*), 384
normalize_coordinates() (*sage.schemes.projective.projective_morphism.SchemeMorphism_polynomial_projective_space method*), 253
normalize_coordinates() (*sage.schemes.projective.projective_point.SchemeMorphism_point_projective_field method*), 291
normalize_coordinates() (*sage.schemes.projective.projective_point.SchemeMorphism_point_projective_ring method*), 302
normalize_defining_polynomials() (*sage.schemes.generic.algebraic_scheme.AlgebraicScheme_subscheme method*), 59

normalize_names() (*in module sage.schemes.toric.variety*), 454
nth_iterate() (*sage.schemes.projective.projective_subscheme.AlgebraicScheme_subscheme_projective method*), 318
num_components() (*sage.schemes.product_projective.space.ProductProjectiveSpaces_ring method*), 363
numerical_points() (*sage.schemes.affine.affine_homset.SchemeHomset_points_affine method*), 188
numerical_points() (*sage.schemes.projective.projective_homset.SchemeHomset_points_projective_field method*), 343
nvariables() (*sage.schemes.toric.ideal.ToricIdeal method*), 563

O

orbit() (*sage.schemes.projective.projective_subscheme.AlgebraicScheme_subscheme_projective method*), 320
orbit() (*sage.schemes.toric.points.NaiveFinitePointEnumerator method*), 653
orbit_closure() (*sage.schemes.toric.variety.ToricVariety_field method*), 443
order() (*sage.schemes.cyclic_covers.cyclic_cover_generic.CyclicCover_generic method*), 695
origin() (*sage.schemes.affine.affine_space.AffineSpace_generic method*), 129

P

P() (*sage.schemes.toric.library.ToricVarietyFactory method*), 492
P1() (*sage.schemes.toric.library.ToricVarietyFactory method*), 493
P1xA1() (*sage.schemes.toric.library.ToricVarietyFactory method*), 493
P1xP1() (*sage.schemes.toric.library.ToricVarietyFactory method*), 494
P1xP1_Z2() (*sage.schemes.toric.library.ToricVarietyFactory method*), 495
P2() (*sage.schemes.toric.library.ToricVarietyFactory method*), 495
P2_112() (*sage.schemes.toric.library.ToricVarietyFactory method*), 496
P2_123() (*sage.schemes.toric.library.ToricVarietyFactory method*), 497
P4_11133() (*sage.schemes.toric.library.ToricVarietyFactory method*), 497
P4_11133_resolved() (*sage.schemes.toric.library.ToricVarietyFactory method*), 498
P4_11169() (*sage.schemes.toric.library.ToricVarietyFactory method*), 498
P4_11169_resolved() (*sage.schemes.toric.library.ToricVarietyFactory method*), 499
part_of_degree() (*sage.schemes.toric.variety.CohomologyClass method*), 411
path_distance_metric() (*sage.schemes.berkovich.berkovich_cp_element.Berkovich_Element_Cp method*), 710
plot() (*sage.schemes.toric.variety.ToricVariety_field method*), 444
point() (*sage.schemes.generic.scheme.Scheme method*), 14
point() (*sage.schemes.projective.projective_space.ProjectiveSpace_ring method*), 219
point() (*sage.schemes.projective.projective_subscheme.AlgebraicScheme_subscheme_projective method*), 322
point_homset() (*sage.schemes.generic.scheme.Scheme method*), 15
point_on_affine() (*sage.schemes.generic.point.SchemeTopologicalPoint_affine_open method*), 25
point_set() (*sage.schemes.generic.scheme.Scheme method*), 15
point_transformation_matrix() (*sage.schemes.projective.projective_space.ProjectiveSpace_ring method*), 220
points() (*sage.schemes.affine.affine_homset.SchemeHomset_points_affine method*), 189
points() (*sage.schemes.product_projective.homset.SchemeHomset_points_product_projective_spaces_field method*), 368
points() (*sage.schemes.projective.projective_homset.SchemeHomset_points_projective_field method*), 345
points() (*sage.schemes.projective.projective_homset.SchemeHomset_points_projective_ring method*), 348
points_of_bounded_height() (*sage.schemes.affine.affine_space.AffineSpace_field method*), 121
points_of_bounded_height() (*sage.schemes.product_projective.space.ProductProjectiveSpaces_field method*), 354
points_of_bounded_height() (*sage.schemes.projective.projective_space.ProjectiveSpace_ring method*), 225
polyhedron() (*sage.schemes.toric.divisor.ToricDivisor_generic method*), 531
potential_kernel() (*sage.schemes.berkovich.berkovich_cp_element.Berkovich_Element_Cp method*), 711
power() (*sage.schemes.berkovich.berkovich_cp_element.Berkovich_Element_Cp method*), 712
prec() (*sage.schemes.berkovich.berkovich_cp_element.Berkovich_Element_Cp method*), 713
precision() (*sage.schemes.berkovich.berkovich_cp_ele-*

ment.Berkovich_Element_Cp method), 713
preimage() (*sage.schemes.projective.projective_subscheme.AlgebraicScheme_subscheme_projective method*), 323
prime() (*sage.schemes.berkovich.berkovich_cp_element.Berkovich_Element_Cp method*), 713
prime() (*sage.schemes.berkovich.berkovich_space.Berkovich_Cp method*), 736
prime_ideal() (*sage.schemes.generic.point.SchemeTopologicalPoint_prime_ideal method*), 26
ProductProjectiveSpaces() (*in module sage.schemes.product_projective.space*), 353
ProductProjectiveSpaces_field (*class in sage.schemes.product_projective.space*), 354
ProductProjectiveSpaces_finite_field (*class in sage.schemes.product_projective.space*), 357
ProductProjectiveSpaces_morphism_ring (*class in sage.schemes.product_projective.morphism*), 373
ProductProjectiveSpaces_point_field (*class in sage.schemes.product_projective.point*), 378
ProductProjectiveSpaces_point_finite_field (*class in sage.schemes.product_projective.point*), 379
ProductProjectiveSpaces_point_ring (*class in sage.schemes.product_projective.point*), 379
ProductProjectiveSpaces_ring (*class in sage.schemes.product_projective.space*), 358
project_to_degree() (*sage.schemes.toric.chow_group.ChowCycle method*), 548
projective_closure() (*sage.schemes.affine.affine_subscheme.AlgebraicScheme_subscheme_affine method*), 176
projective_closure() (*sage.schemes.cyclic_covers.cycliccover_generic.CyclicCover_generic method*), 695
projective_degrees() (*sage.schemes.projective.projective_morphism.SchemeMorphism_polynomial_projective_subscheme_field method*), 282
projective_embedding() (*sage.schemes.affine.affine_space.AffineSpace_generic method*), 130
projective_embedding() (*sage.schemes.affine.affine_subscheme.AlgebraicScheme_subscheme_affine method*), 177
ProjectiveHypersurface (*class in sage.schemes.generic.hypersurface*), 72
ProjectiveSpace() (*in module sage.schemes.projective.projective_space*), 197
ProjectiveSpace_field (*class in sage.schemes.projective.projective_space*), 199
ProjectiveSpace_finite_field (*class in sage.schemes.projective.projective_space*), 202
ProjectiveSpace_rational_field (*class in sage.schemes.projective.projective_space*), 203
ProjectiveSpace_ring (*class in sage.schemes.projective.projective_space*), 204
pullback_divisor() (*sage.schemes.toric.morphism.SchemeMorphism_fan_fiber_component_toric_variety method*), 577
pullback_divisor() (*sage.schemes.toric.morphism.SchemeMorphism_fan_toric_variety method*), 586
pullback_divisor() (*sage.schemes.toric.morphism.SchemeMorphism_orbit_closure_toric_variety method*), 596

R

radius() (*sage.schemes.berkovich.berkovich_cp_element.Berkovich_Element_Cp method*), 714
radius_function() (*sage.schemes.berkovich.berkovich_cp_element.Berkovich_Element_Cp method*), 714
random_deformation() (*sage.schemes.toric.sheaf.klyachko.KlyachkoBundle_class method*), 675
rank() (*sage.schemes.toric.sheaf.klyachko.KlyachkoBundle_class method*), 676
rational_class_group() (*sage.schemes.toric.variety.ToricVariety_field method*), 445
rational_points() (*sage.schemes.affine.affine_space.AffineSpace_generic method*), 131
rational_points() (*sage.schemes.generic.algebraic_scheme.AlgebraicScheme_quasi method*), 44
rational_points() (*sage.schemes.generic.algebraic_scheme.AlgebraicScheme_subscheme method*), 60
rational_points() (*sage.schemes.product_projective.space.ProductProjectiveSpaces_finite_field method*), 357
rational_points() (*sage.schemes.projective.projective_space.ProjectiveSpace_finite_field method*), 202
rational_points() (*sage.schemes.projective.projective_space.ProjectiveSpace_rational_field method*), 203
rational_points_dictionary() (*sage.schemes.projective.projective_space.ProjectiveSpace_finite_field method*), 203
rational_preimages() (*sage.schemes.projective.projective_morphism.SchemeMorphism_polynomial_projective_space_field method*), 269
rays() (*sage.schemes.toric.points.NaiveFinitePointEnumerator method*), 654
reduce() (*sage.schemes.generic.algebraic_scheme.AlgebraicScheme_subscheme method*), 63

reduce_base_field() (*sage.schemes.affine.affine_morphism.SchemeMorphism_polynomial_affine_space_field method*), 150
reduce_base_field() (*sage.schemes.projective.projective_morphism.SchemeMorphism_polynomial_projective_space_field method*), 274
relation_gens() (*sage.schemes.toric.chow_group.ChowGroup_class method*), 554
representatives() (*sage.schemes.affine.affine_morphism.SchemeMorphism_polynomial_affine_subscheme_field method*), 160
representatives() (*sage.schemes.projective.projective_morphism.SchemeMorphism_polynomial_projective_subscheme_field method*), 282
rescaling_log_generators() (*sage.schemes.toric.points.FiniteFieldPointEnumerator method*), 646
rescalings() (*sage.schemes.toric.points.NaiveFinitePointEnumerator method*), 654
residue_characteristic() (*sage.schemes.berkovich.berkovich_space.BerkovichCp method*), 737
resolve() (*sage.schemes.toric.fano_variety.CPRFanoToricVariety_field method*), 479
resolve() (*sage.schemes.toric.variety.ToricVariety_field method*), 445
resolve_to_orbifold() (*sage.schemes.toric.variety.ToricVariety_field method*), 447
ring_homomorphism() (*sage.schemes.generic.morphism.SchemeMorphism_spec method*), 107
root_generator() (*sage.schemes.toric.points.FiniteFieldPointEnumerator method*), 647
roots() (*sage.schemes.toric.points.NaiveFinitePointEnumerator method*), 655

S

sage.schemes.affine.affine_homset
module, 187
sage.schemes.affine.affine_morphism
module, 134
sage.schemes.affine.affine_point
module, 162
sage.schemes.affine.affine_rational_point
module, 182
sage.schemes.affine.affine_space
module, 119
sage.schemes.affine.affine_subscheme
module, 169
sage.schemes.berkovich.berkovich_cp_element
module, 703
sage.schemes.berkovich.berkovich_space
module, 734
sage.schemes.cyclic_covers.charpoly_frobenius
module, 696
sage.schemes.cyclic_covers.constructor
module, 698
sage.schemes.cyclic_covers.cycliccover_finite_field
module, 681
sage.schemes.cyclic_covers.cyclic_cover_generic
module, 691
sage.schemes.generic.algebraic_scheme
module, 33
sage.schemes.generic.ambient_space
module, 27
sage.schemes.generic.divisor
module, 109
sage.schemes.generic.divisor_group
module, 115
sage.schemes.generic.glue
module, 23
sage.schemes.generic.homset
module, 75
sage.schemes.generic.hypersurface
module, 71
sage.schemes.generic.morphism
module, 83
sage.schemes.generic.point
module, 25
sage.schemes.generic.scheme
module, 5
sage.schemes.generic.spec
module, 21
sage.schemes.overview
module, 1
sage.schemes.product_projective.homset
module, 367
sage.schemes.product_projective.morphism
module, 373
sage.schemes.product_projective.point
module, 377
sage.schemes.product_projective.rational_point
module, 394
sage.schemes.product_projective.space
module, 353
sage.schemes.product_projective.subscheme
module, 385
sage.schemes.projective.projective_homset
module, 341
sage.schemes.projective.projective_morphism
module, 234
sage.schemes.projective.projective_point

module, 286
sage.schemes.projective.projective_rational_point
module, 334
sage.schemes.projective.projective_space
module, 195
sage.schemes.projective.projective_subscheme
module, 306
sage.schemes.toric.chow_group
module, 540
sage.schemes.toric.divisor
module, 504
sage.schemes.toric.divisor_class
module, 539
sage.schemes.toric.fano_variety
module, 457
sage.schemes.toric.homset
module, 634
sage.schemes.toric.ideal
module, 559
sage.schemes.toric.library
module, 485
sage.schemes.toric.morphism
module, 564
sage.schemes.toric.points
module, 642
sage.schemes.toric.sheaf.constructor
module, 656
sage.schemes.toric.sheaf.klyachko
module, 661
sage.schemes.toric.toric_subscheme
module, 598
sage.schemes.toric.variety
module, 401
sage.schemes.toric.weierstrass
module, 612
sage.schemes.toric.weierstrass_covering
module, 623
sage.schemes.toric.weierstrass_higher
module, 632
scale_by() (*sage.schemes.product_projective.point.ProductProjectiveSpaces_point_ring method*), 384
scale_by() (*sage.schemes.projective.projective_morphism.SchemeMorphism_polynomial_projective_space method*), 258
scale_by() (*sage.schemes.projective.projective_point.SchemeMorphism_point_projective_ring method*), 305
Scheme (*class in sage.schemes.generic.scheme*), 8
scheme() (*sage.schemes.generic.divisor_group.DivisorGroup_generic method*), 116
scheme() (*sage.schemes.generic.divisor.Divisor_generic method*), 112
scheme() (*sage.schemes.generic.morphism.SchemeMorphism_point method*), 92
scheme() (*sage.schemes.generic.point.SchemePoint method*), 25
scheme() (*sage.schemes.toric.chow_group.ChowGroup_class method*), 555
SchemeHomset_generic (*class in sage.schemes.generic.homset*), 78
SchemeHomset_points (*class in sage.schemes.generic.homset*), 79
SchemeHomset_points_abelian_variety_field (*class in sage.schemes.projective.projective_homset*), 341
SchemeHomset_points_affine (*class in sage.schemes.affine.affine_homset*), 187
SchemeHomset_points_product_projective_spaces_field (*class in sage.schemes.product_projective.homset*), 368
SchemeHomset_points_product_projective_spaces_ring (*class in sage.schemes.product_projective.homset*), 372
SchemeHomset_points_projective_field (*class in sage.schemes.projective.projective_homset*), 343
SchemeHomset_points_projective_ring (*class in sage.schemes.projective.projective_homset*), 348
SchemeHomset_points_spec (*class in sage.schemes.affine.affine_homset*), 192
SchemeHomset_points_subscheme_toric_field (*class in sage.schemes.toric.homset*), 636
SchemeHomset_points_toric_base (*class in sage.schemes.toric.homset*), 637
SchemeHomset_points_toric_field (*class in sage.schemes.toric.homset*), 638
SchemeHomset_polynomial_affine_space (*class in sage.schemes.affine.affine_homset*), 192
SchemeHomset_polynomial_projective_space (*class in sage.schemes.projective.projective_homset*), 350
SchemeHomset_toric_variety (*class in sage.schemes.toric.homset*), 641
SchemeHomsetFactory (*class in sage.schemes.generic.homset*), 75
SchemeMorphism (*class in sage.schemes.generic.morphism*), 83
SchemeMorphism_fan_fiber_component_toric_variety (*class in sage.schemes.toric.morphism*), 573
SchemeMorphism_fan_toric_variety (*class in sage.schemes.toric.morphism*), 578
SchemeMorphism_fan_toric_variety_dominant (*class in sage.schemes.toric.morphism*), 587
SchemeMorphism_id (*class in sage.schemes.generic.morphism*), 89
SchemeMorphism_orbit_closure_toric_variety

(*class in sage.schemes.toric.morphism*), 594
SchemeMorphism_point (*class in sage.schemes.generic.morphism*), 89
SchemeMorphism_point_abelian_variety_field (*class in sage.schemes.projective.projective_point*), 286
SchemeMorphism_point_affine (*class in sage.schemes.affine.affine_point*), 163
SchemeMorphism_point_affine_field (*class in sage.schemes.affine.affine_point*), 165
SchemeMorphism_point_affine_finite_field (*class in sage.schemes.affine.affine_point*), 168
SchemeMorphism_point_projective_field (*class in sage.schemes.projective.projective_point*), 286
SchemeMorphism_point_projective_finite_field (*class in sage.schemes.projective.projective_point*), 291
SchemeMorphism_point_projective_ring (*class in sage.schemes.projective.projective_point*), 291
SchemeMorphism_point_toric_field (*class in sage.schemes.toric.morphism*), 596
SchemeMorphism_polynomial (*class in sage.schemes.generic.morphism*), 94
SchemeMorphism_polynomial_affine_space (*class in sage.schemes.affine.affine_morphism*), 134
SchemeMorphism_polynomial_affine_space_field (*class in sage.schemes.affine.affine_morphism*), 147
SchemeMorphism_polynomial_affine_space_finite_field (*class in sage.schemes.affine.affine_morphism*), 156
SchemeMorphism_polynomial_affine_subscheme_field (*class in sage.schemes.affine.affine_morphism*), 156
SchemeMorphism_polynomial_id (*class in sage.schemes.generic.morphism*), 105
SchemeMorphism_polynomial_projective_space (*class in sage.schemes.projective.projective_morphism*), 235
SchemeMorphism_polynomial_projective_space_field (*class in sage.schemes.projective.projective_morphism*), 260
SchemeMorphism_polynomial_projective_space_finite_field (*class in sage.schemes.projective.projective_morphism*), 276
SchemeMorphism_polynomial_projective_subscheme_field (*class in sage.schemes.projective.projective_morphism*), 276
SchemeMorphism_polynomial_toric_variety (*class in sage.schemes.toric.morphism*), 597
SchemeMorphism_spec (*class in sage.schemes.generic.morphism*), 106
SchemeMorphism_structure_map (*class in sage.schemes.generic.morphism*), 107
SchemePoint (*class in sage.schemes.generic.point*), 25
SchemeTopologicalPoint (*class in sage.schemes.generic.point*), 25
SchemeTopologicalPoint_affine_open (*class in sage.schemes.generic.point*), 25
SchemeTopologicalPoint_prime_ideal (*class in sage.schemes.generic.point*), 26
sections() (*sage.schemes.toric.divisor.ToricDivisor_generic method*), 534
sections_monomials() (*sage.schemes.toric.divisor.ToricDivisor_generic method*), 535
segre_embedding() (*sage.schemes.product_projective.space.ProductProjectiveSpaces_ring method*), 363
segre_embedding() (*sage.schemes.product_projective.subscheme.AlgebraicScheme_subscheme_product_projective method*), 392
SheafLibrary (*class in sage.schemes.toric.sheaf.constructor*), 657
sheaves (*sage.schemes.toric.variety.ToricVariety_field property*), 448
sieve() (*in module sage.schemes.product_projective.rational_point*), 399
sieve() (*in module sage.schemes.projective.projective_rational_point*), 339
small_metric() (*sage.schemes.berkovich.berkovich_cp_element.Berkovich_Element_Cp method*), 715
solutions() (*sage.schemes.toric.points.FiniteFieldSubschemePointEnumerator method*), 650
solutions_serial() (*sage.schemes.toric.points.FiniteFieldSubschemePointEnumerator method*), 650
Spec() (*in module sage.schemes.generic.spec*), 21
Spec() (*sage.schemes.toric.variety.ToricVariety_field method*), 422
SpecFunctor (*class in sage.schemes.generic.spec*), 22
specialization() (*sage.schemes.generic.algebraic_scheme.AlgebraicScheme_subscheme method*), 64
specialization() (*sage.schemes.generic.morphism.SchemeMorphism_point method*), 92
specialization() (*sage.schemes.generic.morphism.SchemeMorphism_polynomial method*), 102
spherical_kernel() (*sage.schemes.berkovich.berkovich_cp_element.Berkovich_Element_Cp method*), 716
Stanley_Reisner_ideal() (*sage.schemes.toric.variety.ToricVariety_field method*), 423
structure_morphism() (*sage.schemes.generic.scheme.Scheme method*), 16
subscheme() (*sage.schemes.affine.affine_space.AffineSpace_generic method*), 132
subscheme() (*sage.schemes.product_projec-*

tive.space.ProductProjectiveSpaces_ring method), 366
subscheme() (*sage.schemes.projective.projective_space.ProjectiveSpace_ring method*), 230
subscheme() (*sage.schemes.toric.variety.ToricVariety_field method*), 449
subscheme_from_Chow_form() (*sage.schemes.projective.projective_space.ProjectiveSpace_field method*), 200
support() (*sage.schemes.generic.divisor.Divisor_curve method*), 111
symmetric_power() (*sage.schemes.toric.sheaf.klyachko.KlyachkoBundle_class method*), 676

T

tangent_bundle() (*sage.schemes.toric.sheaf.constructor.SheafLibrary method*), 660
tangent_space() (*sage.schemes.affine.affine_subscheme.AlgebraicScheme_subscheme_affine_field method*), 180
TangentBundle() (*in module sage.schemes.toric.sheaf.constructor*), 660
Td() (*sage.schemes.toric.variety.ToricVariety_field method*), 424
tensor_product() (*sage.schemes.toric.sheaf.klyachko.KlyachkoBundle_class method*), 677
Todd_class() (*sage.schemes.toric.variety.ToricVariety_field method*), 424
toric_divisor_group() (*sage.schemes.toric.variety.ToricVariety_field method*), 450
ToricDivisor() (*in module sage.schemes.toric.divisor*), 509
ToricDivisor_generic (*class in sage.schemes.toric.divisor*), 513
ToricDivisorGroup (*class in sage.schemes.toric.divisor*), 511
ToricIdeal (*class in sage.schemes.toric.ideal*), 561
ToricRationalDivisorClass (*class in sage.schemes.toric.divisor_class*), 539
ToricRationalDivisorClassGroup (*class in sage.schemes.toric.divisor*), 536
ToricRationalDivisorClassGroup_basis_lattice (*class in sage.schemes.toric.divisor*), 537
ToricVariety() (*in module sage.schemes.toric.variety*), 414
ToricVariety_field (*class in sage.schemes.toric.variety*), 416
ToricVarietyFactory (*class in sage.schemes.toric.library*), 485
torus() (*sage.schemes.toric.library.ToricVarietyFactory method*), 503
translation() (*sage.schemes.affine.affine_space.AffineSpace_field method*), 122
trivial_bundle() (*sage.schemes.toric.sheaf.constructor.SheafLibrary method*), 660
TrivialBundle() (*in module sage.schemes.toric.sheaf.constructor*), 661
type_of_point() (*sage.schemes.berkovich.berkovich_cp_element.Berkovich_Element_Cp method*), 717

U

union() (*sage.schemes.generic.algebraic_scheme.AlgebraicScheme_subscheme method*), 65
union() (*sage.schemes.generic.scheme.Scheme method*), 17
units() (*sage.schemes.toric.points.NaiveFinitePointEnumerator method*), 656

V

value_ring() (*sage.schemes.generic.homset.SchemeHomset_points method*), 81
variety() (*sage.schemes.toric.sheaf.klyachko.KlyachkoBundle_class method*), 677
veronese_embedding() (*sage.schemes.projective.projective_space.ProjectiveSpace_ring method*), 232
veronese_embedding() (*sage.schemes.projective.projective_subscheme.AlgebraicScheme_subscheme_projective method*), 327
volume_class() (*sage.schemes.toric.variety.ToricVariety_field method*), 451

W

wedge() (*sage.schemes.toric.sheaf.klyachko.KlyachkoBundle_class method*), 678
WeierstrassForm() (*in module sage.schemes.toric.weierstrass*), 617
WeierstrassForm2() (*in module sage.schemes.toric.weierstrass_higher*), 632
WeierstrassForm_P1xP1() (*in module sage.schemes.toric.weierstrass*), 620
WeierstrassForm_P2() (*in module sage.schemes.toric.weierstrass*), 621
WeierstrassForm_P2_112() (*in module sage.schemes.toric.weierstrass*), 621
WeierstrassForm_P3() (*in module sage.schemes.toric.weierstrass_higher*), 632
WeierstrassMap() (*in module sage.schemes.toric.weierstrass_covering*), 625
WeierstrassMap_P1xP1() (*in module sage.schemes.toric.weierstrass_covering*), 628
WeierstrassMap_P2() (*in module sage.schemes.toric.weierstrass_covering*), 629
WeierstrassMap_P2_112() (*in module sage.schemes.toric.weierstrass_covering*), 630

WeierstrassMap_P3() (*in module sage.schemes.toric.weierstrass_higher*), 633
weil_restriction() (*sage.schemes.affine.affine_morphism.SchemeMorphism_polynomial_affine_space_field method*), 155
weil_restriction() (*sage.schemes.affine.affine_point.SchemeMorphism_point_affine_field method*), 167
weil_restriction() (*sage.schemes.affine.affine_space.AffineSpace_field method*), 123
weil_restriction() (*sage.schemes.generic.algebraic_scheme.AlgebraicScheme_subscheme method*), 67
WP() (*sage.schemes.toric.library.ToricVarietyFactory method*), 500
wronskian_ideal() (*sage.schemes.projective.projective_morphism.SchemeMorphism_polynomial_projective_space method*), 259

X

X() (*sage.schemes.generic.algebraic_scheme.AlgebraicScheme_quasi method*), 43

Y

Y() (*sage.schemes.generic.algebraic_scheme.AlgebraicScheme_quasi method*), 43

Z

zero() (*sage.schemes.generic.homset.SchemeHomset_points method*), 81
zero() (*sage.schemes.projective.projective_homset.SchemeHomset_points_abelian_variety_field method*), 342
zeta_function() (*sage.schemes.generic.scheme.Scheme method*), 17
zeta_series() (*sage.schemes.generic.scheme.Scheme method*), 17