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1.1 Constructors for polynomial rings

This module provides the function `PolynomialRing()`, which constructs rings of univariate and multivariate polynomials, and implements caching to prevent the same ring being created in memory multiple times (which is wasteful and breaks the general assumption in Sage that parents are unique).

There is also a function `BooleanPolynomialRing_constructor()`, used for constructing Boolean polynomial rings, which are not technically polynomial rings but rather quotients of them (see module `sage.rings.polynomial.pbori` for more details).

```
sage: sage.rings.polynomial.polynomial_ring_constructor.BooleanPolynomialRing_constructor(n=None, names=None, order='lex')
```

Construct a boolean polynomial ring with the following parameters:

**INPUT:**

- n – number of variables (an integer > 1)
- names – names of ring variables, may be a string or list/tuple of strings
- order – term order (default: lex)

**EXAMPLES:**

```sage
sage: R.<x, y, z> = BooleanPolynomialRing() # indirect doctest
sage: R
Boolean PolynomialRing in x, y, z
sage: p = x*y + x*z + y*z
sage: x*p
x*y*z + x*y + x*z
sage: R.term_order()
Lexicographic term order

sage: R = BooleanPolynomialRing(5,'x',order='deglex(3),deglex(2)')
sage: R
Boolean PolynomialRing in x0, x1, x2, x3, x4
sage: R.term_order()
Block term order with blocks:
(Degree lexicographic term order of length 3,
 Degree lexicographic term order of length 2)
```

(continues on next page)
sage: R = BooleanPolynomialRing(3, 'x', order='degneglex')
sage: R.term_order()
Degree negative lexicographic term order
sage: BooleanPolynomialRing(names=('x', 'y'))
Boolean PolynomialRing in x, y
sage: BooleanPolynomialRing(names='x,y')
Boolean PolynomialRing in x, y

sage.rings.polynomial.polynomial_ring_constructor.PolynomialRing(base_ring, *args, **kwds)

Return the globally unique univariate or multivariate polynomial ring with given properties and variable name or names.

There are many ways to specify the variables for the polynomial ring:

1. PolynomialRing(base_ring, name, ...)
2. PolynomialRing(base_ring, names, ...)
3. PolynomialRing(base_ring, n, names, ...)
4. PolynomialRing(base_ring, n, ..., var_array=var_array, ...)

The ... at the end of these commands stands for additional keywords, like sparse or order.

INPUT:

- base_ring – a ring
- n – an integer
- name – a string
- names – a list or tuple of names (strings), or a comma separated string
- var_array – a list or tuple of names, or a comma separated string
- sparse – bool: whether or not elements are sparse. The default is a dense representation (sparse=False) for univariate rings and a sparse representation (sparse=True) for multivariate rings.
- order – string or TermOrder object, e.g.,
  - 'degrevlex' (default) – degree reverse lexicographic
  - 'lex' – lexicographic
  - 'deglex' – degree lexicographic
  - TermOrder('deglex',3) + TermOrder('deglex',3) – block ordering
- implementation – string or None; selects an implementation in cases where Sage includes multiple choices (currently \( \mathbb{Z}[x] \) can be implemented with 'NTL' or 'FLINT'; default is 'FLINT'). For many base rings, the "singular" implementation is available. One can always specify implementation="generic" for a generic Sage implementation which does not use any specialized library.

Note: If the given implementation does not exist for rings with the given number of generators and the given sparsity, then an error results.

OUTPUT:
PolynomialRing(base_ring, name, sparse=False) returns a univariate polynomial ring; also, PolynomialRing(base_ring, names, sparse=False) yields a univariate polynomial ring, if names is a list or tuple providing exactly one name. All other input formats return a multivariate polynomial ring.

UNIQUENESS and IMMUTABILITY: In Sage there is exactly one single-variate polynomial ring over each base ring in each choice of variable, sparseness, and implementation. There is also exactly one multivariate polynomial ring over each base ring for each choice of names of variables and term order. The names of the generators can only be temporarily changed after the ring has been created. Do this using the localvars context:

EXAMPLES:

1. PolynomialRing(base_ring, name, …)

```
sage: PolynomialRing(QQ, 'w')
Univariate Polynomial Ring in w over Rational Field
sage: PolynomialRing(QQ, name='w')
Univariate Polynomial Ring in w over Rational Field
```

Use the diamond brackets notation to make the variable ready for use after you define the ring:

```
sage: R.<w> = PolynomialRing(QQ)
sage: (1 + w)^3
w^3 + 3*w^2 + 3*w + 1
```

You must specify a name:

```
sage: PolynomialRing(QQ)
Traceback (most recent call last):
...  
TypeError: you must specify the names of the variables
sage: R.<abc> = PolynomialRing(QQ, sparse=True); R
Sparse Univariate Polynomial Ring in abc over Rational Field
sage: R.<w> = PolynomialRing(PolynomialRing(GF(7), 'k')); R
Univariate Polynomial Ring in w over Univariate Polynomial Ring in k over Finite Field of size 7
```

The square bracket notation:

```
sage: R.<y> = QQ['y']; R
Univariate Polynomial Ring in y over Rational Field
sage: y^2 + y
y^2 + y
```

In fact, since the diamond brackets on the left determine the variable name, you can omit the variable from the square brackets:

```
sage: R.<zz> = QQ[]; R
Univariate Polynomial Ring in zz over Rational Field
sage: (zz + 1)^2
zz^2 + 2*zz + 1
```

This is exactly the same ring as what PolynomialRing returns:

1.1. Constructors for polynomial rings
However, rings with different variables are different:

```
sage: QQ['x'] == QQ['y']
False
```

Sage has two implementations of univariate polynomials over the integers, one based on NTL and one based on FLINT. The default is FLINT. Note that FLINT uses a “more dense” representation for its polynomials than NTL, so in particular, creating a polynomial like $2^{1000000} \times x^{1000000}$ in FLINT may be unwise.

```
sage: ZxNTL = PolynomialRing(ZZ, 'x', implementation='NTL'); ZxNTL
Univariate Polynomial Ring in x over Integer Ring (using NTL)
sage: ZxFLINT = PolynomialRing(ZZ, 'x', implementation='FLINT'); ZxFLINT
Univariate Polynomial Ring in x over Integer Ring
sage: ZxFLINT is ZZ['x']
True
sage: ZxFLINT is PolynomialRing(ZZ, 'x')
True
sage: xNTL = ZxNTL.gen()
sage: xFLINT = ZxFLINT.gen()
sage: xNTL.parent()
Univariate Polynomial Ring in x over Integer Ring (using NTL)
sage: xFLINT.parent()
Univariate Polynomial Ring in x over Integer Ring
```

There is a coercion from the non-default to the default implementation, so the values can be mixed in a single expression:

```
sage: (xNTL + xFLINT^2)
x^2 + x
```

The result of such an expression will use the default, i.e., the FLINT implementation:

```
sage: (xNTL + xFLINT^2).parent()
Univariate Polynomial Ring in x over Integer Ring
```

The generic implementation uses neither NTL nor FLINT:

```
sage: Zx = PolynomialRing(ZZ, 'x', implementation='generic'); Zx
Univariate Polynomial Ring in x over Integer Ring
sage: Zx.element_class
<... 'sage.rings.polynomial.polynomial_element.Polynomial_generic_dense'>
```

2. PolynomialRing(base_ring, names,...)

```
sage: R = PolynomialRing(QQ, ['a','b','c']); R
Multivariate Polynomial Ring in a, b, c over Rational Field
sage: S = PolynomialRing(QQ, ['a','b','c']); S
Multivariate Polynomial Ring in a, b, c over Rational Field
```

(continues on next page)
sage: T = PolynomialRing(QQ, ('a','b','c')); T
Multivariate Polynomial Ring in a, b, c over Rational Field

All three rings are identical:

sage: R is S
True
sage: S is T
True

There is a unique polynomial ring with each term order:

sage: R = PolynomialRing(QQ, 'x,y,z', order='degrevlex'); R
Multivariate Polynomial Ring in x, y, z over Rational Field
sage: S = PolynomialRing(QQ, 'x,y,z', order='invlex'); S
Multivariate Polynomial Ring in x, y, z over Rational Field
sage: S is PolynomialRing(QQ, 'x,y,z', order='invlex')
True
sage: R == S
False

Note that a univariate polynomial ring is returned, if the list of names is of length one. If it is of length zero, a multivariate polynomial ring with no variables is returned.

sage: PolynomialRing(QQ, 'x')
Univariate Polynomial Ring in x over Rational Field
sage: PolynomialRing(QQ, [])
Multivariate Polynomial Ring in no variables over Rational Field

The Singular implementation always returns a multivariate ring, even for 1 variable:

sage: PolynomialRing(QQ, 'x', implementation="singular")
Multivariate Polynomial Ring in x over Rational Field
sage: P.<x> = PolynomialRing(QQ, implementation="singular"); P
Multivariate Polynomial Ring in x over Rational Field

3. PolynomialRing(base_ring, n, names, ...) (where the arguments n and names may be reversed)

If you specify a single name as a string and a number of variables, then variables labeled with numbers are created.

sage: PolynomialRing(QQ, 'x', 10)
Multivariate Polynomial Ring in x0, x1, x2, x3, x4, x5, x6, x7, x8, x9 over Rational Field
sage: PolynomialRing(QQ, 2, 'alpha0')
Multivariate Polynomial Ring in alpha00, alpha01 over Rational Field
sage: PolynomialRing(GF(7), 'y', 5)
Multivariate Polynomial Ring in y0, y1, y2, y3, y4 over Finite Field of size 7
sage: PolynomialRing(QQ, 'y', 3, sparse=True)
Multivariate Polynomial Ring in y0, y1, y2 over Rational Field

1.1. Constructors for polynomial rings
Note that a multivariate polynomial ring is returned when an explicit number is given.

```sage
sage: PolynomialRing(QQ,"x",1)
Multivariate Polynomial Ring in x over Rational Field
sage: PolynomialRing(QQ,"x",0)
Multivariate Polynomial Ring in no variables over Rational Field
```

It is easy in Python to create fairly arbitrary variable names. For example, here is a ring with generators labeled by the primes less than 100:

```sage
sage: R = PolynomialRing(ZZ, ['x%s'%%p for p in primes(100)]); R
Multivariate Polynomial Ring in x2, x3, x5, x7, x11, x13, x17, x19, x23, x29, x31, \rightarrow x37, x41, x43, x47, x53, x59, x61, x67, x71, x73, x79, x83, x89, x97 over Integer \rightarrow Ring
```

By calling the `inject_variables()` method, all those variable names are available for interactive use:

```sage
sage: R.inject_variables()
Defining x2, x3, x5, x7, x11, x13, x17, x19, x23, x29, x31, \rightarrow x37, x41, x43, x47, x53, x59, x61, x67, x71, x73, x79, x83, x89, x97
sage: (x2 + x41 + x71)^2
x2^2 + 2*x2*x41 + x41^2 + 2*x2*x71 + 2*x41*x71 + x71^2
```

4. PolynomialRing(base_ring, n, ..., var_array=var_array, ...)

This creates an array of variables where each variables begins with an entry in `var_array` and is indexed from 0 to `n - 1`.

```sage
sage: PolynomialRing(ZZ, 3, var_array=['x', 'y'])
Multivariate Polynomial Ring in x0, y0, x1, y1, x2, y2 over Integer Ring
sage: PolynomialRing(ZZ, 3, var_array='a,b')
Multivariate Polynomial Ring in a0, b0, a1, b1, a2, b2 over Integer Ring
```

It is possible to create higher-dimensional arrays:

```sage
sage: PolynomialRing(ZZ, 2, 3, var_array=('p', 'q'))
Multivariate Polynomial Ring in p00, q00, p01, q01, p02, q02, p10, q10, p11, q11, \rightarrow p12, q12 over Integer Ring
sage: PolynomialRing(ZZ, 2, 3, 4, var_array='m')
Multivariate Polynomial Ring in m000, m001, m002, m003, m010, m011, m012, m013, \rightarrow m020, m021, m022, m023, m100, m101, m102, m103, m110, m111, m112, m113, m120, \rightarrow m121, m122, m123 over Integer Ring
```

The array is always at least 2-dimensional. So, if `var_array` is a single string and only a single number `n` is given, this creates an `n x n` array of variables:

```sage
sage: PolynomialRing(ZZ, 2, var_array='m')
Multivariate Polynomial Ring in m00, m01, m10, m11 over Integer Ring
```

**Square brackets notation**

You can alternatively create a polynomial ring over a ring $R$ with square brackets:

```sage
sage: RR["x"]
Univariate Polynomial Ring in x over Real Field with 53 bits of precision
sage: RR["x,y"]
```

(continues on next page)
Multivariate Polynomial Ring in x, y over Real Field with 53 bits of precision

```
sage: P.<x,y> = RR[]; P
```
Multivariate Polynomial Ring in x, y over Real Field with 53 bits of precision

This notation does not allow to set any of the optional arguments.

**Changing variable names**

Consider

```
sage: R.<x,y> = PolynomialRing(QQ,2); R
```
Multivariate Polynomial Ring in x, y over Rational Field

```
sage: f = x^2 - 2*y^2
```

You can’t just globally change the names of those variables. This is because objects all over Sage could have pointers to that polynomial ring.

```
sage: R._assign_names(['z', 'w'])
Traceback (most recent call last):
  ...
ValueError: variable names cannot be changed after object creation.
```

However, you can very easily change the names within a `with` block:

```
sage: with localvars(R, ['z', 'w']):
    print(f)
z^2 - 2*w^2
```

After the `with` block the names revert to what they were before:

```
sage: print(f)
x^2 - 2*y^2
```

`sage.rings.polynomial.polynomial_ring_constructor.polynomial_default_category(n_variables)`

Choose an appropriate category for a polynomial ring.

It is assumed that the corresponding base ring is nonzero.

**INPUT:**

- `base_ring_category` – The category of ring over which the polynomial ring shall be defined
- `n_variables` – number of variables

**EXAMPLES:**

```
sage: from sage.rings.polynomial.polynomial_ring_constructor import polynomial_default_category
```

```
sage: polynomial_default_category(Rings(),1) is Algebras(Rings()).Infinite()
True
```

```
sage: polynomial_default_category(Rings().Commutative(),1) is Algebras(Rings().Commutative()).Infinite()
True
```

```
sage: polynomial_default_category(Fields(),1) is EuclideanDomains() &<
    Algebras(Fields()).Infinite()
True
```

1.1. Constructors for polynomial rings
sage: polynomial_default_category(Fields(),2) is UniqueFactorizationDomains() \&␣
    \rightarrow CommutativeAlgebras(Fields()).Infinite()
True

sage: QQ['t'].category() is EuclideanDomains() \& CommutativeAlgebras(QQ.category()).\rightarrow Infinite()
True

sage: QQ['s','t'].category() is UniqueFactorizationDomains() \&
    \rightarrow CommutativeAlgebras(QQ.category()).Infinite()
True

sage: QQ['s'][['t']].category() is UniqueFactorizationDomains() \&
    \rightarrow CommutativeAlgebras(QQ['s'].category()).Infinite()
True

sage.rings.polynomial.polynomial_ring_constructor.unpickle_PolynomialRing(base_ring,
    arg1=None,
    arg2=None,
    sparse=False)

Custom unpickling function for polynomial rings.

This has the same positional arguments as the old PolynomialRing constructor before github issue #23338.
2.1 Univariate Polynomials and Polynomial Rings

Sage’s architecture for polynomials ‘under the hood’ is complex, interfacing to a variety of C/C++ libraries for polynomials over specific rings. In practice, the user rarely has to worry about which backend is being used.

The hierarchy of class inheritance is somewhat confusing, since most of the polynomial element classes are implemented as Cython extension types rather than pure Python classes and thus can only inherit from a single base class, whereas others have multiple bases.

2.1.1 Univariate Polynomial Rings

Sage implements sparse and dense polynomials over commutative and non-commutative rings. In the non-commutative case, the polynomial variable commutes with the elements of the base ring.

AUTHOR:

• William Stein
• Kiran Kedlaya (2006-02-13): added macaulay2 option
• Martin Albrecht (2006-08-25): removed it again as it isn’t needed anymore
• Simon King (2011-05): Dense and sparse polynomial rings must not be equal.
• Simon King (2011-10): Choice of categories for polynomial rings.

EXAMPLES:

```
sage: z = QQ['z'].0
sage: (z^3 + z - 1)^3
z^9 + 3*z^7 - 3*z^6 + 3*z^5 - 6*z^4 + 4*z^3 - 3*z^2 + 3*z - 1
```

Saving and loading of polynomial rings works:

```
sage: loads(dumps(QQ['x'])) == QQ['x']
True
sage: k = PolynomialRing(QQ['x','y']); loads(dumps(k))==k
True
sage: k = PolynomialRing(ZZ,'y'); loads(dumps(k)) == k
True
sage: k = PolynomialRing(ZZ,'y', sparse=True); loads(dumps(k))
Sparse Univariate Polynomial Ring in y over Integer Ring
```
Rings with different variable names are not equal; in fact, by github issue #9944, polynomial rings are equal if and only if they are identical (which should be the case for all parent structures in Sage):

\[
sage: \ QQ[\ 'y'] \neq \ QQ[\ 'x'] \\
\text{True}
\]
\[
sage: \ QQ[\ 'y'] \neq \ QQ[\ 'z'] \\
\text{True}
\]

We create a polynomial ring over a quaternion algebra:

\[
sage: \ A.\langle i,j,k\rangle \ = \ QuaternionAlgebra(QQ, \ -1,-1) \\
sage: \ R.\langle w\rangle \ = \ PolynomialRing(A,\text{sparse=True}) \\
sage: \ f \ = \ w^3 + (i+j)\cdot w + 1 \\
sage: \ f \\
w^3 + (i + j)\cdot w + 1 \\
sage: \ f^2 \\
w^6 + (2i + 2j)\cdot w^4 + 2w^3 - 2w^2 + (2i + 2j)\cdot w + 1 \\
sage: \ f \ = \ w + i; \ g \ = \ w + j \\
sage: \ f \cdot g \\
w^2 + (i + j)\cdot w + k \\
sage: \ g \cdot f \\
w^2 + (i + j)\cdot w - k
\]

\[
\text{github issue #9944 introduced some changes related with coercion. Previously, a dense and a sparse polynomial ring with the same variable name over the same base ring evaluated equal, but of course they were not identical. Coercion maps are cached - but if a coercion to a dense ring is requested and a coercion to a sparse ring is returned instead (since the cache keys are equal!), all hell breaks loose.}
\]

Therefore, the coercion between rings of sparse and dense polynomials works as follows:

\[
sage: \ R.\langle x\rangle \ = \ PolynomialRing(QQ, \text{sparse=True}) \\
sage: \ S.\langle x\rangle \ = \ QQ[] \\
sage: \ S \ == \ R \\
\text{False} \\
sage: \ S.\text{has_coerce_map_from}(R) \\
\text{True} \\
sage: \ R.\text{has_coerce_map_from}(S) \\
\text{False} \\
sage: \ (R.\langle 0\rangle + S.\langle 0\rangle)\cdot \text{parent()} \\
Univariate Polynomial Ring in x over Rational Field \\
sage: \ (S.\langle 0\rangle + R.\langle 0\rangle)\cdot \text{parent()} \\
Univariate Polynomial Ring in x over Rational Field
\]

It may be that one has rings of dense or sparse polynomials over different base rings. In that situation, coercion works by means of the \texttt{pushout()} formalism:

\[
sage: \ R.\langle x\rangle \ = \ PolynomialRing(GF(5), \text{sparse=True}) \\
sage: \ S.\langle x\rangle \ = \ PolynomialRing(ZZ) \\
sage: \ S.\text{has_coerce_map_from}(S) \\
\text{False} \\
sage: \ S.\text{has_coerce_map_from}(R) \\
\text{False} \\
sage: \ S.\langle 0\rangle + R.\langle 0\rangle \\
2\cdot x \\
sage: \ (S.\langle 0\rangle + R.\langle 0\rangle)\cdot \text{parent()} \\
\text{(continues on next page)}
\]
Similarly, there is a coercion from the (non-default) NTL implementation for univariate polynomials over the integers to the default FLINT implementation, but not vice versa:

```python
sage: R.<x> = PolynomialRing(ZZ, implementation='NTL')
sage: S.<x> = PolynomialRing(ZZ, implementation='FLINT')
sage: (S.0+R.0).parent() is S
True
sage: (R.0+S.0).parent() is S
True
```

```python
class sage.rings.polynomial.polynomial_ring.PolynomialRing_cdvf(base_ring, name=None, sparse=False, implementation=None, element_class=None, category=None):
    Bases: PolynomialRing_cdvr, PolynomialRing_field
    
    A class for polynomial ring over complete discrete valuation fields

class sage.rings.polynomial.polynomial_ring.PolynomialRing_cdvr(base_ring, name=None, sparse=False, implementation=None, element_class=None, category=None):
    Bases: PolynomialRing_integral_domain
    
    A class for polynomial ring over complete discrete valuation rings

class sage.rings.polynomial.polynomial_ring.PolynomialRing_commutative(base_ring, name=None, sparse=False, implementation=None, element_class=None, category=None):
    Bases: PolynomialRing_general, CommutativeAlgebra

    Univariate polynomial ring over a commutative ring.

    quotient_by_principal_ideal(f, names=None, **kwds)
    
    Return the quotient of this polynomial ring by the principal ideal (generated by) \( f \).
    
    INPUT:
    
    - \( f \) - either a polynomial in \( \text{self} \), or a principal ideal of \( \text{self} \).
    
    - further named arguments that are passed to the quotient constructor.
    
    EXAMPLES:

    ```python
    sage: R.<x> = QQ[]
sage: I = (x^2-1)^R
    sage: R.quotient_by_principal_ideal(I)
    Univariate Quotient Polynomial Ring in xbar over Rational Field with modulus x^2 - 1
    ```
```
The same example, using the polynomial instead of the ideal, and customizing the variable name:

```
sage: R.<x> = QQ[]
sage: R.quotient_by_principal_ideal(x^2-1, names=('foo',))
Univariate Quotient Polynomial Ring in foo over Rational Field with modulus x^2 - 1
```

```
weyl_algebra()

Return the Weyl algebra generated from self.

EXAMPLES:

```
sage: R = QQ['x']
sage: W = R.weyl_algebra(); W
Differential Weyl algebra of polynomials in x over Rational Field
sage: W.polynomial_ring() == R
True
```
```
class sage.rings.polynomial.polynomial_ring.PolynomialRing_dense_finite_field(base_ring, name='x', element_class=None, implementation=None, with_category=True)

Bases: PolynomialRing_field

Univariate polynomial ring over a finite field.

EXAMPLES:

```
sage: R = PolynomialRing(GF(27, 'a'), 'x')
sage: type(R)
<class 'sage.rings.polynomial.polynomial_ring.PolynomialRing_dense_finite_field_with_category'>
```
```
irreducible_element(n, algorithm=None)

Construct a monic irreducible polynomial of degree n.

INPUT:

- n – integer: degree of the polynomial to construct
- algorithm – string: algorithm to use, or None
  - 'random' or None: try random polynomials until an irreducible one is found.
  - 'first_lexicographic': try polynomials in lexicographic order until an irreducible one is found.

OUTPUT:

A monic irreducible polynomial of degree n in self.

EXAMPLES:

```
sage: f = GF(5^3, 'a')['x'].irreducible_element(2)
sage: f.degree()
2
sage: f.is_irreducible()
True
```
AUTHORS:

• Peter Bruin (June 2013)
• Jean-Pierre Flori (May 2014)

class sage.rings.polynomial.polynomial_ring.PolynomialRing_dense_mod_n(base_ring, name=None, element_class=None, implementation=None, category=None)

Bases: PolynomialRing_commutative

modulus()

EXAMPLES:

sage: R.<x> = Zmod(15)[]
sage: R.modulus()
15

residue_field(ideal, names=None)

Return the residue finite field at the given ideal.

EXAMPLES:

sage: R.<t> = GF(2)[]
sage: k.<a> = R.residue_field(t^3+t+1); k
Residue field in a of Principal ideal (t^3 + t + 1) of Univariate Polynomial Ring in t over Finite Field of size 2 (using GF2X)
sage: k.list()
[0, a, a^2, a + 1, a^2 + a, a^2 + a + 1, a^2 + 1, 1]
sage: R.residue_field(t)
Residue field of Principal ideal (t) of Univariate Polynomial Ring in t over Finite Field of size 2 (using GF2X)
sage: P = R.irreducible_element(8) * R
sage: P
Principal ideal (t^8 + t^4 + t^3 + t^2 + 1) of Univariate Polynomial Ring in t over Finite Field of size 2 (using GF2X)
sage: k.<a> = R.residue_field(P); k
Residue field in a of Principal ideal (t^8 + t^4 + t^3 + t^2 + 1) of Univariate Polynomial Ring in t over Finite Field of size 2 (using GF2X)
sage: k.cardinality()
256

Non-maximal ideals are not accepted:

sage: R.residue_field(t^2 + 1)
Traceback (most recent call last):...

(continues on next page)
class sage.rings.polynomial.polynomial_ring.PolynomialRing_dense_mod_p(base_ring, name='x',
implementation=None, element_class=None, category=None)

irreducible_element(n, algorithm=None)

Construct a monic irreducible polynomial of degree \( n \).

INPUT:

- \( n \) – integer: the degree of the polynomial to construct
- \( \text{algorithm} \) – string: algorithm to use, or None. Currently available options are:
  - 'adleman-lenstra': a variant of the Adleman–Lenstra algorithm as implemented in PARI.
  - 'conway': look up the Conway polynomial of degree \( n \) over the field of \( p \) elements in the database; raise a RuntimeError if it is not found.
  - 'ffprimroot': use the ffprimroot() function from PARI.
  - 'first_lexicographic': return the lexicographically smallest irreducible polynomial of degree \( n \).
  - 'minimal_weight': return an irreducible polynomial of degree \( n \) with minimal number of non-zero coefficients. Only implemented for \( p = 2 \).
  - 'primitive': return a polynomial \( f \) such that a root of \( f \) generates the multiplicative group of the finite field extension defined by \( f \). This uses the Conway polynomial if possible, otherwise it uses ffprimroot.
  - 'random': try random polynomials until an irreducible one is found.

If \( \text{algorithm} \) is None, use \( x - 1 \) in degree 1. In degree > 1, the Conway polynomial is used if it is found in the database. Otherwise, the algorithm minimal_weight is used if \( p = 2 \), and the algorithm adleman-lenstra if \( p > 2 \).

OUTPUT:

A monic irreducible polynomial of degree \( n \) in self.

EXAMPLES:

```python
sage: GF(5)['x'].irreducible_element(2)
x^2 + 4*x + 2
sage: GF(5)['x'].irreducible_element(2, algorithm="adleman-lenstra")
```
Polynomials, Release 10.0

x^2 + x + 1

sage: GF(5)['x'].irreducible_element(2, algorithm="primitive")
x^2 + 4*x + 2

sage: GF(5)['x'].irreducible_element(32, algorithm="first_lexicographic")
x^32 + 2

sage: GF(5)['x'].irreducible_element(32, algorithm="conway")
Traceback (most recent call last):
...
RuntimeError: requested Conway polynomial not in database.

sage: GF(5)['x'].irreducible_element(32, algorithm="primitive")
x^32 + ...

In characteristic 2:

sage: GF(2)['x'].irreducible_element(33)
x^33 + x^13 + x^12 + x^11 + x^10 + x^8 + x^6 + x^3 + 1

sage: GF(2)['x'].irreducible_element(33, algorithm="minimal_weight")
x^33 + x^10 + 1

In degree 1:

sage: GF(97)['x'].irreducible_element(1)
x + 96

sage: GF(97)['x'].irreducible_element(1, algorithm="conway")
x + 92

sage: GF(97)['x'].irreducible_element(1, algorithm="adleman-lenstra")
x

AUTHORS:

• Peter Bruin (June 2013)

• Jeroen Demeyer (September 2014): add “ffprimroot” algorithm, see github issue #8373.
class sage.rings.polynomial.polynomial_ring.PolynomialRing_dense_padic_field_generic(base_ring, name=None, implementation=None, element_class=None, category=None)

Bases: PolynomialRing_cdvf

A class for dense polynomial ring over p-adic fields

class sage.rings.polynomial.polynomial_ring.PolynomialRing_dense_padic_ring_capped_absolute(base_ring, name=None, implementation=None, element_class=None, category=None)

Bases: PolynomialRing_dense_padic_ring_generic

class sage.rings.polynomial.polynomial_ring.PolynomialRing_dense_padic_ring_capped_relative(base_ring, name=None, implementation=None, element_class=None, category=None)

Bases: PolynomialRing_dense_padic_ring_generic
class sage.rings.polynomial.polynomial_ring.PolynomialRing_dense_padic_ring_fixed_mod:
    Bases: PolynomialRing_dense_padic_ring_generic

class sage.rings.polynomial.polynomial_ring.PolynomialRing_dense_padic_ring_generic:
    Bases: PolynomialRing_cdvr

A class for dense polynomial ring over padic rings

class sage.rings.polynomial.polynomial_ring.PolynomialRing_field:
    Bases: PolynomialRing_integral_domain, PrincipalIdealDomain

divided_difference(points, full_table=False)

Return the Newton divided-difference coefficients of the Lagrange interpolation polynomial through points.

INPUT:

• points – a list of pairs \((x_0, y_0), (x_1, y_1), \ldots, (x_n, y_n)\) of elements of the base ring of self, where \(x_i - x_j\) is invertible for \(i \neq j\). This method converts the \(x_i\) and \(y_i\) into the base ring of self.

• full_table – boolean (default: False): If True, return the full divided-difference table. If False, only return entries along the main diagonal; these are the Newton divided-difference coefficients \(F_{i,i}\).

OUTPUT:

The Newton divided-difference coefficients of the \(n\)-th Lagrange interpolation polynomial \(P_n(x)\) that passes through the points in points (see lagrange_polynomial()). These are the coefficients \(F_{0,0}, F_{1,1}, \ldots, F_{n,n}\) in the base ring of self such that

\[
P_n(x) = \sum_{i=0}^{n} F_{i,i} \prod_{j=0}^{i-1} (x - x_j)
\]

EXAMPLES:
Only return the divided-difference coefficients $F_{i,i}$. This example is taken from Example 1, page 121 of [BF2005]:

```python
sage: points = [(1.0, 0.7651977), (1.3, 0.6200860), (1.6, 0.4554022), (1.9, 0.2818186), (2.2, 0.1103623)]
sage: R = PolynomialRing(RR, "x")
sage: R.divided_difference(points)
[0.765197700000000,
-0.483705666666666,
-0.108733888888889,
0.0658783950617283,
0.00182510288066044]
```

Now return the full divided-difference table:

```python
sage: points = [(1.0, 0.7651977), (1.3, 0.6200860), (1.6, 0.4554022), (1.9, 0.2818186), (2.2, 0.1103623)]
sage: R = PolynomialRing(RR, "x")
sage: R.divided_difference(points, full_table=True)
[[0.765197700000000],
[0.620086000000000, -0.483705666666666],
[0.455402200000000, -0.548946000000000, -0.108733888888889],
[0.281818600000000, -0.578612000000000, -0.049443333333339],
[0.110362300000000, -0.571520999999999, 0.011818333333349],
[0.0658783950617283, 0.0680685185185209],
[0.00182510288066044]]
```

The following example is taken from Example 4.12, page 225 of [MF1999]:

```python
sage: points = [(1, -3), (2, 0), (3, 15), (4, 48), (5, 105), (6, 192)]
sage: R = PolynomialRing(QQ, "x")
sage: R.divided_difference(points)
[-3, 3, 6, 1, 0, 0]
sage: R.divided_difference(points, full_table=True)
[[-3],
[0, 3],
[15, 15, 6],
[48, 33, 9, 1],
[105, 57, 12, 1, 0],
[192, 87, 15, 1, 0, 0]]
```

```
fraction_field()
```

Returns the fraction field of self.

**EXAMPLES:**

```python
sage: R.<t> = GF(5)[]
sage: R.fraction_field()
Fraction Field of Univariate Polynomial Ring in t over Finite Field of size 5
```

---

**Chapter 2. Univariate Polynomials**
Return the Lagrange interpolation polynomial through the given points.

INPUT:

- `points` -- a list of pairs \((x_0, y_0), (x_1, y_1), \ldots, (x_n, y_n)\) of elements of the base ring of `self`, where \(x_i - x_j\) is invertible for \(i \neq j\). This method converts the \(x_i\) and \(y_i\) into the base ring of `self`.

- `algorithm` -- (default: `divided_difference`): one of the following:
  - `'divided_difference'`: use the method of divided differences.
  - `'neville'`: adapt Neville’s method as described on page 144 of [BF2005] to recursively generate the Lagrange interpolation polynomial. Neville’s method generates a table of approximating polynomials, where the last row of that table contains the \(n\)-th Lagrange interpolation polynomial. The adaptation implemented by this method is to only generate the last row of this table, instead of the full table itself. Generating the full table can be memory inefficient.

- `previous_row` -- (default: `None`): This option is only relevant if used with `algorithm='neville'`. If provided, this should be the last row of the table resulting from a previous use of Neville’s method. If such a row is passed, then `points` should consist of both previous and new interpolating points. Neville’s method will then use that last row and the interpolating points to generate a new row containing an interpolation polynomial for the new points.

OUTPUT:

The Lagrange interpolation polynomial through the points \((x_0, y_0), (x_1, y_1), \ldots, (x_n, y_n)\). This is the unique polynomial \(P_n\) of degree at most \(n\) in `self` satisfying \(P_n(x_i) = y_i\) for \(0 \leq i \leq n\).

EXAMPLES:

By default, we use the method of divided differences:

```
sage: R = PolynomialRing(QQ, 'x')
sage: f = R.lagrange_polynomial([[0,1],[2,2],[3,-2],[-4,9]]); f
-23/84*x^3 - 11/84*x^2 + 13/7*x + 1
sage: f(0)
1
sage: f(2)
2
sage: f(3)
-2
sage: f(-4)
9

sage: R = PolynomialRing(GF(2**3, 'a'), 'x')
sage: a = R.base_ring().gen()
sage: f = R.lagrange_polynomial([[a^2+a,a],[a,1],[a^2,a^2+a+1]]); f
a^2*x^2 + a^2*x + a^2
sage: f(a^2+a)
a
sage: f(a)
1
sage: f(a^2)
a^2 + a + 1
```

Now use a memory efficient version of Neville’s method:
sage: R = PolynomialRing(QQ, 'x')
sage: R.lagrange_polynomial([(0,1),(2,2),(3,-2),(-4,9)], algorithm="neville")
[9,
-11/7*x + 19/7,
-17/42*x^2 - 83/42*x + 53/7,
-23/84*x^3 - 11/84*x^2 + 13/7*x + 1]
sage: R = PolynomialRing(GF(2**3, 'a'), 'x')
sage: a = R.base_ring().gen()
sage: R.lagrange_polynomial([(a^2+a,a),(a,1),(a^2,a^2+a+1)], algorithm="neville")
[a^2 + a + 1, x + a + 1, a^2*x^2 + a^2*x + a^2]

Repeated use of Neville’s method to get better Lagrange interpolation polynomials:

sage: p = R.lagrange_polynomial([(0,1),(2,2)], algorithm="neville")
sage: R.lagrange_polynomial([(0,1),(2,2),(3,-2),(-4,9)], algorithm="neville", previous_row=p)[-1]
-23/84*x^3 - 11/84*x^2 + 13/7*x + 1
sage: p = R.lagrange_polynomial([(a^2+a,a),(a,1)], algorithm="neville")
sage: R.lagrange_polynomial([(a^2+a,a),(a,1),(a^2,a^2+a+1)], algorithm="neville", previous_row=p)[-1]
a^2*x^2 + a^2*x + a^2

class sage.rings.polynomial.polynomial_ring.PolynomialRing_general(base_ring, name=None, sparse=False, implementation=None, element_class=None, category=None)

Bases: Algebra

Univariate polynomial ring over a ring.

base_extend(R)

Return the base extension of this polynomial ring to R.

EXAMPLES:

sage: R.<x> = RR[]; R
Univariate Polynomial Ring in x over Real Field with 53 bits of precision
sage: R.base_extend(CC)
Univariate Polynomial Ring in x over Complex Field with 53 bits of precision
sage: R.base_extend(QQ)
Traceback (most recent call last):
...
TypeError: no such base extension
sage: R.change_ring(QQ)
Univariate Polynomial Ring in x over Rational Field

change_ring(R)

Return the polynomial ring in the same variable as self over R.

EXAMPLES:
sage: R.<ZZZ> = RealIntervalField(); R
Univariate Polynomial Ring in ZZZ over Real Interval Field with 53 bits of
→precision
sage: R.change_ring(GF(19^2, 'b'))
Univariate Polynomial Ring in ZZZ over Finite Field in b of size 19^2

**change_var(var)**

Return the polynomial ring in variable var over the same base ring.

**EXAMPLES:**

```
sage: R.<x> = ZZ[]; R
Univariate Polynomial Ring in x over Integer Ring
sage: R.change_var('y')
Univariate Polynomial Ring in y over Integer Ring
```

**characteristic()**

Return the characteristic of this polynomial ring, which is the same as that of its base ring.

**EXAMPLES:**

```
sage: R.<ZZZ> = RealIntervalField(); R
Univariate Polynomial Ring in ZZZ over Real Interval Field with 53 bits of
→precision
sage: R.characteristic()
0
sage: S = R.change_ring(GF(19^2, 'b')); S
Univariate Polynomial Ring in ZZZ over Finite Field in b of size 19^2
sage: S.characteristic()
19
```

**completion(p=None, prec=20, extras=None)**

Return the completion of self with respect to the irreducible polynomial p.

Currently only implemented for p=self.gen() (the default), i.e. you can only complete \( R[x] \) with respect to \( x \), the result being a ring of power series in \( x \). The `prec` variable controls the precision used in the power series ring. If `prec` is \( \infty \), then this returns a `LazyPowerSeriesRing`.

**EXAMPLES:**

```
sage: P.<x> = PolynomialRing(QQ)
sage: P
Univariate Polynomial Ring in x over Rational Field
sage: PP = P.completion(x)
sage: PP
Power Series Ring in x over Rational Field
sage: f = 1 - x
sage: PP(f)
1 - x
sage: 1 / f
-1/(x - 1)
sage: g = 1 / PP(f); g
1 + x + x^2 + x^3 + x^4 + x^5 + x^6 + x^7 + x^8 + x^9 + x^10 + x^11
+ x^12 + x^13 + x^14 + x^15 + x^16 + x^17 + x^18 + x^19 + O(x^20)
sage: 1 / g
```

(continues on next page)
$1 - x + O(x^{20})$

```sage```
PP = P.completion(x, prec=oo); PP
```
Lazy Taylor Series Ring in x over Rational Field
```
```sage```
g = 1 / PP(f); g
```
1 + x + x^2 + O(x^3)
```
```sage```
1 / g == f
```
True
```

### construction()

Return the construction functor.

### cyclotomic_polynomial(n)

Return the $n$th cyclotomic polynomial as a polynomial in this polynomial ring. For details of the implementation, see the documentation for `sage.rings.polynomial.cyclotomic.cyclotomic_coeffs()`.

**EXAMPLES:**

```sage```
R = ZZ['x']; R
```
Univariate Polynomial Ring in x over Integer Ring
```
```sage```
R.cyclotomic_polynomial(8)
```
x^4 + 1
```
```sage```
R.cyclotomic_polynomial(12)
```
x^4 - x^2 + 1
```
```sage```
S = PolynomialRing(FiniteField(7), 'x'); S
```
```
```sage```
S.cyclotomic_polynomial(12)
```
x^4 + 6*x^2 + 1
```
```sage```
S.cyclotomic_polynomial(1)
```
x + 6
```

### extend_variables(added_names, order='degrevlex')

Returns a multivariate polynomial ring with the same base ring but with added_names as additional variables.

**EXAMPLES:**

```sage```
R.<x> = ZZ[]; R
```
Univariate Polynomial Ring in x over Integer Ring
```
```sage```
R.extend_variables(('y', 'z'))
```
Multivariate Polynomial Ring in x, y, z over Integer Ring
```
```sage```
R.extend_variables(('y', 'z'))
```
Multivariate Polynomial Ring in x, y, z over Integer Ring
```

### flattening_morphism()

Return the flattening morphism of this polynomial ring

**EXAMPLES:**

```sage```
QQ['a','b']['x'].flattening_morphism()
```
Flattening morphism:
  From: Univariate Polynomial Ring in x over Multivariate Polynomial Ring in a,b over Rational Field
  To:   Multivariate Polynomial Ring in a, b, x over Rational Field
sage: QQ['x'].flattening_morphism()
Identity endomorphism of Univariate Polynomial Ring in x over Rational Field

gen($n=0$)
Return the indeterminate generator of this polynomial ring.

EXAMPLES:

sage: R.<abc> = Integers(8)[]; R
Univariate Polynomial Ring in abc over Ring of integers modulo 8
sage: t = R.gen(); t
abc
sage: t.is_gen()
True

An identical generator is always returned.

sage: t is R.gen()
True

gens_dict()
Return a dictionary whose entries are {name:variable,...}, where name stands for the variable names of this object (as strings) and variable stands for the corresponding generators (as elements of this object).

EXAMPLES:

sage: R.<y,x,a42> = RR[]
Rings:
R.<y,x,a42> = RR[]
\{ 'a42': a42, 'x': x, 'y': y \}

is_exact()
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: a.f()  # Doctest: +NORMALIZE_WHITESPACE
4
sage: a.f.cache
4

is_field(proof=True)
Return False, since polynomial rings are never fields.

EXAMPLES:
Polynomials, Release 10.0

```sage
sage: R.<z> = Integers(2)[]; R
Univariate Polynomial Ring in z over Ring of integers modulo 2 (using GF2X)
sage: R.is_field()
False
```

**is_integral_domain**(proof=True)

EXAMPLES:

```sage
sage: ZZ['x'].is_integral_domain()
True
sage: Integers(8)['x'].is_integral_domain()
False
```

**is_noetherian**

**is_sparse**

Return true if elements of this polynomial ring have a sparse representation.

EXAMPLES:

```sage
sage: R.<z> = Integers(8)[]; R
Univariate Polynomial Ring in z over Ring of integers modulo 8
sage: R.is_sparse()
False
sage: R.<W> = PolynomialRing(QQ, sparse=True); R
Sparse Univariate Polynomial Ring in W over Rational Field
sage: R.is_sparse()
True
```

**is_unique_factorization_domain**(proof=True)

EXAMPLES:

```sage
sage: ZZ['x'].is_unique_factorization_domain()
True
sage: Integers(8)['x'].is_unique_factorization_domain()
False
```

**karatsuba_threshold**

Return the Karatsuba threshold used for this ring by the method _mul_karatsuba to fall back to the schoolbook algorithm.

EXAMPLES:

```sage
sage: K = QQ['x']
sage: K.karatsuba_threshold()
8
sage: K = QQ['x']['y']
sage: K.karatsuba_threshold()
0
```

**krull_dimension**

Return the Krull dimension of this polynomial ring, which is one more than the Krull dimension of the base ring.

EXAMPLES:
Polynomials, Release 10.0

```sage
sage: R.<x> = QQ[]
sage: R.krull_dimension()
1
sage: R.<z> = GF(9, 'a')[]; R
Univariate Polynomial Ring in z over Finite Field in a of size 3^2
sage: R.krull_dimension()
1
sage: S.<t> = R[]
sage: S.krull_dimension()
2
sage: for n in range(10):
....:     S = PolynomialRing(S, 'w')
....: sage: S.krull_dimension()
12

monics(of_degree=None, max_degree=None)

Return an iterator over the monic polynomials of specified degree.

INPUT: Pass exactly one of:
  • max_degree - an int; the iterator will generate all monic polynomials which have degree less than or equal to max_degree
  • of_degree - an int; the iterator will generate all monic polynomials which have degree of_degree

OUTPUT: an iterator

EXAMPLES:
```
```sage
sage: P = PolynomialRing(GF(4, 'a'), 'y')
sage: for p in P.monics( of_degree = 2 ): print(p)
y^2
y^2 + a
y^2 + a + 1
y^2 + 1
y^2 + a*y
y^2 + a*y + a
y^2 + a*y + a + 1
y^2 + a*y + 1
y^2 + (a + 1)*y
y^2 + (a + 1)*y + a
y^2 + (a + 1)*y + a + 1
y^2 + (a + 1)*y + 1
y^2 + y
y^2 + y + a
y^2 + y + a + 1
y^2 + y + 1
sage: for p in P.monics( max_degree = 1 ): print(p)
1
y
y + a
y + a + 1
y + 1
sage: for p in P.monics( max_degree = 1, of_degree = 3 ): print(p)
Traceback (most recent call last):...
```
monomial(exponent)

Return the monomial with the exponent.

INPUT:

• exponent – nonnegative integer

EXAMPLES:

```
sage: R.<x> = PolynomialRing(ZZ)
sage: R.monomial(5)
x^5
sage: e=(10,)
sage: R.monomial(*e)
x^10
sage: m = R.monomial(100)
sage: R.monomial(m.degree()) == m
True
```

ngens()

Return the number of generators of this polynomial ring, which is 1 since it is a univariate polynomial ring.

EXAMPLES:

```
sage: R.<z> = Integers(8)[]; R
Univariate Polynomial Ring in z over Ring of integers modulo 8
sage: R.ngens()
1
```

parameter()

Return the generator of this polynomial ring.

This is the same as self.gen().

polynomials(of_degree=None, max_degree=None)

Return an iterator over the polynomials of specified degree.

INPUT: Pass exactly one of:

• max_degree - an int; the iterator will generate all polynomials which have degree less than or equal to max_degree

• of_degree - an int; the iterator will generate all polynomials which have degree of_degree

OUTPUT: an iterator

EXAMPLES:

```
sage: P = PolynomialRing(GF(3), 'y')
sage: for p in P.polynomials( of_degree = 2 ): print(p)
y^2
```
y^2 + 1
y^2 + 2
y^2 + y
y^2 + y + 1
y^2 + y + 2
y^2 + 2*y
y^2 + 2*y + 1
y^2 + 2*y + 2
2*y^2
2*y^2 + 1
2*y^2 + 2
2*y^2 + y
2*y^2 + y + 1
2*y^2 + y + 2
2*y^2 + 2*y
2*y^2 + 2*y + 1
2*y^2 + 2*y + 2
sage: for p in P.polynomials( max_degree = 1 ): print(p)
  0
  1
  y
  y + 1
  y + 2
  2*y
  2*y + 1
  2*y + 2
sage: for p in P.polynomials( max_degree = 1, of_degree = 3 ): print(p)
Traceback (most recent call last):
  ... ValueError: you should pass exactly one of of_degree and max_degree

AUTHORS:
  • Joel B. Mohler

random_element(degree=(-1, 2), *args, **kwds)

Return a random polynomial of given degree or with given degree bounds.

INPUT:
  • degree - optional integer for fixing the degree or a tuple of minimum and maximum degrees. By
default set to (-1,2).
  • *args, **kwds - Passed on to the random_element method for the base ring

EXAMPLES:

sage: R.<x> = ZZ[]
sage: f = R.random_element(10, 5, 10)
sage: f.degree()
10
sage: f.parent() is R
True
sage: all(a in range(5, 10) for a in f.coefficients())

(continues on next page)
True

```python
 sage: R.random_element(6).degree()
 6
```

If a tuple of two integers is given for the degree argument, a degree is first uniformly chosen, then a polynomial of that degree is given:

```python
 sage: R.random_element(degree=(0, 8)).degree() in range(0, 9)
 True
```

```python
 sage: found = [False]*9
 sage: while not all(found):
 ....:     found[R.random_element(degree=(0, 8)).degree()] = True
```

Note that the zero polynomial has degree -1, so if you want to consider it set the minimum degree to -1:

```python
 sage: while R.random_element(degree=(-1,2),x=-1,y=1) != R.zero():
 ....:     pass
```

### \texttt{set\_karatsuba\_threshold}(Karatsuba\_threshold)

Changes the default threshold for this ring in the method \texttt{mul\_karatsuba} to fall back to the schoolbook algorithm.

**Warning:** This method may have a negative performance impact in polynomial arithmetic. So use it at your own risk.

**EXAMPLES:**

```python
 sage: K = QQ['x']
 sage: K.karatsuba_threshold()
 8
 sage: K.set_karatsuba_threshold(0)
 sage: K.karatsuba_threshold()
 0
```

### \texttt{some\_elements}()

Return a list of polynomials. This is typically used for running generic tests.

**EXAMPLES:**

```python
 sage: R.<x> = QQ[]
 sage: R.some_elements()
 [x, 1, 1/2, x + 1, x^3, x^2 - 1, x^2 + 1, 2*x^2 + 2]
```

### \texttt{variable\_names\_recursive}(depth=+Infinity)

Return the list of variable names of this ring and its base rings, as if it were a single multi-variate polynomial.

**INPUT:**

- \texttt{depth} – an integer or \texttt{Infinity}.

**OUTPUT:**

A tuple of strings.
EXAMPLES:

```python
sage: R = QQ['x']['y']['z']
sage: R.variable_names_recursive()
('x', 'y', 'z')
sage: R.variable_names_recursive(2)
('y', 'z')
```

```python
class sage.rings.polynomial.polynomial_ring.PolynomialRing_integral_domain
    base_ring, name='x',
    sparse=False,
    implementation=None,
    element_class=None,
    category=None

class sage.rings.polynomial.polynomial_ring.PolynomialRing_commutative,
    PolynomialRing_singular_repr, IntegralDomain

construction()
    Return the construction functor.

EXAMPLES:

```python
sage: from sage.rings.polynomial.polynomial_ring import PolynomialRing_integral_-
    →domain as PRing
sage: R = PRing(ZZ, 'x'); R
Univariate Polynomial Ring in x over Integer Ring
sage: functor, arg = R.construction(); functor, arg
(Poly[x], Integer Ring)
sage: functor.implementation
is None
True
sage: R = PRing(ZZ, 'x', implementation='NTL'); R
Univariate Polynomial Ring in x over Integer Ring (using NTL)
sage: functor, arg = R.construction(); functor, arg
(Poly[x], Integer Ring)
sage: functor.implementation
'NTL'
```

```python
weil_polynomials(d, q, sign=1, lead=1)
    Return all integer polynomials whose complex roots all have a specified absolute value.
    Such polynomials \( f \) satisfy a functional equation
    \[
    T^d f(q/T) = sq^{d/2} f(T)
    \]
    where \( d \) is the degree of \( f \), \( s \) is a sign and \( q^{1/2} \) is the absolute value of the roots of \( f \).
    INPUT:
    • \( d \) – integer, the degree of the polynomials
    • \( q \) – integer, the square of the complex absolute value of the roots
    • \( sign \) – integer (default 1), the sign \( s \) of the functional equation
```
• lead – integer, list of integers or list of pairs of integers (default 1),
  constraints on the leading few coefficients of the generated polynomials. If pairs \((a, b)\) of integers are given, they are treated as a constraint of the form \(a \equiv b \pmod{\text{lead}}\); the moduli must be in decreasing order by divisibility, and the modulus of the leading coefficient must be 0.

See also:

More documentation and additional options are available using the iterator `sage.rings.polynomial.weil.weil_polynomials.WeilPolynomials` directly. In addition, polynomials have a method `is_weil_polynomial` to test whether or not the given polynomial is a Weil polynomial.

EXAMPLES:

```python
sage: R.<T> = ZZ
sage: L = R.weil_polynomials(4, 2)
sage: len(L)
35
sage: L[9]
T^4 + T^3 + 2*T^2 + 2*T + 4
sage: all(p.is_weil_polynomial() for p in L)
True
```

Setting multiple leading coefficients:

```python
sage: R.<T> = QQ
sage: l = R.weil_polynomials(4, 2, lead=((1,0),(2,4),(1,2)))
sage: l
[T^4 + 2*T^3 + 5*T^2 + 4*T + 4,
 T^4 + 2*T^3 + 3*T^2 + 4*T + 4,
 T^4 - 2*T^3 + 5*T^2 - 4*T + 4,
 T^4 - 2*T^3 + 3*T^2 - 4*T + 4]
```

We do not require Weil polynomials to be monic. This example generates Weil polynomials associated to K3 surfaces over GF(2) of Picard number at least 12:

```python
sage: R.<T> = QQ
sage: l = R.weil_polynomials(10, 1, lead=2)
sage: len(l)
4865
sage: l[len(l)//2]
2*T^10 + T^8 + T^6 + T^4 + T^2 + 2
```

`sage.rings.polynomial.polynomial_ring.is_PolynomialRing(x)`

Return True if x is a univariate polynomial ring (and not a sparse multivariate polynomial ring in one variable).

EXAMPLES:

```python
sage: from sage.rings.polynomial.polynomial_ring import is_PolynomialRing
sage: from sage.rings.polynomial.multi_polynomial_ring import is_MPolynomialRing
sage: is_PolynomialRing(2)
False
sage: is_PolynomialRing(ZZ['x,y,z'])
False
```

This polynomial ring is not univariate.
Univariate means not only in one variable, but is a specific data type. There is a multivariate (sparse) polynomial ring data type, which supports a single variable as a special case.

```sage
sage: R.<w> = PolynomialRing(ZZ, implementation="singular"); R
Multivariate Polynomial Ring in w over Integer Ring
sage: is_PolynomialRing(R)
False
sage: type(R)
<class 'sage.rings.polynomial.multi_polynomial_libsingular.MPolynomialRing_libsingular'>
```

```sage
sage.rings.polynomial.polynomial_ring.polygen(ring_or_element, name='x')
```

Return a polynomial indeterminate.

**INPUT:**
- `polygen(base_ring, name='x')`
- `polygen(ring_element, name='x')`

If the first input is a ring, return a polynomial generator over that ring. If it is a ring element, return a polynomial generator over the parent of the element.

**EXAMPLES:**

```sage
sage: z = polygen(QQ, 'z')
sage: z^3 + z + 1
z^3 + z + 1
sage: parent(z)
Univariate Polynomial Ring in z over Rational Field
```

**Note:** If you give a list or comma separated string to `polygen`, you’ll get a tuple of indeterminates, exactly as if you called `polygens`.

```sage
sage.rings.polynomial.polynomial_ring.polygens(base_ring, names='x', *args)
```

Return indeterminates over the given base ring with the given names.

**EXAMPLES:**

```sage
sage: x,y,z = polygens(QQ, 'x,y,z')
sage: (x+y+z)^2
x^2 + 2*x*y + y^2 + 2*x*z + 2*y*z + z^2
sage: parent(x)
Multivariate Polynomial Ring in x, y, z over Rational Field
sage: t = polygens(QQ, ['x', 'yz', 'abc'])
sage: t
(x, yz, abc)
```
The number of generators can be passed as a third argument:

```sage
polygens(QQ, 'x', 4)
```

(x0, x1, x2, x3)

### 2.1.2 Ring homomorphisms from a polynomial ring to another ring

This module currently implements the canonical ring homomorphism from $A[x]$ to $B[x]$ induced by a ring homomorphism from $A$ to $B$.

**Todo:** Implement homomorphisms from $A[x]$ to an arbitrary ring $R$, given by a ring homomorphism from $A$ to $R$ and the image of $x$ in $R$.

**AUTHORS:**
- Peter Bruin (March 2014): initial version

```python
class PolynomialRingHomomorphism_from_base

Bases: RingHomomorphism_from_base

The canonical ring homomorphism from $R[x]$ to $S[x]$ induced by a ring homomorphism from $R$ to $S$.

EXAMPLES:

```sage
QQ['x'].coerce_map_from(ZZ['x'])
```

Ring morphism:
- From: Univariate Polynomial Ring in x over Integer Ring
- To: Univariate Polynomial Ring in x over Rational Field
- Defn: Induced from base ring by
  - Natural morphism:
    - From: Integer Ring
    - To: Rational Field

```python
is_injective()
```

Return whether this morphism is injective.

**EXAMPLES:**

```sage
R.<x> = ZZ[]
sage: S.<x> = QQ[]
sage: R.hom(S).is_injective()
True
```

```python
is_surjective()
```

Return whether this morphism is surjective.

**EXAMPLES:**

```sage
R.<x> = ZZ[]
sage: S.<x> = Zmod(2)[]
sage: R.hom(S).is_surjective()
True
```
2.1.3 Univariate polynomial base class

AUTHORS:
- William Stein: first version
- Martin Albrecht: added singular coercion
- Robert Bradshaw: moved Polynomial_generic_dense to Cython
- Miguel Marco: implemented resultant in the case where PARI fails
- Simon King: used a faster way of conversion from the base ring
- Kwankyu Lee (2013-06-02): enhanced quo_rem()
- Julian Rueth (2012-05-25,2014-05-09): fixed is_squarefree() for imperfect fields, fixed division without remainder over QQbar; added _cache_key for polynomials with unhashable coefficients
- Simon King (2013-10): implemented copying of PolynomialBaseringInjection
- Bruno Grenet (2014-07-13): enhanced quo_rem()
- Kiran Kedlaya (2016-03): added root counting
- Edgar Costa (2017-07): added rational reconstruction
- Kiran Kedlaya (2017-09): added reciprocal transform, trace polynomial
- David Zureick-Brown (2017-09): added is_weil_polynomial
- Sebastian Oehms (2018-10): made roots() and factor() work over more cases of proper integral domains (see github issue #26421)

```python
class sage.rings.polynomial.polynomial_element.ConstantPolynomialSection
    Bases: Map

This class is used for conversion from a polynomial ring to its base ring.

Since github issue #9944, it calls the constant_coefficient method, which can be optimized for a particular polynomial type.

EXAMPLES:

```
sage: P0.<y_1> = GF(3)[]
sage: P1.<y_2,y_1,y_0> = GF(3)[]
sage: P0(-y_1)  # indirect doctest
2*y_1

sage: phi = GF(3).convert_map_from(P0); phi
Generic map:
    From: Univariate Polynomial Ring in y_1 over Finite Field of size 3
    To:    Finite Field of size 3
sage: type(phi)
<class 'sage.rings.polynomial.polynomial_element.ConstantPolynomialSection'>
sage: phi(P0.one())
1
sage: phi(y_1)
Traceback (most recent call last):
  ... TypeError: not a constant polynomial
```
class sage.rings.polynomial.polynomial_element.Polynomial

Bases: CommutativePolynomial

A polynomial.

EXAMPLES:

sage: R.<y> = QQ['y']
sage: S.<x> = R['x']
sage: S
Univariate Polynomial Ring in x over Univariate Polynomial Ring in y over Rational Field
sage: f = x*y; f
y*x
sage: type(f)
<class 'sage.rings.polynomial.polynomial_element.Polynomial_generic_dense'>
sage: p = (y+1)^10; p(1)
1024

_add_(right)

Add two polynomials.

EXAMPLES:

sage: R = ZZ['x']
sage: p = R([1,2,3,4])
sage: q = R([4,-3,2,-1])
sage: p + q
3*x^3 + 5*x^2 - x + 5

_sub_(other)

Default implementation of subtraction using addition and negation.

_lmul_(left)

Multiply self on the left by a scalar.

EXAMPLES:

sage: R.<x> = ZZ[]
sage: f = (x^3 + x + 5)
sage: f._lmul_(7)
7*x^3 + 7*x + 35
sage: 7*f
7*x^3 + 7*x + 35

_rmul_(right)

Multiply self on the right by a scalar.

EXAMPLES:

sage: R.<x> = ZZ[]
sage: f = (x^3 + x + 5)
sage: f._rmul_(7)
7*x^3 + 7*x + 35
sage: f*7
7*x^3 + 7*x + 35
_mul_(right)

EXAMPLES:

```
sage: R.<x> = ZZ[]
sage: (x - 4)*(x^2 - 8*x + 16)
x^3 - 12*x^2 + 48*x - 64
sage: C.<t> = PowerSeriesRing(ZZ)
sage: D.<s> = PolynomialRing(C)
sage: z = (1 + O(t)) + t*s^2
sage: z*z
t^2*s^4 + (2*t + O(t^2))*s^2 + 1 + O(t)
```

## More examples from trac 2943, added by Kiran S. Kedlaya 2 Dec 09

```
sage: C.<t> = PowerSeriesRing(Integers())
sage: D.<s> = PolynomialRing(C)
sage: z = 1 + (t + O(t^2))*s + (t^2 + O(t^3))*s^2
sage: z*z
(t^4 + O(t^5))*s^4 + (2*t^3 + O(t^4))*s^3 + (3*t^2 + O(t^3))*s^2 + (2*t + O(t^2))*s + 1
```

_mul_trunc_(right, n)

Return the truncated multiplication of two polynomials up to n.

This is the default implementation that does the multiplication and then truncate! There are custom implementations in several subclasses:

- on dense polynomial over integers (via FLINT)
- on dense polynomial over Z/nZ (via FLINT)
- on dense rational polynomial (via FLINT)
- on dense polynomial on Z/nZ (via NTL)

EXAMPLES:

```
sage: R = QQ['x']['y']
sage: y = R.gen()
sage: x = R.base_ring().gen()
sage: p1 = 1 - x*y + 2*y**3
sage: p2 = -1/3 + y**5
sage: p1._mul_trunc_(p2, 5)
-2/3*y^3 + 1/3*x*y - 1/3
```

Todo: implement a generic truncated Karatsuba and use it here.

adams_operator(n, monic=False)

Return the polynomial whose roots are the $n$-th power of the roots of this.

INPUT:

- $n$ – an integer
- monic – boolean (default False) if set to True, force the output to be monic

EXAMPLES:
sage: f = cyclotomic_polynomial(30)
sage: f.adams_operator(7)==f
True
sage: f.adams_operator(6) == cyclotomic_polynomial(5)**2
True
sage: f.adams_operator(10) == cyclotomic_polynomial(3)**4
True
sage: f.adams_operator(15) == cyclotomic_polynomial(2)**8
True
sage: f.adams_operator(30) == cyclotomic_polynomial(1)**8
True

sage: x = polygen(QQ)
sage: f = x^2-2*x+2
sage: f.adams_operator(10)
x^2 + 1024

When \( f \) is monic the output will have leading coefficient \( \pm 1 \) depending on the degree, but we can force it to be monic:

sage: R.<a,b,c> = ZZ[]
sage: x = polygen(R)
sage: f = (x-a)*(x-b)*(x-c)
sage: f.adams_operator(3).factor()
(-1) * (x - c^3) * (x - b^3) * (x - a^3)
sage: f.adams_operator(3,monic=True).factor()
(x - c^3) * (x - b^3) * (x - a^3)

add_bigoh(\texttt{prec})

Return the power series of precision at most \( \texttt{prec} \) got by adding \( O(q^{\texttt{prec}}) \) to self, where \( q \) is its variable.

EXAMPLES:

sage: R.<x> = ZZ[]
sage: f = 1 + 4*x + x^3
sage: f.add_bigoh(7)
1 + 4*x + x^3 + O(x^7)
sage: f.add_bigoh(2)
1 + 4*x + O(x^2)
sage: f.add_bigoh(2).parent()
Power Series Ring in x over Integer Ring

all_roots_in_interval(\texttt{a=None, b=None})

Return True if the roots of this polynomial are all real and contained in the given interval.

EXAMPLES:

sage: R.<x> = PolynomialRing(ZZ)
sage: pol = (x-1)^2 * (x-2)^2 * (x-3)
sage: pol.all_roots_in_interval(1, 3)
True
sage: pol.all_roots_in_interval(1.01, 3)
False
sage: pol = chebyshev_T(5,x)

(continues on next page)
any_root\(\text{(ring=None, degree=None, assume\_squarefree=False)}\)

Return a root of this polynomial in the given ring.

INPUT:

- \text{ring} – The ring in which a root is sought. By default this is the coefficient ring.
- degree (None or nonzero integer) – Used for polynomials over finite fields. Return a root of degree \text{abs(degree)} over the ground field. If negative, also assumes that all factors of this polynomial are of degree \text{abs(degree)}. If None, returns a root of minimal degree contained within the given ring.
- assume\_squarefree (bool) – Used for polynomials over finite fields. If True, this polynomial is assumed to be squarefree.

EXAMPLES:

```python
sage: R.<x> = GF(11)[]
sage: f = 7*x^7 + 8*x^6 + 4*x^5 + x^4 + 6*x^3 + 10*x^2 + 8*x + 5
sage: f.any_root()
2
sage: f.factor()
(7) * (x + 9) * (x^6 + 10*x^4 + 6*x^3 + 5*x^2 + 2*x + 2)
sage: f = x^6 + 10*x^4 + 6*x^3 + 5*x^2 + 2*x + 2
sage: f.any_root(GF(11^6, 'a'))
a^5 + a^4 + 7*a^3 + 2*a^2 + 10*a
sage: sorted(f.roots(GF(11^6, 'a')))
[(a^5 + a^4 + 7*a^3 + 2*a^2 + 10*a, 1), (10*a^5 + 3*a^4 + 8*a^3 + a^2 + 10*a + 4, 1), (2*a^5 + 8*a^4 + 3*a^3 + 6*a^2 + 2, 1), (a^5 + 3*a^4 + 8*a^3 + 2*a^2 + 3*a + 4, 1), (9*a^5 + 5*a^4 + 10*a^3 + 8*a^2 + 3*a + 1, 1), (2*a^5 + 8*a^4 + 3*a^3 + 6*a^2 + 2*a + 1, 1), (10*a^5 + 3*a^4 + 8*a^3 + 2*a^2 + 3*a + 4, 1), (a^5 + a^4 + 7*a^3 + 2*a^2 + 10*a, 1), (10*a^5 + 3*a^4 + 8*a^3 + 2*a^2 + 3*a + 4, 1), (9*a^5 + 5*a^4 + 10*a^3 + 8*a^2 + 3*a + 1, 1), (2*a^5 + 8*a^4 + 3*a^3 + 6*a^2 + 2*a + 1, 1), (10*a^5 + 3*a^4 + 8*a^3 + 2*a^2 + 3*a + 4, 1), (a^5 + a^4 + 7*a^3 + 2*a^2 + 10*a, 1)]
```

```python
sage: g = (x-1)*(x^2 + 3*x + 9) * (x^5 + 5*x^4 + 8*x^3 + 5*x^2 + 3*x + 5)
sage: g.any_root(ring=GF(11^10, 'b'), degree=1)
1
```

```
args()

Return the generator of this polynomial ring, which is the (only) argument used when calling self.

EXAMPLES:

```
A constant polynomial has no variables, but still takes a single argument.

```
sage: R.<x> = QQ[]
sage: x.args()
(x,)
```

`base_extend(R)`

Return a copy of this polynomial but with coefficients in R, if there is a natural map from coefficient ring of self to R.

EXAMPLES:

```
sage: R.<x> = QQ[]
sage: f = x^3 - 17*x + 3
sage: f.base_extend(GF(7))
Traceback (most recent call last):
  ...TypeError: no such base extension
sage: f.change_ring(GF(7))
x^3 + 4*x + 3
```

`base_ring()`

Return the base ring of the parent of self.

EXAMPLES:

```
sage: R.<x> = ZZ[]
sage: x.base_ring()
Integer Ring
sage: (2*x+3).base_ring()
Integer Ring
```

`change_ring(R)`

Return a copy of this polynomial but with coefficients in R, if at all possible.

INPUT:

- R - a ring or morphism.

EXAMPLES:

```
sage: K.<z> = CyclotomicField(3)
sage: f = K.defining_polynomial()
sage: f.change_ring(GF(7))
x^2 + x + 1
sage: K.<z> = CyclotomicField(3)
sage: R.<x> = K[]
sage: f = x^2 + z
sage: f.change_ring(K.embeddings(CC)[1])
x^2 - 0.500000000000000 - 0.866025403784438*I
```
\begin{verbatim}
\texttt{sage: R.<x> = QQ[]}
\texttt{sage: f = x^2 + 1}
\texttt{sage: f.change_ring(QQ.embeddings(CC)[0])}
\texttt{x^2 + 1.00000000000000}
\end{verbatim}

\texttt{change\_variable\_name(var)}

Return a new polynomial over the same base ring but in a different variable.

\texttt{coefficients(sparse=True)}

Return the coefficients of the monomials appearing in self. If \texttt{sparse=True} (the default), it returns only the non-zero coefficients. Otherwise, it returns the same value as \texttt{self.list()}. (In this case, it may be slightly faster to invoke \texttt{self.list()} directly.)

\texttt{complex\_roots()}

Return the complex roots of this polynomial, without multiplicities.

Calls \texttt{self.roots(ring=CC)}, unless this is a polynomial with floating-point coefficients, in which case it is uses the appropriate precision from the input coefficients.

\texttt{compose\_power(k, algorithm=None, monic=False)}

Return the \(k\)-th iterate of the composed product of this polynomial with itself.

\begin{itemize}
\item \texttt{k} – a non-negative integer
\item \texttt{algorithm} – \texttt{None} (default), "resultant" or "BFSS". See \texttt{composed\_op()}
\item \texttt{monic} – \texttt{False} (default) or \texttt{True}. See \texttt{composed\_op()}
\end{itemize}

\texttt{OUTPUT:}
The polynomial of degree $d^k$ where $d$ is the degree, whose roots are all $k$-fold products of roots of this polynomial. That is, $f \ast f \ast \cdots \ast f$ where this is $f$ and $f \ast f = f.composed_op(f,operator.mul)$.

**EXAMPLES:**

```
sage: R.<a,b,c> = ZZ[]
sage: x = polygen(R)
sage: f = (x-a)*(x-b)*(x-c)
sage: f.compose_power(2).factor()  
(x - c^2) * (x - b^2) * (x - a^2) * (x - b*c)^2 * (x - a*c)^2 * (x - a*b)^2

sage: x = polygen(QQ)
sage: f = x^2-2*x+2
sage: f2 = f.compose_power(2); f2
x^4 - 4*x^3 + 8*x^2 - 16*x + 16
sage: f2 == f.composed_op(f,operator.mul)  
True
sage: f3 = f.compose_power(3); f3
x^8 - 8*x^7 + 32*x^6 - 64*x^5 + 128*x^4 - 512*x^3 + 2048*x^2 - 4096*x + 4096
sage: f3 == f2.composed_op(f,operator.mul)  
True
sage: f4 = f.compose_power(4)
```

**compose_trunc**(other, n)

Return the composition of self and other, truncated to $O(x^n)$.

This method currently works for some specific coefficient rings only.

**EXAMPLES:**

```
sage: Pol.<x> = CBF[]
sage: (1 + x + x^2/2 + x^3/6 + x^4/24 + x^5/120).compose_trunc(1 + x, 2)
([2.708333333333333 +/- ...e-16])*x + [2.71666666666667 +/- ...e-15]

sage: Pol.<x> = QQ['y'][]
sage: (1 + x + x^2/2 + x^3/6 + x^4/24 + x^5/120).compose_trunc(1 + x, 2)
Traceback (most recent call last):
...  
NotImplementedError: truncated composition is not implemented for this subclass, 
\rightarrow of polynomials
```

**composed_op**(p1, p2, op=\text{None}, monic=\text{False})

Return the composed sum, difference, product or quotient of this polynomial with another one.

In the case of two monic polynomials $p_1$ and $p_2$ over an integral domain, the composed sum, difference, etc. are given by

$$\prod_{p_1(a)=p_2(b)=0} (x - (a \ast b)), \quad * \in \{+,-,\times,/\}$$

where the roots $a$ and $b$ are to be considered in the algebraic closure of the fraction field of the coefficients and counted with multiplicities. If the polynomials are not monic this quantity is multiplied by

$$\alpha_1^{\text{deg}(p_2)} \alpha_2^{\text{deg}(p_1)}$$

where
\(\alpha_1\) and \(\alpha_2\) are the leading coefficients of \(p_1\) and \(p_2\) respectively.

INPUT:
- \(p_2\) – univariate polynomial belonging to the same polynomial ring as this polynomial
- \(\text{op}\) – \text{operator.OP} where \(\text{OP}=\text{add}\) or \text{sub} or \text{mul} or \text{truediv}.
- \(\text{algorithm}\) – can be “resultant” or “BFSS”; by default the former is used when the polynomials have few nonzero coefficients and small degrees or if the base ring is not \(\mathbb{Z}\) or \(\mathbb{Q}\). Otherwise the latter is used.
- \(\text{monic}\) – whether to return a monic polynomial. If True the coefficients of the result belong to the fraction field of the coefficients.

ALGORITHM:
The computation is straightforward using resultants. Indeed for the composed sum it would be \(Res_y(p_1(x-y), p_2(y))\). However, the method from [BFSS2006] using series expansions is asymptotically much faster. Note that the algorithm BFSS with polynomials with coefficients in \(\mathbb{Z}\) needs to perform operations over \(\mathbb{Q}\).

Todo:
- The [BFSS2006] algorithm has been implemented here only in the case of polynomials over rationals. For other rings of zero characteristic (or if the characteristic is larger than the product of the degrees), one needs to implement a generic method \text{_exp_series}. In the general case of non-zero characteristic there is an alternative algorithm in the same paper.
- The Newton series computation can be done much more efficiently! See [BFSS2006].

EXAMPLES:

```sage
sage: x = polygen(ZZ)
sage: p1 = x^2 - 1
sage: p2 = x^4 - 1
sage: p1.composed_op(p2, operator.add)
x^8 - 4*x^6 + 4*x^4 - 16*x^2
sage: p1.composed_op(p2, operator.mul)
x^8 - 2*x^4 + 1
sage: p1.composed_op(p2, operator.truediv)
x^8 - 2*x^4 + 1
```

This function works over any field. However for base rings other than \(\mathbb{Z}\) and \(\mathbb{Q}\) only the resultant algorithm is available:

```sage
sage: x = polygen(QQbar)
sage: p1 = x^2 - AA(2).sqrt()
sage: p2 = x^3 - AA(3).sqrt()
sage: r1 = p1.roots(multiplicities=False)
sage: r2 = p2.roots(multiplicities=False)
sage: p = p1.composed_op(p2, operator.add)
sage: p
x^6 - 4.2426406871192857*x^4 - 3.4641016151377550*x^3 + 6*x^2 - 14.
\rightarrow-69693845669907.5728752538099?
sage: all(p(x+y).is_zero() for x in r1 for y in r2)
```

(continues on next page)
Polynomials, Release 10.0

True

```
sage: x = polygen(GF(2))
sage: p1 = x**2 + x - 1
sage: p2 = x**3 + x - 1
sage: p_add = p1.composed_op(p2, operator.add)
sage: p_add
x^6 + x^5 + x^3 + x^2 + 1
sage: p_mul = p1.composed_op(p2, operator.mul)
sage: p_mul
x^6 + x^4 + x^2 + x + 1
sage: p_div = p1.composed_op(p2, operator.truediv)
sage: p_div
x^6 + x^5 + x^4 + x^2 + 1
sage: K = GF(2**6, 'a')
sage: r1 = p1.roots(K, multiplicities=False)
sage: r2 = p2.roots(K, multiplicities=False)
sage: all(p_add(x1+x2).is_zero() for x1 in r1 for x2 in r2)
True
sage: all(p_mul(x1*x2).is_zero() for x1 in r1 for x2 in r2)
True
sage: all(p_div(x1/x2).is_zero() for x1 in r1 for x2 in r2)
True
```

**constant_coefficient()**

Return the constant coefficient of this polynomial.

**OUTPUT:** element of base ring

**EXAMPLES:**

```
sage: R.<x> = QQ[]
sage: f = -2*x^3 + 2*x - 1/3
sage: f.constant_coefficient()
-1/3
```

**content_ideal()**

Return the content ideal of this polynomial, defined as the ideal generated by its coefficients.

**EXAMPLES:**

```
sage: R.<x> = IntegerModRing(4)[]
sage: f = x^4 + 3*x^2 + 2
sage: f.content_ideal().gen()
Ideal (2, 3, 1) of Ring of integers modulo 4
```

When the base ring is a gcd ring, the content as a ring element is the generator of the content ideal:

```
sage: R.<x> = ZZ[]
sage: f = 2*x^3 - 4*x^2 + 6*x - 10
sage: f.content_ideal().gen()
2
```
cyclo
tomic_part()

Return the product of the irreducible factors of this polynomial which are cyclotomic polynomials.

The algorithm assumes that the polynomial has rational coefficients.

See also:

is_cyclotomic() is_cyclotomic_product() has_cyclotomic_factor()

EXAMPLES:

```
sage: P.<x> = PolynomialRing(Integers())
sage: pol = 2*(x^4 + 1)
sage: pol.cyclotomic_part()
x^4 + 1
sage: pol = x^4 + 2
sage: pol.cyclotomic_part()
1
sage: pol = (x^4 + 1)^2 * (x^4 + 2)
sage: pol.cyclotomic_part()
x^8 + 2*x^4 + 1
```

```
sage: P.<x> = PolynomialRing(QQ)
sage: pol = (x^4 + 1)^2 * (x^4 + 2)
sage: pol.cyclotomic_part()
x^8 + 2*x^4 + 1
sage: pol = (x - 1) * x * (x + 2)
sage: pol.cyclotomic_part()
x - 1
```

degree(gen=None)

Return the degree of this polynomial. The zero polynomial has degree -1.

EXAMPLES:

```
sage: x = ZZ['x'].0
sage: f = x^93 + 2*x + 1
sage: f.degree()
93
sage: x = PolynomialRing(QQ, 'x', sparse=True).0
sage: f = x^100000
sage: f.degree()
100000

sage: x = QQ['x'].0
sage: f = 2006*x^2006 - x^2 + 3
sage: f.degree()
2006
sage: f = 0^x
sage: f.degree()
-1
sage: f = x + 33
sage: f.degree()
1
```

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AUTHORS:

- Naqi Jaffery (2006-01-24): examples

denominator()

Return a denominator of self.

First, the lcm of the denominators of the entries of self is computed and returned. If this computation fails, the unit of the parent of self is returned.

Note that some subclasses may implement their own denominator function. For example, see `sage.rings.polynomial.polynomial_rational_flint.Polynomial_rational_flint`

Warning: This is not the denominator of the rational function defined by self, which would always be 1 since self is a polynomial.

EXAMPLES:

First we compute the denominator of a polynomial with integer coefficients, which is of course 1.

```
sage: R.<x> = ZZ[]
sage: f = x^3 + 17*x + 1
sage: f.denominator()
1
```

Next we compute the denominator of a polynomial with rational coefficients.

```
sage: R.<x> = PolynomialRing(QQ)
sage: f = (1/17)*x^19 - (2/3)*x + 1/3; f
1/17*x^19 - 2/3*x + 1/3
sage: f.denominator()
51
```

Finally, we try to compute the denominator of a polynomial with coefficients in the real numbers, which is a ring whose elements do not have a denominator method.

```
sage: R.<x> = RR[]
sage: f = x + RR('0.3'); f
x + 0.300000000000000
sage: f.denominator()
1.00000000000000
```

Check that the denominator is an element over the base whenever the base has no denominator function. This closes github issue #9063.

```
sage: R.<a> = GF(5)[]
sage: x = R(0)
sage: x.denominator()
1
sage: type(x.denominator())
<class 'sage.rings.finite_rings.integer_mod.IntegerMod_int'>
sage: isinstance(x.numerator() / x.denominator(), Polynomial)
True
sage: isinstance(x.numerator() / R(1), Polynomial)
False
```
derivative(*args)
The formal derivative of this polynomial, with respect to variables supplied in args.
Multiple variables and iteration counts may be supplied; see documentation for the global derivative() function for more details.

See also:
_derivative()

EXAMPLES:

```sage
sage: R.<x> = PolynomialRing(QQ)
sage: g = -x^4 + x^2/2 - x
sage: g.derivative()
-4*x^3 + x - 1
sage: g.derivative(x)
-4*x^3 + x - 1
sage: g.derivative(x, x)
-12*x^2 + 1
sage: g.derivative(x, 2)
-12*x^2 + 1
sage: R.<t> = PolynomialRing(ZZ)
sage: S.<x> = PolynomialRing(R)
sage: f = t^3*x^2 + t^4*x^3
sage: f.derivative()
3*t^4*x^2 + 2*t^3*x
sage: f.derivative(x)
3*t^4*x^2 + 2*t^3*x
sage: f.derivative(t)
4*t^3*x^3 + 3*t^2*x^2
```

dict()
Return a sparse dictionary representation of this univariate polynomial.

EXAMPLES:

```sage
sage: R.<x> = QQ[]
sage: f = x^3 + -1/7*x + 13
sage: f.dict()
{0: 13, 1: -1/7, 3: 1}
```

diff(*args)
The formal derivative of this polynomial, with respect to variables supplied in args.
Multiple variables and iteration counts may be supplied; see documentation for the global derivative() function for more details.

See also:
_derivative()

EXAMPLES:

```sage
sage: R.<x> = PolynomialRing(QQ)
sage: g = -x^4 + x^2/2 - x
```

(continues on next page)
\begin{verbatim}
sage: g.derivative()
sage: g.derivative(x)
sage: g.derivative(x, x)
sage: g.derivative(x, 2)
sage: R.<t> = PolynomialRing(ZZ)
sage: S.<x> = PolynomialRing(R)
sage: f = t^3*x^2 + t^4*x^3
sage: f.derivative()
sage: f.derivative(x)
sage: f.derivative(t)
sage: R.<t> = PolynomialRing(ZZ)
sage: S.<x> = PolynomialRing(R)
sage: f = t^3*x^2 + t^4*x^3
sage: f.derivative()
sage: f.derivative(x)
sage: f.derivative(t)
\end{verbatim}

\textbf{differentiate\texttt{(*args)}}

The formal derivative of this polynomial, with respect to variables supplied in \texttt{args}.

Multiple variables and iteration counts may be supplied; see documentation for the global \texttt{derivative()} function for more details.

\textbf{See also:}

\_derivative()

\textbf{EXAMPLES:}

\begin{verbatim}
sage: R.<t> = PolynomialRing(ZZ)
sage: S.<x> = PolynomialRing(R)
sage: f = t^3*x^2 + t^4*x^3
sage: f.derivative()
sage: f.derivative(x)
sage: f.derivative(t)
\end{verbatim}

\textbf{discriminant()}

Return the discriminant of \texttt{self}.

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The discriminant is
\[ R_n := a_n^{2n-2} \prod_{1<i<j<n} (r_i - r_j)^2, \]
where \( n \) is the degree of self, \( a_n \) is the leading coefficient of self and the roots of self are \( r_1, \ldots, r_n \).

**OUTPUT:** An element of the base ring of the polynomial ring.

**ALGORITHM:**

Uses the identity \( R_n(f) := (-1)^{n(n-1)/2} R(f, f') a_n^{n-k-2} \), where \( n \) is the degree of self, \( a_n \) is the leading coefficient of self, \( f' \) is the derivative of \( f \), and \( k \) is the degree of \( f' \). Calls `resultant()`.

**EXAMPLES:**

In the case of elliptic curves in special form, the discriminant is easy to calculate:

```python
sage: R.<x> = QQ[]
sage: f = x^3 + x + 1
sage: d = f.discriminant(); d
-31
sage: d.parent() is QQ
True
sage: EllipticCurve([1, 1]).discriminant()/16
-31
```

We can compute discriminants over univariate and multivariate polynomial rings:

```python
sage: R.<a> = QQ[]
sage: S.<x> = R[]
sage: f = a*x + x + a + 1
sage: d = f.discriminant(); d
1
sage: d.parent() is R
True
```

```python
sage: R.<a, b> = QQ[]
sage: S.<x> = R[]
sage: f = x^2 + a + b
sage: d = f.discriminant(); d
-4*a - 4*b
sage: d.parent() is R
True
```

**dispersion(other=None)**

Compute the dispersion of a pair of polynomials.

The dispersion of \( f \) and \( g \) is the largest nonnegative integer \( n \) such that \( f(x+n) \) and \( g(x) \) have a nonconstant common factor.

When `other` is `None`, compute the auto-dispersion of `self`, i.e., its dispersion with itself.
See also:

\[ \text{dispersion}\_\text{set}() \]

EXAMPLES:

```
sage: Pol.<x> = QQ[]
sage: x.dispersion(x + 1)
1
sage: (x + 1).dispersion(x)
-Infinity

sage: Pol.<x> = QQbar[]
sage: pol = Pol([sqrt(5), 1, 3/2])
sage: pol.dispersion()
0
sage: (pol*pol(x+3)).dispersion()
3
```

\[ \text{dispersion}\_\text{set}(\text{other}=\text{None}) \]

Compute the dispersion set of two polynomials.

The dispersion set of \( f \) and \( g \) is the set of nonnegative integers \( n \) such that \( f(x + n) \) and \( g(x) \) have a nonconstant common factor.

When \text{other} is \text{None}, compute the auto-dispersion set of \text{self}, i.e., its dispersion set with itself.

ALGORITHM:

See Section 4 of Man & Wright [MW1994].

See also:

\[ \text{dispersion}() \]

EXAMPLES:

```
sage: Pol.<x> = QQ[]
sage: x.dispersion_set(x + 1)
[1]
sage: (x + 1).dispersion_set(x)
[]

sage: pol = x^3 + x - 7
sage: (pol*pol(x+3)^2).dispersion_set()
[0, 3]
```

\[ \text{divides}(p) \]

Return \text{True} if this polynomial divides \( p \).

This method is only implemented for polynomials over an integral domain.

EXAMPLES:

```
sage: R.<x> = ZZ[]
sage: (2*x + 1).divides(4*x**2 - 1)
True
sage: (2*x + 1).divides(4*x**2 + 1)
False
```

(continues on next page)
sage: (2*x + 1).divides(R(0))
True
sage: R(0).divides(2*x + 1)
False
sage: R(0).divides(R(0))
True
sage: S.<y> = R[]
sage: p = x * y**2 + (2*x + 1) * y + x + 1
sage: q = (x + 1) * y + (3*x + 2)
sage: q.divides(p)
False
sage: q.divides(p * q)
True
sage: R.<x> = Zmod(6)[]
sage: p = 4*x + 3
sage: q = 5*x**2 + x + 2
sage: p.divides(q)
Traceback (most recent call last):
...
NotImplementedError: divisibility test only implemented for polynomials over an...

Euclidean degree()

Return the degree of this element as an element of an Euclidean domain.

If this polynomial is defined over a field, this is simply its degree().

Examples:

sage: R.<x> = QQ[]

sage: x.euclidean_degree()
1

sage: R.<x> = ZZ[]

sage: x.euclidean_degree()
Traceback (most recent call last):
...
NotImplementedError

Exponents()

Return the exponents of the monomials appearing in self.

Examples:

sage: _.<x> = PolynomialRing(ZZ)

sage: f = x^4+2*x^2+1

sage: f.exponents()
[0, 2, 4]

Factor(**kwargs)

Return the factorization of self over its base ring.

Input:

- kwargs – any keyword arguments are passed to the method _factor_univariate_polynomial() of the base ring if it defines such a method.
OUTPUT:

- A factorization of self over its parent into a unit and irreducible factors. If the parent is a polynomial ring over a field, these factors are monic.

EXAMPLES:

Factorization is implemented over various rings. Over \( \mathbb{Q} \):

```
sage: x = QQ['x'].0
sage: f = (x^3 - 1)^2
sage: f.factor()
(x - 1)^2 * (x^2 + x + 1)^2
```

Since \( \mathbb{Q} \) is a field, the irreducible factors are monic:

```
sage: f = 10*x^5 - 1
sage: f.factor()
(10) * (x^5 - 1/10)
sage: f = 10*x^5 - 10
sage: f.factor()
(10) * (x - 1) * (x^4 + x^3 + x^2 + x + 1)
```

Over \( \mathbb{Z} \) the irreducible factors need not be monic:

```
sage: x = ZZ['x'].0
sage: f = 10*x^5 - 1
sage: f.factor()
10*x^5 - 1
```

We factor a non-monic polynomial over a finite field of 25 elements:

```
sage: k.<a> = GF(25)
sage: R.<x> = k[]
sage: f = 2*x^10 + 2*x + 2*a
sage: F = f.factor(); F
(2) * (x + a + 2) * (x^4 + 3*a + 4) * (x^2 + (a + 1)*x + a + 2) * (x^5 + (3*a + 4)*x^4 + (3*a + 3)*x^3 + (3*a + 2)*x^2 + (3*a + 1)*x + 3*a + 1)
```

Notice that the unit factor is included when we multiply \( F \) back out:

```
sage: expand(F)
2*x^10 + 2*x + 2*a
```

A new ring. In the example below, we set the special method \_factor_univariate_polynomial() in the base ring which is called to factor univariate polynomials. This facility can be used to easily extend polynomial factorization to work over new rings you introduce:

```
sage: R.<x> = PolynomialRing(IntegerModRing(4),implementation="NTL")
sage: (x^2).factor()
Traceback (most recent call last):
...
NotImplementedError: factorization of polynomials over rings with composite_˓→characteristic is not implemented
sage: R.base_ring()._factor_univariate_polynomial = lambda f: f.change_ring(ZZ).˓→factor()
```
Polynomials, Release 10.0

Arbitrary precision real and complex factorization:

```
sage: R.<x> = RealField(100)[]
sage: F = factor(x^2-3); F
(x - 1.7320508075688772935274463415) * (x + 1.7320508075688772935274463415)
sage: expand(F)
x^2 - 3.0000000000000000000000000000
sage: factor(x^2 + 1)
x^2 + 1.0000000000000000000000000000
sage: R.<x> = ComplexField(100)[]
sage: F = factor(x^2+3); F
(x - 1.7320508075688772935274463415*I) * (x + 1.7320508075688772935274463415*I)
sage: expand(F)
x^2 + 3.0000000000000000000000000000
sage: factor(x^2+1)
(x - I) * (x + I)
sage: f = R(I) * (x^2 + 1) ; f
I*x^2 + I
sage: F = factor(f); F
(1.0000000000000000000000000000*I) * (x - I) * (x + I)
sage: expand(F)
I*x^2 + I
```

Over a number field:

```
sage: K.<z> = CyclotomicField(15)
sage: x = polygen(K)
sage: ((x^3 + z^6*x + 1)^3*(x - z)).factor()
(x - z) * (x^3 + z^6*x + 1)^3
sage: cyclotomic_polynomial(12).change_ring(K).factor()
(x^2 - z^5 - 1) * (x^2 + z^5)
sage: ((x^3 + z^6*x + 1)^3*(x/(z+2) - 1/3)).factor()
(-1/331*z^7 + 3/331*z^6 - 6/331*z^5 + 11/331*z^4 - 21/331*z^3 + 41/331*z^2 - 82/331*z + 165/331) * (x - 1/3*z - 2/3) * (x^3 + z^6*x + 1)^3
```

Over a relative number field:

```
sage: x = polygen(QQ)
sage: K.<z> = CyclotomicField(3)
sage: L.<a> = K.extension(x^3 - 2)
sage: t = polygen(L, 't')
sage: f = (t^3 + t + a)*(t^5 + t + z); f
t^8 + t^6 + a*t^5 + t^4 + z*t^3 + t^2 + (a + z)*t + z*a
sage: f.factor()
(t^3 + t + a) * (t^5 + t + z)
```

Over the real double field:
The above output is incorrect because it relies on the `roots()` method, which does not detect that all the roots are real:

```
sage: f.roots() # abs tol 2e-5
[(1.0000065719436413, 1)]
```

Over the complex double field the factors are approximate and therefore occur with multiplicity 1:

```
sage: R.<x> = CDF[]
sage: f = (x^2 + 2*R(I))^3
sage: F = f.factor()
sage: F
# abs tol 3e-5
(x - 1.0000138879287663 + 1.0000013435286547*I) * (x - 0.9999985293216753 - 0.7653668647301795*I) * (x + 0.70710678118654758 + 0.70710678118654758*I)
sage: [f(t[0][0]).abs() for t in F] # abs tol 1e-13
[1.979365054e-14, 1.97936298566e-14, 1.97936990747e-14, 3.65220890052e-14]
```

Factoring polynomials over \(\mathbb{Z}/n\mathbb{Z}\) for composite \(n\) is not implemented:

```
sage: R.<x> = PolynomialRing(Integers(35))
sage: f = (x^2+2*x+2)*(x^2+3*x+9)
sage: f.factor()
Traceback (most recent call last):
  ...
NotImplementedError: factorization of polynomials over rings with composite characteristic is not implemented
```

Factoring polynomials over the algebraic numbers (see github issue #8544):

```
sage: R.<x> = QQbar[]
sage: (x^8-1).factor()
(x - 1) * (x - 0.70710678118654757 - 0.70710678118654757*I) * \ldots
```

Factoring polynomials over the algebraic reals (see github issue #8544):

```
sage: R.<x> = AA[]
sage: (x^8+1).factor()
(x^2 - 1.8477590650225746?*x + 1.0000000000000000?0) * \ldots
```

(continues on next page)
The actual algorithm for computing greatest common divisors depends on the base ring underlying the polynomial ring. If the base ring defines a method \_gcd_univariate_polynomial, then this method will be called (see examples below).

EXTRACTIONS:

\[ x + 1.000000000000000? \] \[ (x^2 + 0.7653668647301795?x + 1.000000000000000?) \] \[ (x^2 + 1.847759065022574?x + 1.000000000000000?) \]

\[
gcd(other)\]

Return a greatest common divisor of this polynomial and other.

INPUT:

\[ \bullet \text{ other} - \text{ a polynomial in the same ring as this polynomial} \]

OUTPUT:

A greatest common divisor as a polynomial in the same ring as this polynomial. If the base ring is a field, the return value is a monic polynomial.

Note: The actual algorithm for computing greatest common divisors depends on the base ring underlying the polynomial ring. If the base ring defines a method \_gcd_univariate_polynomial, then this method will be called (see examples below).

EXAMPLES:

\[
sage: R.<x> = QQ[]
sage: (2*x^2).gcd(2*x)
x
sage: R.zero().gcd(0)
0
sage: (2*x).gcd(0)
x
\]

One can easily add gcd functionality to new rings by providing a method \_gcd_univariate_polynomial:

\[
sage: O = ZZ[-sqrt(5)]
sage: R.<x> = O[]
sage: a = O.1
sage: p = x + a
sage: q = x^2 - 5
sage: p.gcd(q)
Traceback (most recent call last):
...
NotImplementedError: Order in Number Field in a with defining polynomial x^2 - 5 with a = -2.236067777302189? does not provide a gcd implementation for univariate polynomials

\[
sage: S.<x> = O.number_field()[]
sage: O._gcd_univariate_polynomial = lambda f,g : R(S(f).gcd(S(g)))
sage: p.gcd(q)
x + a
sage: del O._gcd_univariate_polynomial
\]

Use multivariate implementation for polynomials over polynomials rings:

\[
sage: R.<x> = ZZ[]
sage: S.<y> = R[]
sage: T.<z> = S[]
\]

(continues on next page)
sage: r = 2*x*y + z
sage: p = r * (3*x*y*z - 1)
sage: q = r * (x + y + z - 2)
sage: p.gcd(q)
z + 2*x*y

sage: R.<x> = QQ[]
sage: S.<y> = R[]
sage: r = 2*x*y + 1
sage: p = r * (x - 1/2 * y)
sage: q = r * (x*y^2 - x + 1/3)
sage: p.gcd(q)
2*x*y + 1

**global_height**(prec=None)

Return the (projective) global height of the polynomial.

This returns the absolute logarithmic height of the coefficients thought of as a projective point.

**INPUT:**

- prec – desired floating point precision (default: default RealField precision).

**OUTPUT:**

- a real number.

**EXAMPLES:**

sage: R.<x> = PolynomialRing(QQ)
sage: f = 3*x^3 + 2*x^2 + x
sage: exp(f.global_height())
3.00000000000000

Scaling should not change the result:

sage: R.<x> = PolynomialRing(QQ)
sage: f = 1/25*x^2 + 25/3*x + 1
sage: f.global_height()
6.43775164973640
sage: g = 100 * f
sage: g.global_height()
6.43775164973640

sage: R.<x> = PolynomialRing(QQbar)
sage: f = QQbar(i)*x^2 + 3*x
sage: f.global_height()
1.09861228866811

sage: R.<x> = PolynomialRing(QQ)

sage: K.<k> = NumberField(x^2 + 5)
sage: T.<t> = PolynomialRing(K)
sage: f = 1/1331 * t^2 + 5 * t + 7
sage: f.global_height()
9.13959596745043

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```python
sage: R.<x> = QQ[]
sage: f = 1/123*x^2 + 12
sage: f.global_height(prec=2)
8.0
```

```python
sage: R.<x> = QQ[]
sage: f = 0*x
sage: f.global_height()
0.000000000000000
```

**gradient()**
Return a list of the partial derivative of `self` with respect to the variable of this univariate polynomial.

There is only one partial derivative.

**EXAMPLES:**

```python
sage: P.<x> = QQ[]
sage: f = x^2 + (2/3)*x + 1
sage: f.gradient()
[2*x + 2/3]
sage: f = P(1)
sage: f.gradient()
[0]
```

**hamming_weight()**
Return the number of non-zero coefficients of `self`.

Also called weight, Hamming weight or sparsity.

**EXAMPLES:**

```python
sage: R.<x> = ZZ[]
sage: f = x^3 - x
sage: f.number_of_terms()
2
sage: R(0).number_of_terms()
0
sage: f = (x+1)^100
sage: f.number_of_terms()
101
sage: S = GF(5)['y']
sage: S(f).number_of_terms()
5
sage: cyclotomic_polynomial(105).number_of_terms()
33
```

The method `hamming_weight()` is an alias:

```python
sage: f.hamming_weight()
101
```

**has_cyclotomic_factor()**
Return True if the given polynomial has a nontrivial cyclotomic factor.

The algorithm assumes that the polynomial has rational coefficients.
If the polynomial is known to be irreducible, it may be slightly more efficient to call \texttt{is\_cyclotomic} instead.

See also:

\texttt{is\_cyclotomic()} \texttt{is\_cyclotomic\_product()} \texttt{cyclotomic\_part()}

EXAMPLES:

```
sage: pol.<x> = PolynomialRing(Rationals())
sage: u = x^5-1; u.has_cyclotomic_factor()
True
sage: u = x^5-2; u.has_cyclotomic_factor()
False
sage: u = pol(cyclotomic_polynomial(7)) * pol.random_element() # random
sage: u.has_cyclotomic_factor() # random
True
```

\textbf{homogenize(\texttt{var='h'})}

Return the homogenization of this polynomial.

The polynomial itself is returned if it is homogeneous already. Otherwise, its monomials are multiplied with the smallest powers of \texttt{var} such that they all have the same total degree.

INPUT:

- \texttt{var} – a variable in the polynomial ring (as a string, an element of the ring, or \texttt{0}) or a name for a new variable (default: \texttt{‘h’})

OUTPUT:

If \texttt{var} specifies the variable in the polynomial ring, then a homogeneous element in that ring is returned. Otherwise, a homogeneous element is returned in a polynomial ring with an extra last variable \texttt{var}.

EXAMPLES:

```
sage: R.<x> = QQ[]
sage: f = x^2 + 1
sage: f.homogenize()
x^2 + h^2
sage: g = f.homogenize(’z’); g
x^2 + z^2
sage: g.parent()
Multivariate Polynomial Ring in x, z over Rational Field
```

The parameter \texttt{var} can be used to specify the name of the variable:

```
sage: g = f.homogenize(’z’); g
x^2 + z^2
```

However, if the polynomial is homogeneous already, then that parameter is ignored and no extra variable is added to the polynomial ring:

```
sage: f = x^2
sage: g = f.homogenize(’z’); g
x^2
sage: g.parent()
Univariate Polynomial Ring in x over Rational Field
```

For compatibility with the multivariate case, if \texttt{var} specifies the variable of the polynomial ring, then the monomials are multiplied with the smallest powers of \texttt{var} such that the result is homogeneous; in other words, we end up with a monomial whose leading coefficient is the sum of the coefficients of the polynomial:
sage: \( f = x^2 + x + 1 \)
sage: \( f.\text{homogenize('x')} \)
\( 3^*x^2 \)

In positive characteristic, the degree can drop in this case:

sage: \( R.<x> = \text{GF}(2)[x] \)
sage: \( f = x + 1 \)
sage: \( f.\text{homogenize(x)} \)
\( 0 \)

For compatibility with the multivariate case, the parameter \texttt{var} can also be \( 0 \) to specify the variable in the polynomial ring:

sage: \( R.<x> = \text{QQ}[x] \)
sage: \( f = x^2 + x + 1 \)
sage: \( f.\text{homogenize(0)} \)
\( 3^*x^2 \)

\texttt{integral}(\text{\texttt{var=\textit{None}}})

Return the integral of this polynomial.

By default, the integration variable is the variable of the polynomial.

Otherwise, the integration variable is the optional parameter \texttt{var}

\textbf{Note:} The integral is always chosen so that the constant term is 0.

\textbf{EXAMPLES:}

sage: \( R.<x> = \text{ZZ}[x] \)
sage: \( R(0).\text{integral()} \)
\( 0 \)
sage: \( f = R(2).\text{integral()}; f \)
\( 2^*x \)

Note that the integral lives over the fraction field of the scalar coefficients:

sage: \( f.\text{parent()} \)
Univariate Polynomial Ring in \( x \) over Rational Field
sage: \( R(0).\text{integral()}.\text{parent()} \)
Univariate Polynomial Ring in \( x \) over Rational Field

sage: \( f = x^3 + x - 2 \)
sage: \( g = f.\text{integral()}; g \)
\( 1/4^*x^4 + 1/2^*x^2 - 2^*x \)
sage: \( g.\text{parent()} \)
Univariate Polynomial Ring in \( x \) over Rational Field

This shows that the issue at \texttt{github issue #7711} is resolved:

sage: \( P.<x,z> = \text{PolynomialRing}(<\text{\texttt{GF(2147483647)}}>) \)
sage: \( Q.<y> = \text{PolynomialRing}(P) \)

(continues on next page)
sage: p=x+y+z
sage: p.integral()
-1073741823*y^2 + (x + z)*y

sage: P.<x,z> = PolynomialRing(GF(next_prime(2147483647)))
sage: Q.<y> = PolynomialRing(P)
sage: p=x+y+z
sage: p.integral()
1073741830*y^2 + (x + z)*y

A truly convoluted example:

sage: A.<a1, a2> = PolynomialRing(ZZ)
sage: B.<b> = PolynomialRing(A)
sage: C.<c> = PowerSeriesRing(B)
sage: R.<x> = PolynomialRing(C)
sage: f = a2*x^2 + c*x - a1*b
sage: f.parent()
Univariate Polynomial Ring in x over Power Series Ring in c over Univariate Polynomial Ring in b over Multivariate Polynomial Ring in a1, a2 over Integer Ring
sage: f.integral()
1/3*a2*x^3 + 1/2*c*x^2 - a1*b*x
sage: f.integral().parent()
Univariate Polynomial Ring in x over Power Series Ring in c over Univariate Polynomial Ring in b over Multivariate Polynomial Ring in a1, a2 over Rational Field

sage: g = 3*a2*x^2 + 2*c*x - a1*b
sage: g.integral()
a2*x^3 + c*x^2 - a1*b*x
sage: g.integral().parent()
Univariate Polynomial Ring in x over Power Series Ring in c over Univariate Polynomial Ring in b over Multivariate Polynomial Ring in a1, a2 over Rational Field

Integration with respect to a variable in the base ring:

sage: R.<x> = QQ[]
sage: t = PolynomialRing(R,'t').gen()
sage: f = x*t +5*t^2
sage: f.integral(x)
5*x^2*t + 1/2*x^2*t^2

**inverse_mod(a, m)**

Inverts the polynomial a with respect to m, or raises a ValueError if no such inverse exists. The parameter m may be either a single polynomial or an ideal (for consistency with inverse_mod in other rings).

**See also:**

If you are only interested in the inverse modulo a monomial $x^k$ then you might use the specialized method **inverse_series_trunc()** which is much faster.

**EXAMPLES:**
Polynomials, Release 10.0

```python
sage: S.<t> = QQ[]
sage: f = inverse_mod(t^2 + 1, t^3 + 1); f
-1/2*t^2 - 1/2*t + 1/2
sage: f * (t^2 + 1) % (t^3 + 1)
1
sage: f = t.inverse_mod((t+1)^7); f
-t^6 - 7*t^5 - 21*t^4 - 35*t^3 - 35*t^2 - 21*t - 7
sage: (f * t) + (t+1)^7
1
sage: t.inverse_mod(S.ideal((t + 1)^7)) == f
True
```

This also works over inexact rings, but note that due to rounding error the product may not always exactly equal the constant polynomial 1 and have extra terms with coefficients close to zero.

```python
sage: R.<x> = RDF[]
sage: epsilon = RDF(1).ulp()*50  # Allow an error of up to 50 ulp
sage: f = inverse_mod(x^2 + 1, x^5 + x + 1); f  # abs tol 1e-14
0.4*x^4 - 0.2*x^3 - 0.4*x^2 + 0.2*x + 0.8
sage: poly = f * (x^2 + 1) % (x^5 + x + 1)
sage: # Remove noisy zero terms:
sage: parent(poly)([ 0.0 if abs(c)<=epsilon else c for c in poly.coefficients(sparse=False) ])
1.0
sage: f = inverse_mod(x^3 - x + 1, x - 2); f
0.14285714285714285
sage: f * (x^3 - x + 1) % (x - 2)
1.0
sage: g = 5*x^3+x-7; m = x^4-12*x+13; f = inverse_mod(g, m); f
-0.031963612521962896*x^3 - 0.038326975955204496*x^2 - 0.046305090020941615*x + 0.34647968758236495
sage: poly = f*g % m
sage: # Remove noisy zero terms:
sage: parent(poly)([ 0.0 if abs(c)<=epsilon else c for c in poly.coefficients(sparse=False) ])
# abs tol 1e-14
1.0000000000000004
```

ALGORITHM: Solve the system as \( as + mt = 1 \), returning \( s \) as the inverse of \( a \) mod \( m \).

Uses the Euclidean algorithm for exact rings, and solves a linear system for the coefficients of \( s \) and \( t \) for inexact rings (as the Euclidean algorithm may not converge in that case).

AUTHORS:

inverse_of_unit()

EXAMPLES:

```python
sage: R.<x> = QQ[]
sage: f = x - 90283
sage: f.inverse_of_unit()
Traceback (most recent call last):
...
ArithmeticError: x - 90283 is not a unit in Univariate Polynomial Ring in x...
  over Rational Field
```

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Polynomials, Release 10.0

```
sage: f = R(-90283); g = f.inverse_of_unit(); g
-1/90283
sage: parent(g)
Univariate Polynomial Ring in x over Rational Field
```

**inverse_series_trunc(prec)**

Return a polynomial approximation of precision prec of the inverse series of this polynomial.

**See also:**

The method *inverse_mod()* allows more generally to invert this polynomial with respect to any ideal.

**EXAMPLES:**

```
sage: x = polygen(ZZ)
sage: s = (1+x).inverse_series_trunc(5)
sage: s
x^4 - x^3 + x^2 - x + 1
sage: s * (1+x)
x^5 + 1
```

Note that the constant coefficient needs to be a unit:

```
sage: ZZx.<x> = ZZ[]
sage: ZZxy.<y> = ZZx[]
sage: (1+x + y**2).inverse_series_trunc(4)
Traceback (most recent call last):
...
ValueError: constant term x + 1 is not a unit
```

The method works over any polynomial ring:

```
sage: R = Zmod(4)
sage: Rx.<x> = R[]
sage: Rxy.<y> = Rx[]
sage: p = 1 + (1+2*x)*y + x**2*y**4
sage: q = p.inverse_series_trunc(10)
sage: (p*q).truncate(11)
(2*x^4 + 3*x^2 + 3)*y^10 + 1
```

Even noncommutative ones:

```
sage: M = MatrixSpace(ZZ,2)
sage: x = polygen(M)
sage: p = M([1,2,3,4])*x^3 + M([1,0,0,1])*x^2 + M([1,3,-1,0])*x + M.one()
sage: q = p.inverse_series_trunc(5)
sage: (p*q).truncate(5) == M.one()
True
sage: q = p.inverse_series_trunc(13)
sage: (p*q).truncate(13) == M.one()
True
```
AUTHORS:

• David Harvey (2006-09-09): Newton’s method implementation for power series
• Vincent Delecroix (2014-2015): move the implementation directly in polynomial

**is_constant()**

Return True if this is a constant polynomial.

**OUTPUT:**

• bool - True if and only if this polynomial is constant

**EXAMPLES:**

```python
sage: R.<x> = ZZ[]
sage: x.is_constant()
False
sage: R(2).is_constant()
True
sage: R(0).is_constant()
True
```

**is_cyclotomic(certificate=False, algorithm='pari')**

Test if this polynomial is a cyclotomic polynomial.

A **cyclotomic polynomial** is a monic, irreducible polynomial such that all roots are roots of unity.

By default the answer is a boolean. But if certificate is True, the result is a non-negative integer: it is 0 if self is not cyclotomic, and a positive integer n if self is the n-th cyclotomic polynomial.

**See also:**

`is_cyclotomic_product()` `cyclotomic_part()` `has_cyclotomic_factor()`

**INPUT:**

• certificate – boolean, default to False. Only works with algorithm set to “pari”.
• algorithm – either “pari” or “sage” (default is “pari”)

**ALGORITHM:**

The native algorithm implemented in Sage uses the first algorithm of [BD1989]. The algorithm in pari (using pari:poliscyclo) is more subtle since it does compute the inverse of the Euler φ function to determine the n such that the polynomial is the n-th cyclotomic polynomial.

**EXAMPLES:**

Quick tests:

```python
sage: P.<x> = ZZ['x']
sage: (x - 1).is_cyclotomic()
True
sage: (x + 1).is_cyclotomic()
True
sage: (x^2 - 1).is_cyclotomic()
False
sage: (x^2 + x + 1).is_cyclotomic(certificate=True)
3
sage: (x^2 + 2*x + 1).is_cyclotomic(certificate=True)
0
```
Test first 100 cyclotomic polynomials:

```sage
sage: all(cyclotomic_polynomial(i).is_cyclotomic() for i in range(1,101))
True
```

Some more tests:

```sage
sage: (x^16 + x^14 - x^10 + x^8 - x^6 + x^2 + 1).is_cyclotomic(algorithm="pari")
False
sage: (x^16 + x^14 - x^10 + x^8 - x^6 + x^2 + 1).is_cyclotomic(algorithm="sage")
False
sage: (x^16 + x^14 - x^10 - x^8 - x^6 + x^2 + 1).is_cyclotomic(algorithm="pari")
True
sage: (x^16 + x^14 - x^10 - x^8 - x^6 + x^2 + 1).is_cyclotomic(algorithm="sage")
True
sage: y = polygen(QQ)
sage: (y/2 - 1/2).is_cyclotomic()
False
sage: (2*(y/2 - 1/2)).is_cyclotomic()
True
```

Invalid arguments:

```sage
sage: (x - 3).is_cyclotomic(algorithm="sage", certificate=True)
Traceback (most recent call last):
...  
ValueError: no implementation of the certificate within Sage
```

Test using other rings:

```sage
sage: z = polygen(GF(5))
sage: (z - 1).is_cyclotomic()
Traceback (most recent call last):
...  
NotImplementedError: not implemented in non-zero characteristic
```

**is_cyclotomic_product()**

Test whether this polynomial is a product of cyclotomic polynomials.

This method simply calls the function `pari:poliscycloprod` from the Pari library.

See also:

**is_cyclotomic() cyclotomic_part() has_cyclotomic_factor()**

EXAMPLES:

```sage
sage: x = polygen(ZZ)
sage: (x^5 - 1).is_cyclotomic_product()
True
sage: (x^5 + x^4 - x^2 + 1).is_cyclotomic_product()
False
sage: p = prod(cyclotomic_polynomial(i) for i in [2,5,7,12])
```

(continues on next page)
\begin{verbatim}
sage: p.is_cyclotomic_product()
True

sage: (x^5 - 1/3).is_cyclotomic_product()
False

sage: x = polygen(Zmod(5))
sage: (x-1).is_cyclotomic_product()
Traceback (most recent call last):
...
NotImplementedError: not implemented in non-zero characteristic
\end{verbatim}

**is_gen()**

Return True if this polynomial is the distinguished generator of the parent polynomial ring.

**EXAMPLES:**

\begin{verbatim}
sage: R.<x> = QQ[]
sage: R(1).is_gen()
False
sage: R(x).is_gen()
True
\end{verbatim}

Important - this function doesn't return True if self equals the generator; it returns True if self is the generator.

\begin{verbatim}
sage: f = R([0,1]); f
x
sage: f.is_gen()
False
sage: f is x
False
sage: f == x
True
\end{verbatim}

**is_homogeneous()**

Return True if this polynomial is homogeneous.

**EXAMPLES:**

\begin{verbatim}
sage: P.<x> = PolynomialRing(QQ)
sage: x.is_homogeneous()
True
sage: P(0).is_homogeneous()
True
sage: (x+1).is_homogeneous()
False
\end{verbatim}

**is_irreducible()**

Return whether this polynomial is irreducible.

**EXAMPLES:**
The base ring does matter: for example, $2x$ is irreducible as a polynomial in $\mathbb{Q}[x]$, but not in $\mathbb{Z}[x]$:

```python
sage: R.<x> = ZZ[]
sage: R(2*x).is_irreducible()
False
sage: R.<x> = QQ[]
sage: R(2*x).is_irreducible()
True
```

**is_lorentzian** *(explain=False)*  
Return True if this is a Lorentzian polynomial.  
A univariate real polynomial is Lorentzian if and only if it is a monomial with positive coefficient, or zero.  
The definition is more involved for multivariate real polynomials.  

**INPUT:**  
• explain – boolean (default: False); if True return a tuple whose first element is the boolean result of the test, and the second element is a string describing the reason the test failed, or None if the test succeeded  

**EXAMPLES:**

```python
sage: P.<x> = QQ[]
sage: p1 = x^2
sage: p1.is_lorentzian()
True
sage: p2 = 1 + x^2
sage: p2.is_lorentzian()
False
sage: p3 = P.zero()
```

```python
sage: p3.is_lorentzian()
True
```

```python
sage: p4 = -2*x^3
sage: p4.is_lorentzian()
False
```

It is an error to check if a polynomial is Lorentzian if its base ring is not a subring of the real numbers, as the notion is not defined in this case:

```python
sage: Q.<y> = CC[]
sage: q = y^2
sage: q.is_lorentzian()
```

Traceback (most recent call last):
(continues on next page)
The method can give a reason for a polynomial failing to be Lorentzian:

```python
sage: p = x^2 + 2*x
sage: p.is_lorentzian(explain=True)
(False, 'inhomogeneous')
```

REFERENCES:

For full definitions and related discussion, see [BrHu2019] and [HMMS2019].

**is_monic()**

Returns True if this polynomial is monic. The zero polynomial is by definition not monic.

EXAMPLES:

```python
sage: x = QQ['x'].0
sage: f = x + 33
sage: f.is_monic()  # True
sage: f = 0*x
sage: f.is_monic()  # False
sage: f = 3*x^3 + x^4 + x^2
sage: f.is_monic()  # True
sage: f = 2*x^2 + x^3 + 56*x^5
sage: f.is_monic()  # False
```

AUTHORS:

• Naqi Jaffery (2006-01-24): examples

**is_monomial()**

Return True if self is a monomial, i.e., a power of the generator.

EXAMPLES:

```python
sage: R.<x> = QQ[]
sage: x.is_monomial()  # True
sage: (x+1).is_monomial()  # False
sage: (x^2).is_monomial()  # True
sage: R(1).is_monomial()  # True
```

The coefficient must be 1:

```python
sage: (2*x^5).is_monomial()  # False
```
To allow a non-1 leading coefficient, use is_term():

```
sage: (2*x^5).is_term()
True
```

**Warning:** The definition of is_monomial in Sage up to 4.7.1 was the same as is_term, i.e., it allowed a coefficient not equal to 1.

**is_nilpotent()**

Return True if this polynomial is nilpotent.

**EXAMPLES:**

```
sage: R = Integers(12)
sage: S.<x> = R[]
sage: f = 5 + 6*x
sage: f.is_nilpotent()
False
sage: f = 6 + 6*x^2
sage: f.is_nilpotent()
True
sage: f^2
0
```

EXERCISE (Atiyah-McDonald, Ch 1): Let \( A[x] \) be a polynomial ring in one variable. Then \( f = \sum a_i x^i \in A[x] \) is nilpotent if and only if every \( a_i \) is nilpotent.

**is_one()**

Test whether this polynomial is 1.

**EXAMPLES:**

```
sage: R.<x> = QQ[]
sage: (x-3).is_one()
False
sage: R(1).is_one()
True
sage: R2.<y> = R[]
sage: R2(x).is_one()
False
sage: R2(1).is_one()
True
sage: R2(-1).is_one()
False
```

**is_primitive** (n=None, n_prime_divs=None)

Return True if the polynomial is primitive.

The semantics of “primitive” depend on the polynomial coefficients.

- (field theory) A polynomial of degree \( m \) over a finite field \( F_q \) is primitive if it is irreducible and its root in \( F_q^m \) generates the multiplicative group \( F_q^* \).
- (ring theory) A polynomial over a ring is primitive if its coefficients generate the unit ideal.
Calling \texttt{isprimitive} on a polynomial over an infinite field will raise an error.

The additional inputs to this function are to speed up computation for field semantics (see note).

INPUT:

\begin{itemize}
  \item \texttt{n} (default: \texttt{None}) - if provided, should equal \(q-1\) where \texttt{self.parent()} is the field with \(q\) elements; otherwise it will be computed.
  \item \texttt{n\_prime\_divs} (default: \texttt{None}) - if provided, should be a list of the prime divisors of \(n\); otherwise it will be computed.
\end{itemize}

\textbf{Note:} Computation of the prime divisors of \(n\) can dominate the running time of this method, so performing this computation externally (e.g. \texttt{pdivs=n.prime\_divisors()}) is a good idea for repeated calls to \texttt{is\_primitive} for polynomials of the same degree.

Results may be incorrect if the wrong \(n\) and/or factorization are provided.

\textbf{EXAMPLES:}

\texttt{Field semantics examples.}

\begin{verbatim}
::
sage: R.<x> = GF(2)['x']
sage: f = x^4+x^3+x^2+x+1
sage: f.is_irreducible(), f.is_primitive()
(True, False)
sage: f = x^3+x+1
sage: f.is_irreducible(), f.is_primitive()
(True, True)
sage: R.<x> = GF(3)[]
sage: f = x^3-x+1
sage: f.is_irreducible(), f.is_primitive()
(True, True)
sage: f = x^2+1
sage: f.is_irreducible(), f.is_primitive()
(True, False)
sage: R.<x> = GF(5)[]
sage: f = x^2+x+1
sage: f.is_primitive()
False
sage: f = x^2-x+2
sage: f.is_primitive()
True
sage: x=polygen(QQ); f=x^2+1
sage: f.is_primitive()  # Not implemented, isPrimitive not defined for polynomials over infinite fields.

::
\end{verbatim}
sage: x=polygen(ZZ)
sage: f = 5*x^2+2
sage: f.is_primitive()
True
sage: f = 5*x^2+5
sage: f.is_primitive()
False

sage: K=NumberField(x^2+5,'a')
sage: R=K.ring_of_integers()
sage: a=R.gen(1)
sage: a^2
-5
sage: f=a*x+2
sage: f.is_primitive()
True
sage: f=(1+a)*x+2
sage: f.is_primitive()
False

sage: x = polygen(Integers(10))
sage: f = 5*x^2+2
sage: #f.is_primitive() #BUG:: elsewhere in Sage, should return True
sage: f=4*x^2+2
sage: #f.is_primitive() #BUG:: elsewhere in Sage, should return False

**is_real_rooted()**

Return True if the roots of this polynomial are all real.

**EXAMPLES:**

```sage
sage: R.<x> = PolynomialRing(ZZ)
sage: pol = chebyshev_T(5, x)
sage: pol.is_real_rooted()
True
sage: pol = x^2 + 1
sage: pol.is_real_rooted()
False
```

**is_square**(root=False)

Return whether or not polynomial is square.

If the optional argument root is set to True, then also returns the square root (or None, if the polynomial is not square).

**INPUT:**

- root - whether or not to also return a square root (default: False)

**OUTPUT:**

- bool - whether or not a square
- root - (optional) an actual square root if found, and None otherwise.
EXAMPLES:

```
sage: R.<x> = PolynomialRing(QQ)
sage: (x^2 + 2*x + 1).is_square()
True
sage: (x^4 + 2*x^3 - x^2 - 2*x + 1).is_square(root=True)
(True, x^2 + x - 1)

sage: f = 12*(x+1)^2 * (x+3)^2
sage: f.is_square()
False
sage: f.is_square(root=True)
(False, None)

sage: h = f/3; h
4*x^4 + 32*x^3 + 88*x^2 + 96*x + 36
sage: h.is_square(root=True)
(True, 2*x^2 + 8*x + 6)

sage: S.<y> = PolynomialRing(RR)
sage: g = 12*(y+1)^2 * (y+3)^2
sage: g.is_square()
True
```

\texttt{is\_squarefree()}\n
Return False if this polynomial is not square-free, i.e., if there is a non-unit \( g \) in the polynomial ring such that \( g^2 \) divides self.

\textbf{Warning:} This method is not consistent with \texttt{squarefree\_decomposition()} since the latter does not factor the content of a polynomial. See the examples below.

EXAMPLES:

```
sage: R.<x> = QQ[]
sage: f = (x-1)*(x-2)*(x^2-5)*(x^17-3); f
x^21 - 3*x^20 - 3*x^19 + 15*x^18 - 10*x^17 - 3*x^4 + 9*x^3 + 9*x^2 - 45*x + 30
sage: f.is_squarefree()
True
sage: (f*(x^2-5)).is_squarefree()
False
```

A generic implementation is available, which relies on gcd computations:

```
sage: R.<x> = ZZ[]
sage: (2*x).is_squarefree()
True
sage: (4*x).is_squarefree()
False
sage: (2*x^2).is_squarefree()
False
sage: R(0).is_squarefree()
```

(continues on next page)
In positive characteristic, we compute the square-free decomposition or a full factorization, depending on which is available:

```
sage: K.<t> = FunctionField(GF(3))
sage: R.<x> = K[]
sage: (x^3-x).is_squarefree()  
   True
sage: (x^3-1).is_squarefree()  
   False
sage: (x^3+t).is_squarefree()  
   True
sage: (x^3+t^3).is_squarefree()  
   False
```

In the following example, \( t^2 \) is a unit in the base field:

```
sage: R(t^2).is_squarefree()  
   True
```

This method is not consistent with `squarefree_decomposition()`:

```
sage: f = 4 * x
sage: f.is_squarefree()  
   False
sage: f.squarefree_decomposition()
   (4) * x
```

If you want this method equally not to consider the content, you can remove it as in the following example:

```
sage: c = f.content()
sage: (f/c).is_squarefree()  
   True
```

If the base ring is not an integral domain, the question is not mathematically well-defined:

```
sage: pol = (x + 3)*(x + 6); pol
   x^2
sage: pol.is_squarefree()  
   Traceback (most recent call last):
   ...  
   TypeError: is_squarefree() is not defined for polynomials over Ring of integers modulo 9
```
is_term()

Return True if this polynomial is a nonzero element of the base ring times a power of the variable.

EXAMPLES:

```
sage: R.<x> = QQ[]
sage: x.is_term()  
True
sage: R(0).is_term()  
False
sage: R(1).is_term()  
True
sage: (3*x^5).is_term()  
True
sage: (1+3*x^5).is_term()  
False
```

To require that the coefficient is 1, use is_monomial() instead:

```
sage: (3*x^5).is_monomial()  
False
```

is_unit()

Return True if this polynomial is a unit.

EXAMPLES:

```
sage: a = Integers(90384098234^3)
sage: b = a(2*191*236607587)
sage: b.is_nilpotent()  
True
sage: R.<x> = a[]
sage: f = 3 + b*x + b^2*x^2
sage: f.is_unit()  
True
sage: f = 3 + b*x + b^2*x^2 + 17*x^3
sage: f.is_unit()  
False
```

EXERCISE (Atiyah-McDonald, Ch 1): Let $A[x]$ be a polynomial ring in one variable. Then $f = \sum a_i x^i \in A[x]$ is a unit if and only if $a_0$ is a unit and $a_1, \ldots, a_n$ are nilpotent.

is_weil_polynomial(return_q=False)

Return True if this is a Weil polynomial.

This polynomial must have rational or integer coefficients.

INPUT:

- self – polynomial with rational or integer coefficients

- return_q – (default False) if True, return a second value q
  which is the prime power with respect to which this is $q$-Weil, or 0 if there is no such value.

EXAMPLES:
sage: polRing.<x> = PolynomialRing(Rationals())
sage: P0 = x^4 + 5*x^3 + 15*x^2 + 25*x + 25
sage: P1 = x^4 + 25*x^3 + 15*x^2 + 5*x + 25
sage: P2 = x^4 + 5*x^3 + 25*x^2 + 25*x + 25
sage: P0.is_weil_polynomial(return_q=True)
(True, 5)
sage: P0.is_weil_polynomial(return_q=False)
True
sage: P1.is_weil_polynomial(return_q=True)
(False, 0)
sage: P1.is_weil_polynomial(return_q=False)
False
sage: P2.is_weil_polynomial()
False

See also:
Polynomial rings have a method \texttt{weil} to compute sets of Weil polynomials. This computation
uses the iterator \texttt{sage.rings.polynomial.weil.weil_polynomials.WeilPolynomials}.

AUTHORS:
David Zureick-Brown (2017-10-01)

\texttt{is_zero()}
Test whether this polynomial is zero.

\textbf{EXAMPLES:}

sage: R = GF(2)['x']['y']
sage: R([0,1]).is_zero()
False
sage: R([0]).is_zero()
True
sage: R([-1]).is_zero()
False

\texttt{lc()}
Return the leading coefficient of this polynomial.

\textbf{OUTPUT:} element of the base ring This method is same as \texttt{leading_coefficient()}. 

\textbf{EXAMPLES:}

sage: R.<x> = QQ[]
sage: f = (-2/5)*x^3 + 2*x - 1/3
sage: f.lc()
-2/5

\texttt{lcm(other)}
Let f and g be two polynomials. Then this function returns the monic least common multiple of f and g.

\texttt{leading_coefficient()}
Return the leading coefficient of this polynomial.

\textbf{OUTPUT:} element of the base ring

\textbf{EXAMPLES:}
```
sage: R.<x> = QQ[]
sage: f = (-2/5)*x^3 + 2*x - 1/3
sage: f.leading_coefficient()
-2/5
```

**list**(copy=True)

Return a new copy of the list of the underlying elements of `self`.

**EXAMPLES:**

```
sage: R.<x> = QQ[]
sage: f = (-2/5)*x^3 + 2*x - 1/3
sage: v = f.list(); v
[-1/3, 2, 0, -2/5]
```

Note that `v` is a list, it is mutable, and each call to the list method returns a new list:

```
sage: type(v)
<...
'sage.rings.polynomial.polynomial_element.Polynomial_dense_flint'>
sage: v[0] = 5
```

```
sage: f.list()
[-1/3, 2, 0, -2/5]
```

Here is an example with a generic polynomial ring:

```
sage: R.<x> = QQ[]
sage: S.<y> = R[]
sage: f = y^3 + x*y -3*x; f
y^3 + x*y - 3*x
sage: type(f)
<class 'sage.rings.polynomial.polynomial_element.Polynomial_generic_dense'>
sage: v = f.list(); v
[-3*x, x, 0, 1]
```

```
sage: v[0] = 10
```

```
sage: f.list()
[-3*x, x, 0, 1]
```

**lm()**

Return the leading monomial of this polynomial.

**EXAMPLES:**

```
sage: R.<x> = QQ[]
sage: f = (-2/5)*x^3 + 2*x - 1/3
sage: f.lm()
x^3
```

```
sage: R(5).lm()
1
sage: R(0).lm().parent() is R
True
```

**local_height**(v, prec=None)

Return the maximum of the local height of the coefficients of this polynomial.
INPUT:
- \( v \) – a prime or prime ideal of the base ring.
- \( \text{prec} \) – desired floating point precision (default: default RealField precision).

OUTPUT:
- a real number.

EXAMPLES:

```
sage: R.<x> = PolynomialRing(QQ)
sage: f = 1/1331*x^2 + 1/4000*x
default_field = default_field
sage: f.local_height(1331)
7.19368581839511
```

```
sage: R.<x> = QQ[]
sage: K.<k> = NumberField(x^2 - 5)
sage: T.<t> = K[]
sage: I = K.ideal(3)
sage: f = 1/3*t^2 + 3
default_field = default_field
sage: f.local_height(I)
1.09861228866811
```

```
sage: R.<x> = QQ[]
sage: f = 1/2*x^2 + 2
default_field = default_field
sage: f.local_height(2, prec=2)
0.75
```

`local_height_arch(i, \text{prec=None})`

Return the maximum of the local height at the \( i \)-th infinite place of the coefficients of this polynomial.

INPUT:
- \( i \) – an integer.
- \( \text{prec} \) – desired floating point precision (default: default RealField precision).

OUTPUT:
- a real number.

EXAMPLES:

```
sage: R.<x> = PolynomialRing(QQ)
sage: f = 210*x^2
default_field = default_field
sage: f.local_height_arch(0)
5.34710753071747
```

```
sage: R.<x> = QQ[]
sage: K.<k> = NumberField(x^2 - 5)
sage: T.<t> = K[]
sage: f = 1/2*t^2 + 3
default_field = default_field
sage: f.local_height_arch(1, prec=52)
1.09861228866811
```

Chapter 2. Univariate Polynomials
```
sage: R.<x> = QQ[]
sage: f = 1/2*x^2 + 3
sage: f.local_height_arch(0, prec=2)
1.0
```

`lt()`

Return the leading term of this polynomial.

**EXAMPLES:**
```
sage: R.<x> = QQ[]
sage: f = (-2/5)*x^3 + 2*x - 1/3
sage: f.lt()
-2/5*x^3
sage: R(5).lt()
5
sage: R(0).lt()
0
sage: R(0).lt().parent() is R
True
```

`map_coefficients(f, new_base_ring=None)`

Return the polynomial obtained by applying \( f \) to the non-zero coefficients of \( \text{self} \).

If \( f \) is a `sage.categories.map.Map`, then the resulting polynomial will be defined over the codomain of \( f \). Otherwise, the resulting polynomial will be over the same ring as \( \text{self} \). Set `new_base_ring` to override this behaviour.

**INPUT:**

- \( f \) – a callable that will be applied to the coefficients of `self`.
- `new_base_ring` (optional) – if given, the resulting polynomial will be defined over this ring.

**EXAMPLES:**
```
sage: R.<x> = SR[]
sage: f = (1+I)*x^2 + 3*x - I
sage: f.map_coefficients(lambda z: z.conjugate())
(-I + 1)*x^2 + 3*x + I
sage: R.<x> = ZZ[]
sage: f = x^2 + 2
sage: f.map_coefficients(lambda a: a + 42)
43*x^2 + 44
sage: R.<x> = PolynomialRing(SR, sparse=True)
sage: f = (1+I)*x^(2^32) - I
sage: f.map_coefficients(lambda z: z.conjugate())
(-I + 1)*x^4294967296 + I
sage: R.<x> = PolynomialRing(ZZ, sparse=True)
sage: f = x^(2^32) + 2
sage: f.map_coefficients(lambda a: a + 42)
43*x^4294967296 + 44
```
Examples with different base ring:
sage: R.<x> = ZZ[]
sage: k = GF(2)
sage: residue = lambda x: k(x)
sage: f = 4*x^2+x+3
sage: g = f.map_coefficients(residue); g
x + 1
sage: g.parent()
Univariate Polynomial Ring in x over Integer Ring
sage: g = f.map_coefficients(residue, new_base_ring = k); g
x + 1
sage: g.parent()
Univariate Polynomial Ring in x over Finite Field of size 2 (using GF2X)
sage: residue = k.coerce_map_from(ZZ)
sage: g = f.map_coefficients(residue); g
x + 1
sage: g.parent()
Univariate Polynomial Ring in x over Finite Field of size 2 (using GF2X)

\textbf{mod} (other)

Remainder of division of self by other.

**EXAMPLES:**

```
sage: R.<x> = ZZ[]
sage: x % (x+1)
-1
sage: (x^3 + x - 1) % (x^2 - 1)
2*x - 1
```

\textbf{monic}()

Return this polynomial divided by its leading coefficient. Does not change this polynomial.

**EXAMPLES:**

```
sage: x = QQ['x'].0
sage: f = 2*x^2 + x^3 + 56*x^5
sage: f.monic()
x^5 + 1/56*x^3 + 1/28*x^2
sage: f = (1/4)*x^2 + 3*x + 1
sage: f.monic()
x^2 + 12*x + 4
```

The following happens because $f = 0$ cannot be made into a monic polynomial

```
sage: f = 0*x
sage: f.monic()
Traceback (most recent call last):
... 
ZeroDivisionError: rational division by zero
```

Notice that the monic version of a polynomial over the integers is defined over the rationals.

```
sage: x = ZZ['x'].0
sage: f = 3*x^19 + x^2 - 37
```
AUTHORS:
- Naqi Jaffery (2006-01-24): examples

\textbf{monomial\_coefficient}(m)

Return the coefficient in the base ring of the monomial \texttt{m} in \texttt{self}, where \texttt{m} must have the same parent as \texttt{self}.

INPUT:
- \texttt{m} - a monomial

OUTPUT:
Coefficient in base ring.

EXAMPLES:

\begin{verbatim}sage: P.<x> = QQ[]

The parent of the return is a member of the base ring.
sage: f = 2 * x
sage: c = f.monomial\_coefficient(x); c
2
sage: c.parent()
Rational Field

sage: f = x^9 - 1/2*x^2 + 7*x + 5/11
sage: f.monomial\_coefficient(x^9)
1
sage: f.monomial\_coefficient(x^2)
-1/2
sage: f.monomial\_coefficient(x)
7
sage: f.monomial\_coefficient(x^0)
5/11
sage: f.monomial\_coefficient(x^3)
0
\end{verbatim}

\textbf{monomials()}

Return the list of the monomials in \texttt{self} in a decreasing order of their degrees.

EXAMPLES:

\begin{verbatim}sage: P.<x> = QQ[]
sage: f = x^2 + (2/3)*x + 1
sage: f.monomials()
[x^2, x, 1]
sage: f = P(3/2)
sage: f.monomials()
[1]
\end{verbatim}
sage: f = P(0)
sage: f.monomials()
[]
sage: f = x
sage: f.monomials()
[x]
sage: f = -1/2*x^2 + x^9 + 7*x + 5/11
sage: f.monomials()
[x^9, x^2, x, 1]
sage: x = var('x')
sage: K.<rho> = NumberField(x^2 + 1)
sage: R.<y> = QQ[]
sage: p = rho*y
sage: p.monomials()
[y]

\texttt{multiplication\_trunc}(\textit{other}, \textit{n})

Truncated multiplication

\textbf{EXAMPLES:}

\begin{verbatim}
sage: R.<x> = ZZ[]
sage: (x^10 + 5*x^5 + x^2 - 3).multiplication_trunc(x^7 - 3*x^3 + 1, 11)
x^10 + x^9 - 15*x^8 - 3*x^7 + 2*x^5 + 9*x^3 + x^2 - 3

Check that coercion is working:

\begin{verbatim}
sage: R2 = QQ['x']
sage: x2 = R2.gen()
sage: p1 = (x^3 + 1).multiplication_trunc(x^3 - 2, 5); p1
-x^3 - 2
sage: p2 = (x^3 + 1).multiplication_trunc(x^3 - 2, 5); p2
-x^3 - 2
sage: parent(p1) == parent(p2) == R2
True
\end{verbatim}
\end{verbatim}

\texttt{newton\_raphson}(\textit{n}, \textit{x0})

Return a list of \textit{n} iterative approximations to a root of this polynomial, computed using the Newton-Raphson method.

The Newton-Raphson method is an iterative root-finding algorithm. For \( f(x) \) a polynomial, as is the case here, this is essentially the same as Horner's method.

\textbf{INPUT:}

- \textit{n} - an integer (= the number of iterations),
- \textit{x0} - an initial guess \( x_0 \).

\textbf{OUTPUT:} A list of numbers hopefully approximating a root of \( f(x) = 0 \).

If one of the iterates is a critical point of \( f \) then a \texttt{ZeroDivisionError} exception is raised.

\textbf{EXAMPLES:}
```python
sage: x = PolynomialRing(RealField(), 'x').gen()
sage: f = x^2 - 2
sage: f.newton_raphson(4, 1)
[1.50000000000000, 1.41666666666667, 1.41421568627451, 1.41421356237469]
```

AUTHORS:

- David Joyner and William Stein (2005-11-28)

**newton_slopes**(*p*, *lengths=False*)

Return the *p*-adic slopes of the Newton polygon of self, when this makes sense.

**OUTPUT:**

If *lengths* is *False*, a list of rational numbers. If *lengths* is *True*, a list of couples (*s*, *l*) where *s* is the slope and *l* the length of the corresponding segment in the Newton polygon.

**EXAMPLES:**

```python
sage: x = QQ['x'].0
sage: f = x^3 + 2
sage: f.newton_slopes(2)
[1/3, 1/3, 1/3]
sage: R.<x> = PolynomialRing(ZZ, sparse=True)
sage: p = x^5 + 6*x^2 + 4
sage: p.newton_slopes(2)
[1/2, 1/2, 1/3, 1/3, 1/3]
sage: p.newton_slopes(2, lengths=True)
[(1/2, 2), (1/3, 3)]
sage: (x^2^100 + 27).newton_slopes(3, lengths=True)
[(3/1267650600228229401496703205376, 1267650600228229401496703205376)]
```

**ALGORITHM:** Uses PARI if *lengths* is *False*.

**norm**(*p*)

Return the *p*-norm of this polynomial.

**DEFINITION:** For integer *p*, the *p*-norm of a polynomial is the *p*th root of the sum of the *p*th powers of the absolute values of the coefficients of the polynomial.

**INPUT:**

- *p* - (positive integer or +infinity) the degree of the norm

**EXAMPLES:**

```python
sage: R.<x> = RR[]
sage: f = x^6 + x^2 + -x^4 - 2*x^3
sage: f.norm(2)
2.64575131106459
sage: (sqrt(1^2 + 1^2 + (-1)^2 + (-2)^2)).n()
2.64575131106459
sage: f.norm(1)
5.00000000000000
sage: f.norm(infinity)
2.00000000000000
```

2.1. Univariate Polynomials and Polynomial Rings
AUTHORS:

- Didier Deshommes
- William Stein: fix bugs, add definition, etc.

**nth_root** \((n)\)

Return a \(n\)-th root of this polynomial.

This is computed using Newton method in the ring of power series. This method works only when the base ring is an integral domain. Moreover, for polynomial whose coefficient of lower degree is different from 1, the elements of the base ring should have a method **nth_root** implemented.

EXAMPLES:

```python
sage: R.<x> = ZZ[]
sage: a = 27 * (x+3)**6 * (x+5)**3
sage: a.nth_root(3)
3*x^3 + 33*x^2 + 117*x + 135

sage: b = 25 * (x^2 + x + 1)
sage: b.nth_root(2)
Traceback (most recent call last):
  ... ValueError: not a 2nd power
sage: R(0).nth_root(3)
0

sage: R.<x> = QQ[]
sage: a = 1/4 * (x/7 + 3/2)^2 * (x/2 + 5/3)^4
sage: a.nth_root(2)
1/56*x^3 + 103/336*x^2 + 365/252*x + 25/12

sage: K.<sqrt2> = QuadraticField(2)
sage: R.<x> = K[]
sage: a = (x + sqrt2)^3 * ((1+sqrt2)*x - 1/sqrt2)^6
sage: b = a.nth_root(3); b
(2*sqrt2 + 3)*x^3 + (2*sqrt2 + 2)*x^2 + (-2*sqrt2 - 3/2)*x + 1/2*sqrt2
sage: b^3 == a
True

sage: R.<x> = QQbar[]
sage: p = x**3 + QQbar(2).sqrt() * x - QQbar(3).sqrt()
sage: r = (p**5).nth_root(5)
sage: r * p[0] == p * r[0]
True

sage: p = (x+1)^20 + x^20
sage: p.nth_root(20)
Traceback (most recent call last):
  ... ValueError: not a 20th power
```
sage: z = GF(4).gen()
sage: R.<x> = GF(4)[]
sage: p = z^4*x^4 + 2^2*x - 1
sage: r = (p^15).nth_root(15)
sage: r * p[0] == p * r[0]
True
sage: ((x+1)**2).nth_root(2)
x + 1
sage: ((x+1)**4).nth_root(4)
x + 1
sage: ((x+1)**12).nth_root(12)
x + 1
sage: (x^4 + x^3 + 1).nth_root(2)
Traceback (most recent call last):
...  
ValueError: not a 2nd power
sage: p = (x+1)^17 + x^17
sage: r = p.nth_root(17)
Traceback (most recent call last):
...  
ValueError: not a 17th power

Here we consider a base ring without nth_root method. The third example with a non-trivial coefficient of lowest degree raises an error:

sage: R.<x> = QQ[]
sage: R2 = R.quotient(x^2 + 1)
sage: x = R2.gen()
sage: R3.<y> = R2[]
sage: (((y^2+x)*z^2 + x*y*z + 2*x)**3).nth_root(3)
(y^2 + x)*z^2 + x*y*z + 2*x
sage: ((x+y+z)**5).nth_root(5)
z + y + x

Return the number of real roots of this polynomial, counted without multiplicity.

EXAMPLES:
sage: R.<x> = PolynomialRing(ZZ)
sage: pol = (x-1)^2 * (x-2)^2 * (x-3)
sage: pol.number_of_real_roots()
3
sage: pol = (x-1)*(x-2)*(x-3)
sage: pol2 = pol.change_ring(CC)
sage: pol2.number_of_real_roots()
3
sage: R.<x> = PolynomialRing(CC)
sage: pol = (x-1)*(x-CC(I))
sage: pol.number_of_real_roots()
1

**number_of_roots_in_interval***(a=None, b=None)***

Return the number of roots of this polynomial in the interval [a,b], counted without multiplicity. The endpoints a, b default to -Infinity, Infinity (which are also valid input values).

Calls the PARI routine `pari:polsturm`.

Note that as of version 2.8, PARI includes the left endpoint of the interval (and no longer uses Sturm’s algorithm on exact inputs). `polsturm` requires a polynomial with real coefficients; in case PARI returns an error, we try again after taking the GCD of `self` with its complex conjugate.

**EXAMPLES:**

```python
sage: R.<x> = PolynomialRing(ZZ)
sage: pol = (x-1)^2 * (x-2)^2 * (x-3)
sage: pol.number_of_roots_in_interval(1, 2)
2
sage: pol.number_of_roots_in_interval(1.01, 2)
1
sage: pol.number_of_roots_in_interval(None, 2)
2
sage: pol.number_of_roots_in_interval(1, Infinity)
3
sage: pol.number_of_roots_in_interval()
3
sage: pol = (x-1)*(x-2)*(x-3)
sage: pol2 = pol.change_ring(CC)
sage: pol2.number_of_roots_in_interval()
3
sage: R.<x> = PolynomialRing(CC)
sage: pol = (x-1)*(x-CC(I))
sage: pol.number_of_roots_in_interval(0,2)
1
```

**number_of_terms**()

Return the number of non-zero coefficients of `self`.

Also called weight, Hamming weight or sparsity.

**EXAMPLES:**

```python
sage: R.<x> = ZZ[]
sage: f = x^3 - x
```
The method `hamming_weight()` is an alias:

```
sage: f.hamming_weight()
101
```

`numerator()`

Return a numerator of self computed as self * self.denominator()

Note that some subclasses may implement its own numerator function. For example, see `sage.rings.polynomial.polynomial_rational_flint.Polynomial_rational_flint`

**Warning:** This is not the numerator of the rational function defined by self, which would always be self since self is a polynomial.

**EXAMPLES:**

First we compute the numerator of a polynomial with integer coefficients, which is of course self.

```
sage: R.<x> = ZZ[]
sage: f = x^3 + 17*x + 1
sage: f.numerator()
x^3 + 17*x + 1
sage: f == f.numerator()
True
```

Next we compute the numerator of a polynomial with rational coefficients.

```
sage: R.<x> = PolynomialRing(QQ)
sage: f = (1/17)*x^19 - (2/3)*x + 1/3; f
1/17*x^19 - 2/3*x + 1/3
sage: f.numerator()
3*x^19 - 34*x + 17
sage: f == f.numerator()
False
```

We try to compute the denominator of a polynomial with coefficients in the real numbers, which is a ring whose elements do not have a denominator method.
sage: R.<x> = RR[]
sage: f = x + RR('0.3'); f
x + 0.300000000000000
sage: f.numerator()
x + 0.300000000000000

We check that the computation the numerator and denominator are valid

sage: K=NumberField(symbolic_expression('x^3+2'),'a')['s,t']['x']
sage: f=K.random_element()
sage: f.numerator() / f.denominator() == f
True

sage: R=RR['x']
sage: f=R.random_element()
sage: f.numerator() / f.denominator() == f
True

ord(p=None)
This is the same as the valuation of self at p. See the documentation for self.valuation.

EXAMPLES:

sage: R.<x> = ZZ[]
sage: (x^2+x).ord(x+1)
1

padded_list(n=None)
Return list of coefficients of self up to (but not including) q^n.
Includes 0's in the list on the right so that the list has length n.

INPUT:
• n - (default: None); if given, an integer that is at least 0

EXAMPLES:

sage: x = polygen(QQ)
sage: f = 1 + x^3 + 23*x^5
sage: f.padded_list()
[1, 0, 0, 1, 0, 23]
sage: f.padded_list(10)
[1, 0, 0, 1, 0, 23, 0, 0, 0, 0]
sage: len(f.padded_list(10))
10
sage: f.padded_list(3)
[1, 0, 0]
sage: f.padded_list(0)
[]
sage: f.padded_list(-1)
Traceback (most recent call last):
...
ValueError: n must be at least 0

plot(xmin=None, xmax=None, *args, **kwds)
Return a plot of this polynomial.
INPUT:

• xmin - float
• xmax - float
• *args, **kwds - passed to either plot or point

OUTPUT: returns a graphic object.

EXAMPLES:

```sage
x = polygen(GF(389))
sage: plot(x^2 + 1, rgbcolor=(0,0,1))
Graphics object consisting of 1 graphics primitive
sage: x = polygen(QQ)
sage: plot(x^2 + 1, rgbcolor=(1,0,0))
Graphics object consisting of 1 graphics primitive
```

`polynomial(var)`

Let var be one of the variables of the parent of self. This returns self viewed as a univariate polynomial in var over the polynomial ring generated by all the other variables of the parent.

For univariate polynomials, if var is the generator of the parent ring, we return this polynomial, otherwise raise an error.

EXAMPLES:

```sage
R.<x> = QQ[]
sage: (x+1).polynomial(x)
x + 1
```

`power_trunc(n, prec)`

Truncated n-th power of this polynomial up to precision prec

INPUT:

• n – (non-negative integer) power to be taken
• prec – (integer) the precision

EXAMPLES:

```sage
R.<x> = ZZ[]
sage: (3*x^2 - 2*x + 1).power_trunc(5, 8)
-1800*x^7 + 1590*x^6 - 1052*x^5 + 530*x^4 - 200*x^3 + 55*x^2 - 10*x + 1
sage: ((3*x^2 - 2*x + 1)^5).truncate(8)
-1800*x^7 + 1590*x^6 - 1052*x^5 + 530*x^4 - 200*x^3 + 55*x^2 - 10*x + 1
sage: S.<y> = R[]
sage: (x+y).power_trunc(5,5)
5*x*y^4 + 10*x^2*y^3 + 10*x^3*y^2 + 5*x^4*y + x^5
sage: ((x+y)^5).truncate(5)
5*x*y^4 + 10*x^2*y^3 + 10*x^3*y^2 + 5*x^4*y + x^5
sage: R.<x> = GF(3)[]
sage: p = x^2 - x + 1
sage: q = p.power_trunc(80, 20)
sage: q
```

(continues on next page)
\[x^{19} + x^{18} + \ldots + 2x^4 + 2x^3 + x + 1\]

```python
sage: (p^80).truncate(20) == q
True
```

```python
sage: R.<x> = GF(7)[]
sage: p = (x^2 + x + 1).power_trunc(2^100, 100)
sage: p
2*x^99 + x^98 + x^95 + 2*x^94 + \ldots + 3*x^2 + 2*x + 1
```  

```python
sage: for i in range(100):
    q1 = (x^2 + x + 1).power_trunc(2^100 + i, 100)
    q2 = p * (x^2 + x + 1).power_trunc(i, 100)
    q2 = q2.truncate(100)
    assert q1 == q2, "i = " + str(i)
```

**prec()**

Return the precision of this polynomial. This is always infinity, since polynomials are of infinite precision by definition (there is no big-oh).

**EXAMPLES:**

```python
sage: x = polygen(ZZ)
sage: (x^5 + x + 1).prec()
+Infinity
sage: x.prec()
+Infinity
```

**pseudo_quo_rem(other)**

Compute the pseudo-division of two polynomials.

**INPUT:**

• other – a nonzero polynomial

**OUTPUT:**

Q and R such that \(lm^{-n+1}self = Q \cdot \text{other} + R\) where m is the degree of this polynomial, n is the degree of other, l is the leading coefficient of other. The result is such that \(\deg(R) < \deg(\text{other})\).

**ALGORITHM:**

Algorithm 3.1.2 in [Coh1993].

**EXAMPLES:**

```python
sage: R.<x> = PolynomialRing(ZZ, sparse=True)
sage: p = x^4 + 6*x^3 + x^2 - x + 2
sage: q = 2*x^2 - 3*x - 1
sage: (quo,rem)=p.pseudo_quo_rem(q); quo,rem
(4*x^2 + 30*x + 51, 175*x + 67)
sage: 2^(4-2+1)*p == quo*q + rem
True
sage: S.<T> = R[]
sage: p = (-3*x^2 - x)*T^3 - 3*x*T^2 + (x^2 - x)*T + 2*x^2 + 3*x - 2
sage: q = (-x^2 - 4*x - 5)*T^2 + (6*x^2 + x + 1)*T + 2*x^2 - x
```
sage: quo, rem = p.pseudo_quo_rem(q); quo, rem
((3*x^4 + 13*x^3 + 19*x^2 + 5*x)*T + 18*x^4 + 12*x^3 + 16*x^2 + 16*x,
(-113*x^6 + 106*x^5 - 133*x^4 + 101*x^3 - 42*x^2 - 41*x)*T - 34*x^6 + 13*x^5 +
→ 54*x^4 + 126*x^3 + 134*x^2 - 5*x - 50)
sage: (-x^2 - 4*x - 5)^{(3-2+1)} * p == quo*q + rem
True

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

Over a field, this is the product of the distinct irreducible factors of self. (This is also sometimes called the “square-free part” of self, but that term is ambiguous; it is sometimes used to mean the quotient of self by its maximal square factor.)

**EXAMPLES:**

sage: P.<x> = ZZ[]
sage: t = (x^2-x+1)^3 * (3*x-1)^2
sage: t.radical()
3*x^3 - 4*x^2 + 4*x - 1
sage: radical(12 * x^5)
6*x

If self has a factor of multiplicity divisible by the characteristic (see github issue #8736):

sage: P.<x> = GF(2)[]
sage: (x^3 + x^2).radical()
x^2 + x

**rational_reconstruct(*args, **kwds)**
Deprecated: Use **rational_reconstruction()** instead. See github issue #12696 for details.

**rational_reconstruction(m, n_deg=None, d_deg=None)**
Return a tuple of two polynomials (n, d) where self * d is congruent to n modulo m and n.degree() <= n_deg and d.degree() <= d_deg.

**INPUT:**
- m – a univariate polynomial
- n_deg – (optional) an integer; the default is ⌊(deg(m) – 1)/2⌋
- d_deg – (optional) an integer; the default is ⌊(deg(m) – 1)/2⌋

**ALGORITHM:**
The algorithm is based on the extended Euclidean algorithm for the polynomial greatest common divisor.

**EXAMPLES:**

Over Q[z]:

sage: z = PolynomialRing(QQ, 'z').gen()
sage: p = -z**16 - z**15 - z**14 + z**13 + z**12 + z**11 - z**5 - z**4 - z**3 +
→ z**2 + z + 1
sage: m = z**21
sage: n, d = p.rational_reconstruction(m)
sage: print((n, d))
(z^4 + 2*z^3 + 3*z^2 + 2*z + 1, z^10 + z^9 + z^8 + z^7 + z^6 + z^5 + z^4 + z^3 +
  + z^2 + z + 1)
sage: print(((p*d - n) % m).is_zero())
True

Over \( \mathbb{Z}[z] \):

sage: p = -z^16 - z^15 - z^14 + z^13 + z^12 + z^11 - z^5 - z^4 - z^3 +
  + z^2 + z + 1
sage: m = z^21
sage: n, d = p.rational_reconstruction(m)
sage: print((n, d))
(z^4 + 2*z^3 + 3*z^2 + 2*z + 1, z^10 + z^9 + z^8 + z^7 + z^6 + z^5 + z^4 + z^3 +
  + z^2 + z + 1)
sage: print(((p*d - n) % m).is_zero())
True

Over an integral domain \( d \) might not be monic:

sage: P = PolynomialRing(ZZ, 'x')
sage: x = P.gen()
sage: p = 7*x^5 - 10*x^4 + 16*x^3 - 32*x^2 + 128*x + 256
sage: m = x^5
sage: n, d = p.rational_reconstruction(m, 3, 2)
sage: print((n, d))
(-32*x^3 + 384*x^2 + 2304*x + 2048, 5*x + 8)
sage: print(((p*d - n) % m).is_zero())
True
sage: n, d = p.rational_reconstruction(m, 4, 0)
sage: print((n, d))
(-10*x^4 + 16*x^3 - 32*x^2 + 128*x + 256, 1)
sage: print(((p*d - n) % m).is_zero())
True

Over \( \mathbb{Q}(t)[z] \):

sage: P = PolynomialRing(QQ, 't')
sage: t = P.gen()
sage: Pz = PolynomialRing(P.fraction_field(), 'z')
sage: z = Pz.gen()
sage: p = (1 + t^2*z + z^4)*(1 - t*z).inverse_mod(z^9)
sage: m = z^9
sage: n, d = p.rational_reconstruction(m)
sage: print((n, d))
(-1/t*z^4 - t*z - 1/t, z - 1/t)
sage: print(((p*d - n) % m).is_zero())
True

sage: w = PowerSeriesRing(P.fraction_field(), 'w').gen()
sage: n = -10*t^2*z^4 + (-t^2 + t - 1)*z^3 + (-t - 8)*z^2 + z + 2*t^2 - t
sage: d = z^4 + (2*t + 4)*z^3 + (-t + 5)*z^2 + (t^2 + 2)*z + t^2 + 2*t + 1

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Continued from previous page:

```python
sage: prec = 9
sage: nc, dc = Pz((n.subs(z = w)/d.subs(z = w) + O(w^prec)).list()).rational_reconstruction(z^prec)
sage: print((nc, dc) == (n, d))
True
```

Over \( \mathbb{Q}[t][z] \):

```python
sage: P = PolynomialRing(QQ, 't')
sage: t = P.gen()
sage: z = PolynomialRing(P, 'z').gen()
sage: p = (1 + t^2*z + z^4) / (1 - t*z) mod z^9
sage: m = z^9
sage: n, d = p.rational_reconstruction(m,)
sage: print((n ,d))
(-z^4 - t^2*z - 1, t*z - 1)
sage: print(((p*d - n) \% m).is_zero())
True
```

Over \( \mathbb{Q}_5 \):

```python
sage: x = PolynomialRing(Qp(5), 'x').gen()
sage: p = 4*x^5 + 3*x^4 + 2*x^3 + 2*x^2 + 4*x + 2
sage: m = x^6
sage: n, d = p.rational_reconstruction(m, 3, 2)
sage: print(((p*d - n) \% m).is_zero())
True
```

Can also be used to obtain known Padé approximations:

```python
sage: z = PowerSeriesRing(QQ, 'z').gen()
sage: P = PolynomialRing(QQ, 'x')
sage: x = P.gen()
sage: p = P(exp(z).list())
sage: m = x^5
sage: n, d = p.rational_reconstruction(m, 4, 0)
sage: print((n ,d))
(1/24*x^4 + 1/6*x^3 + 1/2*x^2 + x + 1, 1)
sage: print(((p*d - n) \% m).is_zero())
True
sage: m = x^3
sage: n, d = p.rational_reconstruction(m, 1, 1)
sage: print((n ,d))
(-x - 2, x - 2)
sage: print(((p*d - n) \% m).is_zero())
True
sage: p = P(log(1-z).list())
sage: m = x^9
sage: n, d = p.rational_reconstruction(m, 4, 4)
sage: print((n ,d))
(25/6*x^4 - 130/3*x^3 + 105*x^2 - 70*x, x^4 - 20*x^3 + 90*x^2 - 140*x + 70)
sage: print(((p*d - n) \% m).is_zero())
(continues on next page)
```

(continues on next page)
True
sage: p = P(sqrt(1+z).list())
sage: m = x^6
sage: n, d = p.rational_reconstruction(m, 3, 2)
sage: print((n ,d))
(1/6*x^3 + 3*x^2 + 8*x + 16/3, x^2 + 16/3*x + 16/3)
sage: print(((p*d - n) % m ).is_zero())
True
sage: p = P(exp(2*z).list())
sage: m = x^7
sage: n, d = p.rational_reconstruction(m, 3, 3)
sage: print((n ,d))
(-x^3 - 6*x^2 - 15*x - 15, x^3 - 6*x^2 + 15*x - 15)
sage: print(((p*d - n) % m ).is_zero())
True

Over \( \mathbb{R}[z] \):

sage: z = PowerSeriesRing(RR, 'z').gen()
sage: P = PolynomialRing(RR,'x')
sage: x = P.gen()
sage: p = P(exp(2*z).list())
sage: m = x^7
sage: n, d = p.rational_reconstruction(m, 3, 3)
sage: print((n ,d))  # absolute tolerance 1e-10
(-x^3 - 6.0*x^2 - 15.0*x - 15.0, x^3 - 6.0*x^2 + 15.0*x - 15.0)

See also:

- sage.matrix.berlekamp_massey,
- sage.rings.polynomial.polynomial_zmod_flint.Polynomial_zmod_flint.
  rational_reconstruction()

real_roots()

Return the real roots of this polynomial, without multiplicities.

Calls self.roots(ring=RR), unless this is a polynomial with floating-point real coefficients, in which case it calls self.roots().

EXAMPLES:

sage: x = polygen(ZZ)
sage: (x^2 - x - 1).real_roots()
[-0.618033988749895, 1.618033988749899]

reciprocal_transform\((R=1, q=1)\)

Transform a general polynomial into a self-reciprocal polynomial.

The input \( Q \) and output \( P \) satisfy the relation

\[
P(x) = Q(x + q/x)x^{\deg(Q)} R(x).
\]

In this relation, \( Q \) has all roots in the real interval \([-2\sqrt{q}, 2\sqrt{q}] \) if and only if \( P \) has all roots on the circle \(|x| = \sqrt{q} \) and \( R \) divides \( x^2 - q \).
See also:

The inverse operation is *trace_polynomial()*.

**INPUT:**

- `R` – polynomial
- `q` – scalar (default: 1)

**EXAMPLES:**

```sage
sage: pol.<x> = PolynomialRing(Rationals())
sage: u = x^2+x-1
sage: u.reciprocal_transform()
x^4 + x^3 + x^2 + x + 1
sage: u.reciprocal_transform(R=x-1)
x^5 - 1
sage: u.reciprocal_transform(q=3)
x^4 + x^3 + 5*x^2 + 3*x + 9
```

**resultant(other)**

Return the resultant of `self` and `other`.

**INPUT:**

- `other` – a polynomial

**OUTPUT:** an element of the base ring of the polynomial ring

**ALGORITHM:**

Uses PARI's `polresultant` function. For base rings that are not supported by PARI, the resultant is computed as the determinant of the Sylvester matrix.

**EXAMPLES:**

```sage
sage: R.<x> = QQ[]
sage: f = x^3 + x + 1; g = x^3 - x - 1
sage: r = f.resultant(g); r
-8
sage: r.parent() is QQ
True
```

We can compute resultants over univariate and multivariate polynomial rings:

```sage
sage: R.<a> = QQ[]
sage: S.<x> = R[]
sage: f = x^2 + a; g = x^3 + a
sage: r = f.resultant(g); r
a^3 + a^2
sage: r.parent() is R
True

sage: R.<a, b> = QQ[]
sage: S.<x> = R[]
sage: f = x^2 + a; g = x^3 + b
sage: r = f.resultant(g); r
a^3 + b^2
```

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**reverse**(degree=None)

Return polynomial but with the coefficients reversed.

If an optional degree argument is given the coefficient list will be truncated or zero padded as necessary before reversing it. Assuming that the constant coefficient of self is nonzero, the reverse polynomial will have the specified degree.

**EXAMPLES:**

```sage
R.<x> = ZZ[]; S.<y> = R[]
f = y^3 + x*y -3*x; f
y^3 + x*y^2 - 3*x
f.reverse()
-3*x*y^3 + x*y^2 + 1
f.reverse(degree=2)
-3*x*y^2 + x*y
f.reverse(degree=5)
-3*x*y^5 + x*y^4 + y^2
```

**revert_series**(n)

Return a polynomial f such that f(self(x)) = self(f(x)) = x mod x^n.

Currently, this is only implemented over some coefficient rings.

**EXAMPLES:**

```sage
Pol.<x> = QQ[]
Pol.<x> = CBF[]
Pol.<x> = SR[]
```

**root_field**(names, check_irreducible=True)

Return the field generated by the roots of the irreducible polynomial self. The output is either a number field, relative number field, a quotient of a polynomial ring over a field, or the fraction field of the base ring.

**EXAMPLES:**

```sage
R.<x> = QQ['x']
f = x^3 + x + 17
f.root_field('a')
Number Field in a with defining polynomial x^3 + x + 17
```
Polynomials, Release 10.0

```
sage: R.<x> = QQ['x']
sage: f = x - 3
sage: f.root_field('b')
Rational Field

sage: R.<x> = ZZ['x']
sage: f = x^3 + x + 17
sage: f.root_field('b')
Number Field in b with defining polynomial x^3 + x + 17

sage: y = QQ['x'].0
sage: L.<a> = NumberField(y^3-2)
sage: R.<x> = L['x']
sage: f = x^3 + x + 17
sage: f.root_field('c')
Number Field in c with defining polynomial x^3 + x + 17 over its base field

sage: R.<x> = PolynomialRing(GF(9, 'a'))
sage: f = x^3 + x^2 + 8
sage: K.<alpha> = f.root_field(); K
Univariate Quotient Polynomial Ring in alpha over Finite Field in a of size 3^2
→ with modulus x^3 + x^2 + 2
sage: alpha^2 + 1
alpha^2 + 1
1

sage: R.<x> = QQ[]
sage: f = x^2
sage: K.<alpha> = f.root_field()
Traceback (most recent call last):
...
ValueError: polynomial must be irreducible
```

`roots(ring=None, multiplicities=True, algorithm=None, **kwds)`

Return the roots of this polynomial (by default, in the base ring of this polynomial).

**INPUT:**

- `ring` - the ring to find roots in
- `multiplicities` - bool (default: True) if True return list of pairs (r, n), where r is the root and n is the multiplicity. If False, just return the unique roots, with no information about multiplicities.
- `algorithm` - the root-finding algorithm to use. We attempt to select a reasonable algorithm by default, but this lets the caller override our choice.

By default, this finds all the roots that lie in the base ring of the polynomial. However, the ring parameter can be used to specify a ring to look for roots in.

If the polynomial and the output ring are both exact (integers, rationals, finite fields, etc.), then the output should always be correct (or raise an exception, if that case is not yet handled).

If the output ring is approximate (floating-point real or complex numbers), then the answer will be estimated numerically, using floating-point arithmetic of at least the precision of the output ring. If the polynomial is
ill-conditioned, meaning that a small change in the coefficients of the polynomial will lead to a relatively large change in the location of the roots, this may give poor results. Distinct roots may be returned as multiple roots, multiple roots may be returned as distinct roots, real roots may be lost entirely (because the numerical estimate thinks they are complex roots). Note that polynomials with multiple roots are always ill-conditioned; there’s a footnote at the end of the docstring about this.

If the output ring is a RealIntervalField or ComplexIntervalField of a given precision, then the answer will always be correct (or an exception will be raised, if a case is not implemented). Each root will be contained in one of the returned intervals, and the intervals will be disjoint. (The returned intervals may be of higher precision than the specified output ring.)

At the end of this docstring (after the examples) is a description of all the cases implemented in this function, and the algorithms used. That section also describes the possibilities for “algorithm=”, for the cases where multiple algorithms exist.

EXAMPLES:

```sage
sage: x = QQ['x'].0
sage: f = x^3 - 1
sage: f.roots()
[(1, 1)]

sage: f.roots(ring=CC)  # note -- low order bits slightly different on ppc.
[(1.00000000000000, 1), (-0.500000000000000 - 0.86602540378443...*I, 1), (-0.
˓→500000000000000 + 0.86602540378443...*I, 1)]

sage: f = (x^3 - 1)^2
sage: f.roots()
[(1, 2)]

sage: f = -19*x + 884736
sage: f.roots()
[(884736/19, 1)]

sage: (f^20).roots()
[(884736/19, 20)]

sage: K.<z> = CyclotomicField(3)

sage: f = K.defining_polynomial()

sage: f.roots(ring=GF(7))
[(4, 1), (2, 1)]

sage: g = f.change_ring(GF(7))

sage: g.roots()
[(4, 1), (2, 1)]

sage: g.roots(multiplicities=False)

[4, 2]
```

A new ring. In the example below, we add the special method _roots_univariate_polynomial to the base ring, and observe that this method is called instead to find roots of polynomials over this ring. This facility can be used to easily extend root finding to work over new rings you introduce:

```sage
sage: R.<x> = QQ[]

sage: (x^2 + 1).roots()
[]

sage: g = lambda f, *args, **kwds: f.change_ring(CDF).roots()

sage: QQ._roots_univariate_polynomial = g

sage: (x^2 + 1).roots()  # abs tol 1e-14
```

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An example over RR, which illustrates that only the roots in RR are returned:

```sage
def f = x^3 -2
def f.roots()
[(1.25992104989487, 1)]
```

```sage
def f = x^3 -2
f.factor()
(x - 1.25992104989487) * (x^2 + 1.25992104989487*x + 1.58740105196820)
```

```sage
def f = x^3 -2
f.roots(algorithm='pari')
[(1.25992104989487, 1), (-0.62996052494743... - 1.09112363597172*I, 1), (-0.62996052494743... + 1.09112363597172*I, 1)]
```

Another example showing that only roots in the base ring are returned:

```sage
def f = (2*x-3) * (x-1) * (x+1)
def f.roots()
[(1, 1), (-1, 1)]
```

```sage
def f = (2*x-3) * (x-1) * (x+1)
def f.roots(ring=QQ)
[(3/2, 1), (1, 1), (-1, 1)]
```

An example where we compute the roots lying in a subring of the base ring:

```sage
def pol = QQ.<n> = QQ[]
def pol = (n - 1/2)^2*(n - 1)*2*(n-2)
def pol.roots(ZZ)
[(2, 1), (1, 2)]
```

An example involving large numbers:

```sage
def f = x^10 - 2*(5*x-1)^2
f.roots(multiplicities=False)
[-1.6772670339941..., 0.19995479628..., 0.20004530611..., 1.5763035161844...]
```
sage: x = CC['x'].0
sage: i = CC.0
sage: f = (x - 1)*(x - i)
sage: f.roots(multiplicities=False)
[1.00000000000000, 1.00000000000000*I]
sage: g=(x-1.33+1.33*i)*(x-2.66-2.66*i)
sage: g.roots(multiplicities=False)
[1.33000000000000 - 1.33000000000000*I, 2.66000000000000 + 2.66000000000000*I]

Describing roots using radical expressions:

sage: x = QQ['x'].0
sage: f = x^2 + 2
sage: f.roots(SR)
[(-I*sqrt(2), 1), (I*sqrt(2), 1)]
sage: f.roots(SR, multiplicities=False)
[-I*sqrt(2), I*sqrt(2)]

The roots of some polynomials cannot be described using radical expressions:

sage: (x^5 - x + 1).roots(SR)
[]

For some other polynomials, no roots can be found at the moment due to the way roots are computed. github issue #17516 addresses these defects. Until that gets implemented, one such example is the following:

sage: f = x^6-300*x^5+30361*x^4-1061610*x^3+1141893*x^2-915320*x+101724
sage: f.roots()
[]

A purely symbolic roots example:

sage: X = var('X')
sage: f = expand((X-1)*(X-I)^3*(X^2 - sqrt(2))); f
X^6 - (3*I + 1)*X^5 - sqrt(2)*X^4 + (3*I - 3)*X^4 + (3*I + 1)*sqrt(2)*X^3 + (I+3)*X^3 - (3*I - 3)*sqrt(2)*X^2 - I*X^2 - (I + 3)*sqrt(2)*X + I*sqrt(2)
sage: f.roots()
[(I, 3), (-2^(1/4), 1), (2^(1/4), 1), (1, 1)]

The same operation, performed over a polynomial ring with symbolic coefficients:

sage: X = SR['X'].0
sage: f = (X-1)*(X-I)^3*(X^2 - sqrt(2)); f
X^6 + (-3*I - 1)*X^5 + (-sqrt(2) + 3*I - 3)*X^4 + ((3*I + 1)*sqrt(2) + I + 3)*X^3 + (-(3*I - 3)*sqrt(2) - I)*X^2 + ((-I + 3)*sqrt(2))*X + I*sqrt(2)
sage: f.roots()
[(I, 3), (-2^(1/4), 1), (2^(1/4), 1), (1, 1)]

A couple of examples where the base ring does not have a factorization algorithm (yet). Note that this is currently done via a rather naive enumeration, so could be very slow:
sage: R = Integers(6)
sage: S.<x> = R[

sage: p = x^2-1
sage: p.roots()
Traceback (most recent call last):
  ...NotImplementedError: root finding with multiplicities for this polynomial not␣
˓→implemented (try the multiplicities=False option)
sage: p.roots(multiplicities=False)
[5, 1]
sage: R = Integers(9)
sage: A = PolynomialRing(R, 'y')
sage: y = A.gen()
sage: f = 10*y^2 - y^3 - 9
sage: f.roots(multiplicities=False)
[1, 0, 3, 6]

An example over the complex double field (where root finding is fast, thanks to NumPy):

sage: R.<x> = CDF[

sage: f = R.cyclotomic_polynomial(5); f
x^4 + x^3 + x^2 + x + 1.0
sage: f.roots(multiplicities=False) # abs tol 1e-9
[-0.8090169943749469 - 0.587785252294724*I, -0.8090169943749473 + 0.guarded]
˓→587785252294724*I, 0.30901699437494773 - 0.95105616295154*I, 0.
˓→30901699437494756 + 0.951056162951525*I]
sage: [z^5 for z in f.roots(multiplicities=False)] # abs tol 2e-14
[0.9999999999999957 - 1.2864981197413038e-15*I, 0.9999999999999976 + 3.062854959141552e-15*I, 1.0000000000000024 + 1.1331077795295987e-15*I, 0.
˓→9999999999999953 - 2.0212861992297117e-15*I]
sage: f = CDF['x']([1,2,3,4]); f
4.0*x^3 + 3.0*x^2 + 2.0*x + 1.0
sage: r = f.roots(multiplicities=False)
sage: [f(a).abs() for a in r] # abs tol 1e-14

Another example over RDF:

sage: x = RDF['x'].0
sage: ((x^3 -1)).roots() # abs tol 4e-16
[(1.0000000000000002, 1)]
sage: ((x^3 -1)).roots(multiplicities=False) # abs tol 4e-16
[1.0000000000000002]

More examples involving the complex double field:

sage: x = CDF['x'].0
sage: i = CDF.0
sage: f = x^3 + 2*i; f
x^3 + 2.0*I
sage: f.roots()
[(-1.09112363597172... - 0.62996052494743...*I, 1), (...1.25992104989487...*I,␣
˓→1), (1.09112363597172... - 0.62996052494743...*I, 1)]

(continues on next page)
Examples using real root isolation:

```py
sage: x = polygen(ZZ)
sage: f = x^2 - x - 1
sage: f.roots()
[]
sage: f.roots(ring=RIF)
[(-0.6180339887498948482045868343657?, 1), (1.6180339887498948482045868343657?, 1)]
sage: f.roots(ring=RIF, multiplicities=False)
[-0.6180339887498948482045868343657?, 1.6180339887498948482045868343657?]
sage: f.roots(ring=RealIntervalField(150))
[(-0.6180339887498948482045868343657?, 1, 1.6180339887498948482045868343657?)]
sage: f.roots(ring=AA)
[-0.6180339887498948482045868343657?, 1, 1.6180339887498948482045868343657?]
sage: f = f^2 * (x - 1)
sage: f.roots(ring=RIF)
[(-0.6180339887498948482045868343657?, 2), (1.0000000000000000000000000000000?, 1), (1.6180339887498948482045868343657?, 2)]
sage: f.roots(ring=RIF, multiplicities=False)
[-0.6180339887498948482045868343657?, 1.0000000000000000000000000000000?, 1.6180339887498948482045868343657?]
```

Examples using complex root isolation:

```py
sage: x = polygen(ZZ)
sage: p = x^5 - x - 1
sage: p.roots()
[]
sage: p.roots(ring=CIF)
[(-0.76484433600585? - 0.352471546031727?*I, 1), (-0.76484433600585? + 0.352471546031727?*I, 1), (0.181232444469876? - 1.083954101317711?*I, 1), (0.181232444469876? + 1.083954101317711?*I, 1)]
sage: p.roots(ring=ComplexIntervalField(200))
[(-0.7648443360058472602982318770854173032899665194736756700778? - 0.352471546031727?*I, 1), (-0.7648443360058472602982318770854173032899665194736756700778? + 0.352471546031727?*I, 1), (0.181232444469876? - 1.083954101317711?*I, 1), (0.181232444469876? + 1.083954101317711?*I, 1)]
```
In some cases, it is possible to isolate the roots of polynomials over complex ball fields:

```
sage: Pol.<x> = CBF[]
sage: (x^2 + 2).roots(multiplicities=False)
[[+/- ...e-19] + [-1.414213562373095 +/- ...e-17]*I,
 [+/-. . .e-19] + [1.414213562373095 +/- ...e-17]*I]
sage: (x^3 - 1/2).roots(RBF, multiplicities=False)
[[0.7937005259840997 +/- ...e-17]]
sage: ((x - 1)^2).roots(multiplicities=False, proof=False)
doctest:...
UserWarning: roots may have been lost...
[[1.00000000000 +/- ...e-12] [+/- ...e-11]*I,
 [1.00000000000 +/- ...e-12] [+/- ...e-12]*I]
```

Note that coefficients in a number field with defining polynomial \(x^2 + 1\) are considered to be Gaussian rationals (with the generator mapping to \(+i\)), if you ask for complex roots.

```
sage: K.<im> = QuadraticField(-1)
sage: y = polygen(K)
sage: p = y^4 - 2 - im
sage: p.roots(ring=CC)
[(-1.2146389322441... - 0.14142505258239...*I, 1), (-0.14142505258239... + 1.2146389322441...*I, 1), (0.14142505258239... - 1.2146389322441...*I, 1), (1.2146389322441... + 0.14142505258239...*I, 1)]
sage: p = p^2 * (y^2 - 2)
sage: p.roots(ring=CIF)
[(-1.414213562373095? , 1), (1.414213562373095? , 1), (0.141425052582394? , 2), (-0.141425052582394? + 1.214638932244183?*I, 2), (0.141425052582394? - 1.214638932244183?*I, 2), (1.214638932244183? + 0.141425052582394?*I, 2), (1.214638932244183? - 0.141425052582394?*I, 2)]
```

Note that one should not use NumPy when wanting high precision output as it does not support any of the high precision types:
Polynomials, Release 10.0

sage: R.<x> = RealField(200)[]
sage: f = x^2 - R(pi)
sage: f.roots()
[(-1.7724538509055160272981674833411451827975494561223871282138, 1), (1.
˓→7724538509055160272981674833411451827975494561223871282138, 1)]
sage: f.roots(algorithm='numpy')
doctest... UserWarning: NumPy does not support arbitrary precision arithmetic. ␣
˓→The roots found will likely have less precision than you expect.
[(-1.77245385090551..., 1), (1.77245385090551..., 1)]
We can also find roots over number fields:
sage: K.<z> = CyclotomicField(15)
sage: R.<x> = PolynomialRing(K)
sage: (x^2 + x + 1).roots()
[(z^5, 1), (-z^5 - 1, 1)]
There are many combinations of floating-point input and output types that work. (Note that some of them
are quite pointless like using algorithm='numpy' with high-precision types.)
sage: rflds = (RR, RDF, RealField(100))
sage: cflds = (CC, CDF, ComplexField(100))
sage: def cross(a, b):
....:
return list(cartesian_product_iterator([a, b]))
sage: flds = cross(rflds, rflds) + cross(rflds, cflds) + cross(cflds, cflds)
sage: for (fld_in, fld_out) in flds:
....:
x = polygen(fld_in)
....:
f = x^3 - fld_in(2)
....:
x2 = polygen(fld_out)
....:
f2 = x2^3 - fld_out(2)
....:
for algo in (None, 'pari', 'numpy'):
....:
rts = f.roots(ring=fld_out, multiplicities=False)
....:
if fld_in == fld_out and algo is None:
....:
print("{} {}".format(fld_in, rts))
....:
for rt in rts:
....:
assert(abs(f2(rt)) <= 1e-10)
....:
assert(rt.parent() == fld_out)
Real Field with 53 bits of precision [1.25992104989487]
Real Double Field [1.25992104989...]
Real Field with 100 bits of precision [1.2599210498948731647672106073]
Complex Field with 53 bits of precision [1.25992104989487, -0.62996052494743...␣
˓→- 1.09112363597172*I, -0.62996052494743... + 1.09112363597172*I]
Complex Double Field [1.25992104989..., -0.629960524947... - 1.0911236359717...
˓→*I, -0.629960524947... + 1.0911236359717...*I]
Complex Field with 100 bits of precision [1.2599210498948731647672106073, -0.
˓→62996052494743658238360530364 - 1.0911236359717214035600726142*I, -0.
˓→62996052494743658238360530364 + 1.0911236359717214035600726142*I]
Note that we can find the roots of a polynomial with algebraic coefficients:
sage: rt2 = sqrt(AA(2))
sage: rt3 = sqrt(AA(3))
sage: x = polygen(AA)
(continues on next page)

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Chapter 2. Univariate Polynomials


We can handle polynomials with huge coefficients.

This number doesn’t even fit in an IEEE double-precision float, but RR and CC allow a much larger range of floating-point numbers:

```
sage: bigc = 2^1500
sage: CDF(bigc)
+infinity
sage: CC(bigc)
3.50746621104340e451
```

Polynomials using such large coefficients can’t be handled by numpy, but pari can deal with them:

```
sage: x = polygen(QQ)
sage: p = x + bigc
sage: p.roots(ring=RR, algorithm='numpy')
Traceback (most recent call last):
  ...
LinAlgError: Array must not contain infs or NaNs
sage: p.roots(ring=RR, algorithm='pari')
[(-3.5074662110434039?e451, 1)]
sage: p.roots(ring=AA)
[(-3.5074662110434039?e451, 1)]
sage: p.roots(ring=QQbar)
[(-3.5074662110434039?e451, 1)]
sage: p = bigc*x + 1
sage: p.roots(ring=RR)
[(-2.8510609648967059?e-452, 1)]
sage: p.roots(ring=AA)
[(-2.8510609648967059?e-452, 1)]
sage: p.roots(ring=QQbar)
[(-2.8510609648967059?e-452, 1)]
sage: p = x^2 - bigc
sage: p.roots(ring=RR)
[(-5.9223865215328558?e225, 1), (5.9223865215328558?e225, 1)]
sage: p.roots(ring=QQbar)
[(-5.9223865215328558?e225, 1), (5.9223865215328558?e225, 1)]
```

Check that github issue #30522 is fixed:

```
sage: PolynomialRing(SR, names="x")("x^2")\.roots()
[0, 2]
```

Check that github issue #30523 is fixed:
Algorithms used:

For brevity, we will use RR to mean any RealField of any precision; similarly for RIF, CC, and CIF. Since Sage has no specific implementation of Gaussian rationals (or of number fields with embedding, at all), when we refer to Gaussian rationals below we will accept any number field with defining polynomial \( x^2 + 1 \), mapping the field generator to +I.

We call the base ring of the polynomial K, and the ring given by the ring= argument L. (If ring= is not specified, then L is the same as K.)

If K and L are floating-point (RDF, CDF, RR, or CC), then a floating-point root-finder is used. If L is RDF or CDF then we default to using NumPy’s roots(); otherwise, we use PARI’s polroots(). This choice can be overridden with algorithm='pari' or algorithm='numpy'. If the algorithm is unspecified and NumPy’s roots() algorithm fails, then we fall back to pari (nump will fail if some coefficient is infinite, for instance).

If L is SR (or one of its subrings), then the roots will be radical expressions, computed as the solutions of a symbolic polynomial expression. At the moment this delegates to sage.symbolic.expression.Expression.solve() which in turn uses Maxima to find radical solutions. Some solutions may be lost in this approach. Once github issue #17516 gets implemented, all possible radical solutions should become available.

If L is AA or RIF, and K is ZZ, QQ, or AA, then the root isolation algorithm sage.rings.polynomial.real_roots.real_roots() is used. (You can call real_roots() directly to get more control than this method gives.)

If L is QQbar or CIF, and K is ZZ, QQ, AA, QQbar, or the Gaussian rationals, then the root isolation algorithm sage.rings.polynomial.complex_roots.complex_roots() is used. (You can call complex_roots() directly to get more control than this method gives.)

If L is AA and K is QQbar or the Gaussian rationals, then complex_roots() is used (as above) to find roots in QQbar, then these roots are filtered to select only the real roots.

If L is floating-point and K is not, then we attempt to change the polynomial ring to L (using .change_ring()) (or, if L is complex and K is not, to the corresponding real field). Then we use either PARI or numpy as specified above.

For all other cases where K is different than L, we attempt to use .change_ring(L). When that fails but L is a subring of K, we also attempt to compute the roots over K and filter the ones belonging to L.

The next method, which is used if K is an integral domain, is to attempt to factor the polynomial. If this succeeds, then for every degree-one factor a*x+b, we add -b/a as a root (as long as this quotient is actually in the desired ring).

If factoring over K is not implemented (or K is not an integral domain), and K is finite, then we find the roots by enumerating all elements of K and checking whether the polynomial evaluates to zero at that value.

**Note:** We mentioned above that polynomials with multiple roots are always ill-conditioned; if your input is given to n bits of precision, you should not expect more than n/k good bits for a k-fold root. (You can get solutions that make the polynomial evaluate to a number very close to zero; basically the problem is that with a multiple root, there are many such numbers, and it’s difficult to choose between them.)

To see why this is true, consider the naive floating-point error analysis model where you just pretend that all floating-point numbers are somewhat imprecise - a little ‘fuzzy’, if you will. Then the graph of a floating-point polynomial will be a fuzzy line. Consider the graph of \((x - 1)^3\); this will be a fuzzy line with a
horizontal tangent at $x = 1, y = 0$. If the fuzziness extends up and down by about $j$, then it will extend left and right by about $\text{cube\_root}(j)$.

**shift**($n$)

Return this polynomial multiplied by the power $x^n$. If $n$ is negative, terms below $x^n$ will be discarded. Does not change this polynomial (since polynomials are immutable).

**EXAMPLES:**

```python
sage: R.<x> = QQ[]
sage: p = x^2 + 2*x + 4
sage: p.shift(0)
x^2 + 2*x + 4
sage: p.shift(-1)
x + 2
sage: p.shift(-5)
0
sage: p.shift(2)
x^4 + 2*x^3 + 4*x^2
```

One can also use the infix shift operator:

```python
sage: f = x^3 + x
sage: f >> 2
x
sage: f << 2
x^5 + x^3
```

**AUTHORS:**

- David Harvey (2006-08-06)

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

Specialization of this polynomial.

Given a family of polynomials 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:** a new polynomial

**EXAMPLES:**

```python
sage: R.<c> = PolynomialRing(ZZ)
sage: S.<z> = PolynomialRing(R)
sage: F = c*z^2 + c^2
sage: F.specialization({c:2})
2*z^2 + 4
```

---

2.1. Univariate Polynomials and Polynomial Rings

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splitting_field(names=None, map=False, **kwds)

Compute the absolute splitting field of a given polynomial.

INPUT:

- names – (default: None) a variable name for the splitting field.
- map – (default: False) also return an embedding of self into the resulting field.
- kwds – additional keywords depending on the type. Currently, only number fields are implemented. See sage.rings.number_field.splitting_field.splitting_field() for the documentation of these keywords.

OUTPUT:

If map is False, the splitting field as an absolute field. If map is True, a tuple (K, phi) where phi is an embedding of the base field of self in K.

EXAMPLES:

```python
sage: R.<x> = PolynomialRing(ZZ)
sage: K.<a> = (x^3 + 2).splitting_field(); K
Number Field in a with defining polynomial x^6 + 3*x^5 + 6*x^4 + 11*x^3 + 12*x^2 + 2 - 3*x + 1
sage: K.<a> = (x^3 - 3*x + 1).splitting_field(); K
Number Field in a with defining polynomial x^3 - 3*x + 1
```

Relative situation:

```python
sage: R.<x> = PolynomialRing(QQ)
sage: K.<a> = NumberField(x^3 + 2)
sage: S.<t> = PolynomialRing(K)
sage: L.<b> = (t^2 - a).splitting_field()
sage: L
Number Field in b with defining polynomial t^6 + 2
```

With map=True, we also get the embedding of the base field into the splitting field:

```python
sage: L.<b>, phi = (t^2 - a).splitting_field(map=True)
sage: phi
Ring morphism:
  From: Number Field in a with defining polynomial x^3 + 2
  To:   Number Field in b with defining polynomial t^6 + 2
  Defn: a |--> b^2
```

An example over a finite field:

```python
sage: P.<x> = PolynomialRing(GF(7))
sage: t = x^2 + 1
```
sage: t.splitting_field('b')
Finite Field in b of size 7^2

sage: P.<x> = PolynomialRing(GF(7^3, 'a'))
sage: t = x^2 + 1

sage: t.splitting_field('b', map=True)
(Finite Field in b of size 7^6,
 Ring morphism:
  From: Finite Field in a of size 7^3
  To:  Finite Field in b of size 7^6
  Defn: a |--> 2*b^4 + 6*b^3 + 2*b^2 + 3*b + 2)

If the extension is trivial and the generators have the same name, the map will be the identity:

sage: t = 24*x^13 + 2*x^12 + 14
sage: t.splitting_field('a', map=True)
(Finite Field in a of size 7^3,
 Identity endomorphism of Finite Field in a of size 7^3)

sage: t = x^56 - 14*x^3
sage: t.splitting_field('b', map=True)
(Finite Field in b of size 7^3,
 Ring morphism:
  From: Finite Field in a of size 7^3
  To:  Finite Field in b of size 7^3
  Defn: a |--> b)

See also:

sage.rings.number_field.splitting_field() for more examples over number fields

\textbf{square}()

Return the square of this polynomial.

\textbf{Todo:}

- This is just a placeholder; for now it just uses ordinary multiplication. But generally speaking, squaring is faster than ordinary multiplication, and it’s frequently used, so subclasses may choose to provide a specialised squaring routine.

- Perhaps this even belongs at a lower level? RingElement or something?

\textbf{AUTHORS:}

- David Harvey (2006-09-09)

\textbf{EXAMPLES:}

sage: R.<x> = QQ[]
sage: f = x^3 + 1
sage: f.square()
x^6 + 2*x^3 + 1
squarefree_decomposition()

Return the square-free decomposition of this polynomial. This is a partial factorization into square-free, coprime polynomials.

EXAMPLES:

```
sage: x = polygen(QQ)
sage: p = 37 * (x-1)^3 * (x-2)^3 * (x-1/3)^7 * (x-3/7)
sage: p.squarefree_decomposition()
(37*x - 111/7) * (x^2 - 3*x + 2)^3 * (x - 1/3)^7
sage: p = 37 * (x-2/3)^2
sage: p.squarefree_decomposition()
(37) * (x - 2/3)^2
sage: x = polygen(GF(3))
sage: x.squarefree_decomposition()
x
sage: f = QQbar['x'](1)
sage: f.squarefree_decomposition()
1
```

subresultants(other)

Return the nonzero subresultant polynomials of self and other.

INPUT:

- other – a polynomial

OUTPUT: a list of polynomials in the same ring as self

EXAMPLES:

```
sage: R.<x> = ZZ[]
sage: f = x^8 + x^6 -3*x^4 -3*x^3 +8*x^2 +2*x -5
sage: g = 3*x^6 +5*x^4 -4*x^2 -9*x +21
sage: f.subresultants(g)
[260708, 9326*x - 12300, 169*x^2 + 325*x - 637, 65*x^2 + 125*x - 245, 25*x^4 - 5*x^2 + 15, 15*x^4 - 3*x^2 + 9]
```

ALGORITHM:

We use the schoolbook algorithm with Lazard’s optimization described in [Duc1998]

REFERENCES:

Wikipedia article Polynomial_greatest_common_divisor#Subresultants

subs(*x, **kwds)

Identical to self(*x).

See the docstring for self.__call__.
EXAMPLES:

```
sage: R.<x> = QQ[]
sage: f = x^3 + x - 3
sage: f.subs(x=5)
127
sage: f.subs(5)
127
sage: f.subs({x:2})
7
sage: f.subs({})
x^3 + x - 3
sage: f.subs({'x':2})
Traceback (most recent call last):
...  
TypeError: keys do not match self's parent
```

```
substitute(*x, **kwds)

Identical to self(*x).

See the docstring for self.__call__.

EXAMPLES:

```
sage: R.<x> = QQ[]
sage: f = x^3 + x - 3
sage: f.subs(x=5)
127
sage: f.subs(5)
127
sage: f.subs({x:2})
7
sage: f.subs({})
x^3 + x - 3
sage: f.subs({'x':2})
Traceback (most recent call last):
...  
TypeError: keys do not match self's parent
```

```
sylvester_matrix(right, variable=None)

Return the Sylvester matrix of self and right.

Note that the Sylvester matrix is not defined if one of the polynomials is zero.

INPUT:

- right: a polynomial in the same ring as self.
- variable: optional, included for compatibility with the multivariate case only. The variable of the polynomials.

EXAMPLES:

```
sage: R.<x> = PolynomialRing(ZZ)
sage: f = (6*x + 47)*(7*x^2 - 2*x + 38)
sage: g = (6*x + 47)*(3*x^3 + 2*x + 1)
sage: M = f.sylvester_matrix(g)
(continues on next page)
```
If the polynomials share a non-constant common factor then the determinant of the Sylvester matrix will be zero:

```python
sage: M.determinant()
0
```

If self and right are polynomials of positive degree, the determinant of the Sylvester matrix is the resultant of the polynomials:

```python
sage: h1 = R._random_nonzero_element()
sage: h2 = R._random_nonzero_element()
sage: M1 = h1.sylvester_matrix(h2)
sage: M1.determinant() == h1.resultant(h2)
True
```

The rank of the Sylvester matrix is related to the degree of the gcd of self and right:

```python
sage: f.gcd(g).degree() == f.degree() + g.degree() - M.rank()
True
sage: h1.gcd(h2).degree() == h1.degree() + h2.degree() - M1.rank()
True
```

### symmetric_power

Return the polynomial whose roots are products of $k$-th distinct roots of this.

**EXAMPLES:**

```python
sage: x = polygen(QQ)
sage: f = x^4-x+2
sage: [f.symmetric_power(k) for k in range(5)]
[x - 1, x^4 - x + 2, x^6 - 2*x^4 - x^3 - 4*x^2 + 8, x^4 - x^3 + 8, x - 2]
sage: f = x^5-2*x+2
sage: [f.symmetric_power(k) for k in range(6)]
[x - 1, x^5 - 2*x + 2, x^10 + 2*x^8 - 4*x^6 - 8*x^5 - 8*x^4 - 8*x^3 + 16, x^10 + 4*x^7 - 8*x^6 + 16*x^5 - 16*x^4 + 32*x^2 + 64, x^5 + 2*x^4 - 16, x + 2]
sage: R.<a,b,c,d> = ZZ[]
sage: x = polygen(R)
sage: f = (x-a)^5*(x-b)^6*(x-c)^6*(x-d)
```
sage: [f.symmetric_power(k).factor() for k in range(5)]
[x - 1, 
(-x + d) * (-x + c) * (-x + b) * (-x + a),
(x - c^2d) * (x - b^2d) * (x - a^2d) * (x - b*c) * (x - a*c) * (x - a*b),
(x - b*c^2d) * (x - a^2c^2d) * (x - a^2b^2d) * (x - a^2b*c),
x - a*b*c^2d]

trace_polynomial()

Compute the trace polynomial and cofactor.

The input $P$ and output $Q$ satisfy the relation

$$P(x) = Q(x + q/x)x^{\deg(Q)}R(x).$$

In this relation, $Q$ has all roots in the real interval $[-2\sqrt{q}, 2\sqrt{q}]$ if and only if $P$ has all roots on the circle $|x| = \sqrt{q}$ and $R$ divides $x^2 - q$. We thus require that the base ring of this polynomial have a coercion to the real numbers.

See also:

The inverse operation is reciprocal_transform().

OUTPUT:

• $Q$ – trace polynomial
• $R$ – cofactor
• $q$ – scaling factor

EXAMPLES:

sage: pol.<x> = PolynomialRing(Rationals())
sage: u = x^5 - 1; u.trace_polynomial()
(x^2 + x - 1, x - 1, 1)
sage: u = x^4 + x^3 + 5*x^2 + 3*x + 9
sage: u.trace_polynomial()
(x^2 + x - 1, 1, 3)

We check that this function works for rings that have a coercion to the reals:

sage: K.<a> = NumberField(x^2-2,embedding=1.4)
sage: u = x^4 + a*x^3 + 3*x^2 + 2*a*x + 4
sage: u.trace_polynomial()
(x^2 + a*x - 1, 1, 2)
sage: (u*(x^2-2)).trace_polynomial()
(x^2 + a*x - 1, x^2 - 2, 2)
sage: (u*(x^2-2)^2).trace_polynomial()
(x^4 + a*x^3 - 9*x^2 - 8*a*x + 8, 1, 2)
sage: (u*(x^2-2)^3).trace_polynomial()
(x^4 + a*x^3 - 9*x^2 - 8*a*x + 8, x^2 - 2, 2)
sage: u = x^4 + a*x^3 + 3*x^2 + 4*a*x + 16
sage: u.trace_polynomial()
(x^2 + a*x - 5, 1, 4)
sage: (u*(x-2)).trace_polynomial()
(x^2 + a*x - 5, x - 2, 4)
truncateman(n)

Return the polynomial of degree `< n` which is equivalent to self modulo $x^n$.

EXAMPLES:

```python
sage: R.<x> = ZZ[]; S.<y> = PolynomialRing(R, sparse=True)
sage: f = y^3 + x*y - 3*x; f
y^3 + x*y - 3*x
sage: f.truncate(2)
x*y - 3*x
sage: f.truncate(1)
-3*x
sage: f.truncate(0)
0
```

valuation(p=None)

If $f = a_rx^r + a_{r+1}x^{r+1} + \cdots$, with $a_r$ nonzero, then the valuation of $f$ is $r$. The valuation of the zero polynomial is $\infty$.

If a prime (or non-prime) $p$ is given, then the valuation is the largest power of $p$ which divides self.

The valuation at $\infty$ is -self.degree().

EXAMPLES:

```python
sage: P.<x> = ZZ[]
sage: (x^2+x).valuation()
1
sage: (x^2+x).valuation(x+1)
1
sage: (x^2+1).valuation()
0
sage: (x^3+1).valuation(infinity)
-3
sage: P(0).valuation()
+Infinity
```

variable_name()

Return name of variable used in this polynomial as a string.

OUTPUT: string

EXAMPLES:

```python
sage: R.<t> = QQ[]
sage: f = t^3 + 3/2*t + 5
sage: f.variable_name()
't'
```

variables()

Return the tuple of variables occurring in this polynomial.

EXAMPLES:
A constant polynomial has no variables.

```
sage: R(2).variables()
()
```

\texttt{xgcd} (\texttt{other})

Return an extended gcd of this polynomial and \texttt{other}.

\textbf{INPUT:}

- \texttt{other} – a polynomial in the same ring as this polynomial

\textbf{OUTPUT:}

A tuple \((r, s, t)\) where \(r\) is a greatest common divisor of this polynomial and \texttt{other}, and \(s\) and \(t\) are such that \(r = s\times self + t\times other\) holds.

\textbf{Note:} The actual algorithm for computing the extended gcd depends on the base ring underlying the polynomial ring. If the base ring defines a method \_\texttt{xgcd\_univariate\_polynomial}, then this method will be called (see examples below).

\textbf{EXAMPLES:}

```
sage: R.<x> = QQbar[]
sage: (2*x^2).gcd(2*x)
x
sage: R.zero().gcd(0)
0
sage: (2*x).gcd(0)
x
```

One can easily add \texttt{xgcd} functionality to new rings by providing a method \_\texttt{xgcd\_univariate\_polynomial:}

```
sage: R.<x> = QQ[]
sage: S.<y> = R[]
sage: h1 = y*x
sage: h2 = y^2*x^2
sage: h1.xgcd(h2)
Traceback (most recent call last):
...
NotImplementedError: Univariate Polynomial Ring in x over Rational Field does not provide an xgcd implementation for univariate polynomials
```

```
sage: T.<x,y> = QQ[]
sage: def poor_xgcd(f,g):
...:     ret = S(T(f).gcd(g))
...:     if ret == f: return ret,S.one(),S.zero()
...:     if ret == g: return ret,S.zero(),S.one()
...:     raise NotImplementedError
sage: R._xgcd_univariate_polynomial = poor_xgcd
```
\textbf{class} \texttt{sage.rings.polynomial.polynomial_element.PolynomialBaseringInjection}

\textbf{Bases:} \texttt{Morphism}

This class is used for conversion from a ring to a polynomial over that ring.

It calls the \_\texttt{new\_constant\_poly} method on the generator, which should be optimized for a particular polynomial type.

Technically, it should be a method of the polynomial ring, but few polynomial rings are cython classes, and so, as a method of a cython polynomial class, it is faster.

\textbf{EXAMPLES:}

We demonstrate that most polynomial ring classes use polynomial base injection maps for coercion. They are supposed to be the fastest maps for that purpose. See github issue \#9944.

\begin{verbatim}
sage: R.<x> = Qp(3)[]
sage: R.coerce_map_from(R.base_ring())
Polynomial base injection morphism:
    From: 3-adic Field with capped relative precision 20
    To:   Univariate Polynomial Ring in x over 3-adic Field with capped relative precision 20

sage: R.<x,y> = Qp(3)[]
sage: R.coerce_map_from(R.base_ring())
Polynomial base injection morphism:
    From: 3-adic Field with capped relative precision 20
    To:   Multivariate Polynomial Ring in x, y over 3-adic Field with capped relative precision 20

sage: R.<x,y> = QQ[]
sage: R.coerce_map_from(R.base_ring())
Polynomial base injection morphism:
    From: Rational Field
    To:   Multivariate Polynomial Ring in x, y over Rational Field

sage: R.<x> = QQ[]
sage: R.coerce_map_from(R.base_ring())
Polynomial base injection morphism:
    From: Rational Field
    To:   Univariate Polynomial Ring in x over Rational Field
\end{verbatim}

By github issue \#9944, there are now only very few exceptions:

\begin{verbatim}
sage: PolynomialRing(QQ,names=[]).coerce_map_from(QQ)
Call morphism:
    From: Rational Field
    To:   Multivariate Polynomial Ring in no variables over Rational Field
\end{verbatim}

\textbf{is\_injective()}

Return whether this morphism is injective.

\textbf{EXAMPLES:}
```python
sage: R.<x> = ZZ
sage: S.<y> = R
sage: S.coerce_map_from(R).is_injective()
True

Check that github issue #23203 has been resolved:

```python
sage: R.is_subring(S)  # indirect doctest
True
```

### is_surjective()

Return whether this morphism is surjective.

**EXAMPLES:**

```python
sage: R.<x> = ZZ
sage: R.coerce_map_from(ZZ).is_surjective()
False
```

### section()

**class** `sage.rings.polynomial.polynomial_element.Polynomial_generic_dense`

Bases: `Polynomial`

A generic dense polynomial.

**EXAMPLES:**

```python
sage: f = QQ['x']['y'].random_element()
sage: loads(f.dumps()) == f
True
```

### constant_coefficient()

Return the constant coefficient of this polynomial.

**OUTPUT:**

element of base ring

**EXAMPLES:**

```python
sage: R.<t> = QQ
sage: S.<x> = R
sage: f = x*t + x + t
sage: f.constant_coefficient()
t
```

### degree(gen=None)

**EXAMPLES:**

```python
sage: R.<x> = RDF
sage: f = (1+2*x^7)^5
sage: f = f.degree()
35
```

2.1. Univariate Polynomials and Polynomial Rings

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is_term()
Return True if this polynomial is a nonzero element of the base ring times a power of the variable.

EXAMPLES:

```
sage: R.<x> = SR[]
sage: R(0).is_term()
False
sage: R(1).is_term()
True
sage: (3*x^5).is_term()
True
sage: (1+3*x^5).is_term()
False
```

list(copy=True)
Return a new copy of the list of the underlying elements of self.

EXAMPLES:

```
sage: R.<x> = GF(17)[]
sage: f = (1+2*x)^3 + 3*x; f
8*x^3 + 12*x^2 + 9*x + 1
sage: f.list()
[1, 9, 12, 8]
```

quo_rem(other)
Return the quotient and remainder of the Euclidean division of self and other.

Raises a ZeroDivisionError if other is zero. Raises an ArithmeticError if the division is not exact.

EXAMPLES:

```
sage: P.<x> = QQ[]
sage: R.<y> = P[]
sage: f = y^10 + R.random_element(9)
sage: g = y^5 + R.random_element(4)
sage: q, r = f.quo_rem(g)
sage: f == q*g + r
True
sage: g = x*y^5
sage: f.quo_rem(g)
Traceback (most recent call last):
  ... ArithmeticError: division non exact (consider coercing to polynomials over the fraction field)
sage: g = 0
sage: f.quo_rem(g)
Traceback (most recent call last):
  ... ZeroDivisionError: division by zero polynomial
```

Polynomials over noncommutative rings are also allowed (after github issue #34733):
```python
sage: HH = QuaternionAlgebra(QQ, -1, -1)
sage: P.<x> = HH[]
sage: f = P.random_element(5)
sage: g = P.random_element((0, 5))
sage: q, r = f.quo_rem(g)
sage: f == q*g + r
True
```

**shift\((n)\)**

Return this polynomial multiplied by the power \(x^n\).

If \(n\) is negative, terms below \(x^n\) will be discarded. Does not change this polynomial.

**EXAMPLES:**

```python
sage: R.<x> = PolynomialRing(PolynomialRing(QQ,'y'), 'x')
sage: p = x^2 + 2*x + 4
sage: type(p)
<class 'sage.rings.polynomial.polynomial_element.Polynomial_generic_dense'>
sage: p.shift(0)
x^2 + 2*x + 4
sage: p.shift(-1)
x + 2
sage: p.shift(2)
x^4 + 2*x^3 + 4*x^2
```

**AUTHORS:**

- David Harvey (2006-08-06)

**truncate\((n)\)**

Return the polynomial of degree `< n` which is equivalent to self modulo \(x^n\).

**EXAMPLES:**

```python
sage: S.<q> = QQ['t']['q']
sage: f = (1+q^10+q^11+q^12).truncate(11); f
q^10 + 1
sage: f = (1+q^10+q^100).truncate(50); f
q^10 + 1
sage: f.degree()
10
sage: f = (1+q^10+q^100).truncate(500); f
q^100 + q^10 + 1
```

**Bases:** `Polynomial_generic_dense`

A dense polynomial over an inexact ring.

**AUTHOR:**

- Xavier Caruso (2013-03)

**degree**(secure=False)

**INPUT:**

- secure – a boolean (default: False)
OUTPUT:

The degree of self.

If `secure` is True and the degree of this polynomial is not determined (because the leading coefficient is indistinguishable from 0), an error is raised.

If `secure` is False, the returned value is the largest \( n \) so that the coefficient of \( x^n \) does not compare equal to 0.

EXAMPLES:

```python
sage: K = Qp(3,10)
sage: R.<T> = K[]
sage: f = T + 2; f
(1 + O(3^10))*T + 2 + O(3^10)
sage: f.degree()
1
sage: (f-T).degree()
0
sage: (f-T).degree(secure=True)
Traceback (most recent call last):
  ...  
PrecisionError: the leading coefficient is indistinguishable from 0
```

```python
sage: x = O(3^5)
sage: li = [3^i * x for i in range(0,5)]; li
[O(3^5), O(3^6), O(3^7), O(3^8), O(3^9)]
sage: f = R(li); f
O(3^9)*T^4 + O(3^8)*T^3 + O(3^7)*T^2 + O(3^6)*T + O(3^5)
sage: f.degree()
-1
sage: f.degree(secure=True)
Traceback (most recent call last):
  ...  
PrecisionError: the leading coefficient is indistinguishable from 0
```

AUTHOR:

• Xavier Caruso (2013-03)

**prec_degree()**

Return the largest \( n \) so that precision information is stored about the coefficient of \( x^n \).

Always greater than or equal to degree.

EXAMPLES:

```python
sage: K = Qp(3,10)
sage: R.<T> = K[]
sage: f = T + 2; f
(1 + O(3^10))*T + 2 + O(3^10)
sage: f.degree()
1
sage: f.prec_degree()
1
```

(continues on next page)
sage: g = f - T; g
O(3^{10})T + 2 + O(3^{10})
sage: g.degree()
0
sage: g.prec_degree()
1

AUTHOR:
• Xavier Caruso (2013-03)

sage.rings.polynomial.polynomial_element.generic_power_trunc(p, n, prec)
Generic truncated power algorithm

INPUT:
• p - a polynomial
• n - an integer (of type sage.rings.integer.Integer)
• prec - a precision (should fit into a C long)

sage.rings.polynomial.polynomial_element.is_Polynomial(f)
Return True if f is of type univariate polynomial.
This function is deprecated.

INPUT:
• f – an object

EXAMPLES:

sage: from sage.rings.polynomial.polynomial_element import is_Polynomial
sage: R.<x> = ZZ[]
sage: is_Polynomial(x^3 + x + 1)
True
sage: S.<y> = R[]
sage: f = y^3 + x*y - 3*x; f
y^3 + x*y - 3*x
sage: is_Polynomial(f)
True

However this function does not return True for genuine multivariate polynomial type objects or symbolic polynomials, since those are not of the same data type as univariate polynomials:

sage: R.<x,y> = QQ[]
sage: f = y^3 + x*y - 3*x; f
y^3 + x*y - 3*x
sage: is_Polynomial(f)
False
sage: var('x,y')
(x, y)
sage: f = y^3 + x*y - 3*x; f

y^3 + x*y - 3*x

sage: is_Polynomial(f)
False

sage.rings.polynomial.polynomial_element.make_generic_polynomial

sage.rings.polynomial.polynomial_element.polynomial_is_variable(x)

Test whether the given polynomial is a variable of its parent ring.

Implemented for instances of Polynomial and MPolynomial.

See also:

• sage.rings.polynomial.polynomial_element.Polynomial.is_gen()
• sage.rings.polynomial.multi_polynomial.MPolynomial.is_generator()

EXAMPLES:

sage: from sage.rings.polynomial.polynomial_element import polynomial_is_variable
sage: R.<x> = QQ[]
sage: polynomial_is_variable(x)
True
sage: polynomial_is_variable(R([0,1]))
True
sage: polynomial_is_variable(x^2)
False
sage: polynomial_is_variable(R(42))
False

sage: R.<y,z> = QQ[]
sage: polynomial_is_variable(y)
True
sage: polynomial_is_variable(z)
True
sage: polynomial_is_variable(y^2)
False
sage: polynomial_is_variable(y+z)
False
sage: polynomial_is_variable(R(42))
False

sage: polynomial_is_variable(42)
False

sage.rings.polynomial.polynomial_element.universal_discriminant()

Return the discriminant of the ‘universal’ univariate polynomial
\(a_n x^n + \cdots + a_1 x + a_0\) in \(\mathbb{Z}[a_0, \ldots, a_n] [x]\).

INPUT:

• n - degree of the polynomial

OUTPUT:

The discriminant as a polynomial in \(n+1\) variables over \(\mathbb{Z}\). The result will be cached, so subsequent computations of discriminants of the same degree will be faster.
EXAMPLES:

```
sage: from sage.rings.polynomial.polynomial_element import universal_discriminant
sage: universal_discriminant(1)
1
sage: universal_discriminant(2)
a1^2 - 4*a0*a2
sage: universal_discriminant(3)
a1^2*a2^2 - 4*a0*a2^3 - 4*a1^3*a3 + 18*a0*a1*a2*a3 - 27*a0^2*a3^2
sage: universal_discriminant(4).degrees()
(3, 4, 4, 4, 3)
```

See also:

`Polynomial.discriminant()`

## 2.1.4 Univariate Polynomials over domains and fields

AUTHORS:

- William Stein: first version
- Martin Albrecht: Added singular coercion.
- David Harvey: split off `polynomial_integer_dense_ntl.pyx` (2007-09)
- Robert Bradshaw: split off `polynomial_modn_dense_ntl.pyx` (2007-09)

```python
class sage.rings.polynomial.polynomial_element_generic.Polynomial_generic_cdv(parent, is_gen=False, construct=False)
```

Bases: `Polynomial_generic_domain`

A generic class for polynomials over complete discrete valuation domains and fields.

AUTHOR:

- Xavier Caruso (2013-03)

`factor_of_slope(slope=None)`

**INPUT:**

- slope – a rational number (default: the first slope in the Newton polygon of `self`)

**OUTPUT:**

The factor of `self` corresponding to the slope `slope` (i.e. the unique monic divisor of `self` whose slope is `slope` and degree is the length of `slope` in the Newton polygon).

EXAMPLES:

```
sage: K = Qp(5)
sage: R.<x> = K[]
sage: K = Qp(5)
sage: R.<t> = K[]
sage: f = 5 + 3*t + t^4 + 25*t^10
sage: f.newton_slopes()
[1, 0, 0, -1/3, -1/3, -1/3, -1/3, -1/3, -1/3]
```

(continues on next page)
If slope is not a slope of self, the corresponding factor is 1:

```python
sage: f.factor_of_slope(-1)
1 + O(5^20)
```

AUTHOR:

• Xavier Caruso (2013-03-20)

**hensel_lift(a)**

Lift \(a\) to a root of this polynomial (using Newton iteration).

If \(a\) is not close enough to a root (so that Newton iteration does not converge), an error is raised.

**EXAMPLES:**

```python
sage: K = Qp(5, 10)
sage: P.<x> = PolynomialRing(K)
sage: f = x^2 + 1
sage: root = f.hensel_lift(2); root
2 + 5 + 2*5^2 + 5^3 + 3*5^4 + 4*5^5 + 2*5^6 + 3*5^7 + 3*5^9 + O(5^10)
sage: f(root)
O(5^10)
sage: g = (x^2 + 1)^9*(x - 7)
sage: g.hensel_lift(2) # here, 2 is a multiple root modulo p
Traceback (most recent call last):
  ... ValueError: a is not close enough to a root of this polynomial
```

AUTHOR:

• Xavier Caruso (2013-03-23)

**newton_polygon()**

Returns a list of vertices of the Newton polygon of this polynomial.

**Note:** If some coefficients have not enough precision an error is raised.

**EXAMPLES:**
sage: K = Qp(5)
sage: R.<t> = K[]
sage: f = 5 + 3*t + t^4 + 25*t^10
sage: f.newton_polygon()
Finite Newton polygon with 4 vertices: (0, 1), (1, 0), (4, 0), (10, 2)

sage: g = f + K(0,0)*t^4; g
(5^2 + O(5^22))*t^10 + O(5^0)*t^4 + (3 + O(5^20))*t + 5 + O(5^21)
sage: g.newton_polygon()
Traceback (most recent call last):
  ...  
PrecisionError: The coefficient of t^4 has not enough precision

AUTHOR:
• Xavier Caruso (2013-03-20)

**newton_slopes**(repetition=True)

Returns a list of the Newton slopes of this polynomial.

These are the valuations of the roots of this polynomial.

If repetition is True, each slope is repeated a number of times equal to its multiplicity. Otherwise it appears only one time.

EXAMPLES:

```sage
sage: K = Qp(5)
sage: R.<t> = K[]
sage: f = 5 + 3*t + t^4 + 25*t^10
sage: f.newton_polygon()
Finite Newton polygon with 4 vertices: (0, 1), (1, 0), (4, 0), (10, 2)
sage: f.newton_slopes()
[1, 0, 0, 0, -1/3, -1/3, -1/3, -1/3, -1/3, -1/3]
sage: f.newton_slopes(repetition=False)
[1, 0, -1/3]
```

AUTHOR:
• Xavier Caruso (2013-03-20)

**slope_factorization**()

Return a factorization of self into a product of factors corresponding to each slope in the Newton polygon.

EXAMPLES:

```sage
sage: K = Qp(5)
sage: R.<x> = K[]
sage: K = Qp(5)
sage: R.<t> = K[]
sage: f = 5 + 3*t + t^4 + 25*t^10
sage: f.newton_slopes()
[1, 0, 0, 0, -1/3, -1/3, -1/3, -1/3, -1/3, -1/3]
sage: F = f.slope_factorization()
```

(continues on next page)
AUTHOR:
• Xavier Caruso (2013-03-20)

class sage.rings.polynomial.polynomial_element_generic.Polynomial_generic_cdvf(parent, is_gen=False, construct=False)

Bases: Polynomial_generic_cdv, Polynomial_generic_field

class sage.rings.polynomial.polynomial_element_generic.Polynomial_generic_cdvr(parent, is_gen=False, construct=False)

Bases: Polynomial_generic_cdv

class sage.rings.polynomial.polynomial_element_generic.Polynomial_generic_dense_cdv

Bases: Polynomial_generic_dense_inexact, Polynomial_generic_cdv

class sage.rings.polynomial.polynomial_element_generic.Polynomial_generic_dense_cdvf

Bases: Polynomial_generic_dense_cdv, Polynomial_generic_cdvf

class sage.rings.polynomial.polynomial_element_generic.Polynomial_generic_dense_cdvr

Bases: Polynomial_generic_dense_cdv, Polynomial_generic_cdvr

class sage.rings.polynomial.polynomial_element_generic.Polynomial_generic_dense_field(parent, x=None, check=True, is_gen=False, construct=False)

Bases: Polynomial_generic_dense, Polynomial_generic_field

class sage.rings.polynomial.polynomial_element_generic.Polynomial_generic_domain(parent, is_gen=False, construct=False)

Bases: Polynomial, IntegralDomainElement

is_unit()  
Return True if this polynomial is a unit.

EXERCISE (Atiyah-McDonald, Ch 1): Let $A[x]$ be a polynomial ring in one variable. Then $f = \sum a_i x^i \in A[x]$ is a unit if and only if $a_0$ is a unit and $a_1, \ldots, a_n$ are nilpotent.

EXAMPLES:
class sage.rings.polynomial.polynomial_element_generic.Polynomial_generic_field(parent, is_gen=False, construct=False)

Bases: Polynomial_singular_repr, Polynomial_generic_domain, EuclideanDomainElement

quo_rem(other)

Returns a tuple (quotient, remainder) where
    self = quotient * other + remainder.

EXAMPLES:

sage: R.<y> = PolynomialRing(QQ)
sage: K.<t> = NumberField(y^2 - 2)
sage: P.<x> = PolynomialRing(K)
sage: x.quo_rem(K(1))
(x, 0)
sage: x.xgcd(K(1))
(1, 0, 1)

class sage.rings.polynomial.polynomial_element_generic.Polynomial_generic_sparse(parent, x=None, check=True, is_gen=False, construct=False)

Bases: Polynomial

A generic sparse polynomial.

The Polynomial_generic_sparse class defines functionality for sparse polynomials over any base ring. A sparse polynomial is represented using a dictionary which maps each exponent to the corresponding coefficient. The coefficients must never be zero.

EXAMPLES:

sage: R.<x> = PolynomialRing(PolynomialRing(QQ, 'y'), sparse=True)
sage: f = x^3 - x + 17
sage: type(f)
<class 'sage.rings.polynomial.polynomial_ring.PolynomialRing_integral_domain_with...>
A more extensive example:

```python
sage: A.<T> = PolynomialRing(Integers(5), sparse=True) ; f = T^2+1 ; B = A.quotient(f)

sage: C.<s> = PolynomialRing(B)

sage: C
Univariate Polynomial Ring in s over Univariate Quotient Polynomial Ring in Tbar over Ring of integers modulo 5 with modulus T^2 + 1

sage: s + T
s + Tbar

sage: (s + T)**2
s^2 + 2*Tbar*s + 4
```

**coefficients**(sparse=True)

Return the coefficients of the monomials appearing in `self`.

EXAMPLES:

```python
sage: R.<w> = PolynomialRing(Integers(8), sparse=True)

sage: f = 5 + w^1997 - w^10000; f
7*w^10000 + w^1997 + 5

sage: f.coefficients()
[5, 1, 7]
```

**degree**(gen=None)

Return the degree of this sparse polynomial.

EXAMPLES:

```python
sage: R.<z> = PolynomialRing(ZZ, sparse=True)

sage: f = 13*z^50000 + 15*z^2 + 17*z

sage: f.degree()
50000
```

**dict**()

Return a new copy of the `dict` of the underlying elements of `self`.

EXAMPLES:

```python
sage: R.<w> = PolynomialRing(Integers(8), sparse=True)

sage: f = 5 + w^1997 - w^10000; f
7*w^10000 + w^1997 + 5

sage: d = f.dict(); d
{0: 5, 1997: 1, 10000: 7}

sage: d[0] = 10

sage: f.dict()
{0: 10, 1997: 1, 10000: 7}
```

**exponents**()

Return the exponents of the monomials appearing in `self`.

EXAMPLES:
sage: R.<w> = PolynomialRing(Integers(8), sparse=True)
sage: f = 5 + w^1997 - w^10000; f
7*w^10000 + w^1997 + 5
sage: f.exponents()
[0, 1997, 10000]

\textbf{gcd}(\text{other, algorithm=None})

Return the gcd of this polynomial and other

\textbf{INPUT:}

\begin{itemize}
  \item other – a polynomial defined over the same ring as this polynomial.
\end{itemize}

\textbf{ALGORITHM:}

Two algorithms are provided:

\begin{itemize}
  \item generic: Uses the generic implementation, which depends on the base ring being a UFD or a field.
  \item dense: The polynomials are converted to the dense representation, their gcd is computed and is converted back to the sparse representation.
\end{itemize}

Default is dense for polynomials over ZZ and generic in the other cases.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: R.<x> = PolynomialRing(ZZ, sparse=True)
sage: p = x^6 + 7*x^5 + 8*x^4 + 6*x^3 + 2*x^2 + x + 2
sage: q = 2*x^4 - x^3 - 2*x^2 - 4*x - 1
sage: gcd(p,q)
x^2 + x + 1
sage: gcd(p, q, algorithm = "dense")
x^2 + x + 1
sage: gcd(p, q, algorithm = "generic")
x^2 + x + 1
sage: gcd(p, q, algorithm = "foobar")
Traceback (most recent call last):
  ...
ValueError: Unknown algorithm 'foobar'
\end{verbatim}

\textbf{integral}(\text{var=None})

Return the integral of this polynomial.

By default, the integration variable is the variable of the polynomial.

Otherwise, the integration variable is the optional parameter \texttt{var}

\textbf{Note:} The integral is always chosen so that the constant term is 0.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: R.<x> = PolynomialRing(ZZ, sparse=True)
sage: (1 + 3*x^10 - 2*x^100).integral()
-2/101*x^101 + 3/11*x^11 + x
\end{verbatim}
list\( (\text{copy}=\text{True}) \)

Return a new copy of the list of the underlying elements of self.

EXAMPLES:

```
sage: R.<z> = PolynomialRing(Integers(100), sparse=True)
sage: f = 13*z^5 + 15*z^2 + 17*z
sage: f.list()
[0, 17, 15, 0, 0, 13]
```

number_of_terms()

Return the number of nonzero terms.

EXAMPLES:

```
sage: R.<x> = PolynomialRing(ZZ,sparse=True)
sage: p = x^100 - 3*x^10 + 12
sage: p.number_of_terms()
3
```

quo_rem\( (\text{other}) \)

Returns the quotient and remainder of the Euclidean division of self and other.

Raises ZeroDivisionError if other is zero.

Raises ArithmeticError if other has a nonunit leading coefficient and this causes the Euclidean division to fail.

EXAMPLES:

```
sage: P.<x> = PolynomialRing(ZZ, sparse=True)
sage: R.<y> = PolynomialRing(P, sparse=True)
sage: f = R.random_element(10)
sage: while x.divides(f.leading_coefficient()):
....: f = R.random_element(10)
```

```
sage: g = y^5 + R.random_element(4)
sage: q, r = f.quo_rem(g)
sage: f == q*g + r and r.degree() < g.degree()
True
```
Polynomials, Release 10.0

(continued from previous page)

\[
sage: f \text{.quo_rem}(g) \\
\text{(-y^5 + 2*y^2, y^3 - 2*x^2*y^2 - y)}
\]

Polynomials over noncommutative rings are also allowed:

\[
sage: HH = QuaternionAlgebra(QQ, -1, -1) \\
sage: P.<x> = PolynomialRing(HH, sparse=True) \\
sage: f = P.random_element(5) \\
sage: g = P.random_element((0, 5)) \\
sage: q, r = f \text{.quo_rem}(g) \\
sage: f == q \times g + r \\
True
\]

AUTHORS:

• Bruno Grenet (2014-07-09)

\textbf{reverse}(\textit{degree=\texttt{None}})

Return this polynomial but with the coefficients reversed.

If an optional degree argument is given the coefficient list will be truncated or zero padded as necessary and the reverse polynomial will have the specified degree.

EXAMPLES:

\[
sage: R.<x> = PolynomialRing(ZZ, sparse=True) \\
sage: p = x^4 + 2^x^2^100 \\
sage: type(p) \\
<class 'sage.rings.polynomial.polynomial_ring.PolynomialRing_integral_domain˓
\text{with_category.element_class'}> \\
sage: p.reverse() \\
x^1267650600228229496703205372 + 2 \\
sage: p.reverse(10) \\
x^6
\]

\textbf{shift}(\textit{n})

Returns this polynomial multiplied by the power \(x^n\).

If \(n\) is negative, terms below \(x^n\) will be discarded. Does not change this polynomial.

EXAMPLES:

\[
sage: R.<x> = PolynomialRing(ZZ, sparse=True) \\
sage: p = x^{100000} + 2^x + 4 \\
sage: type(p) \\
<class 'sage.rings.polynomial.polynomial_ring.PolynomialRing_integral_domain_˓
\text{with_category.element_class'}> \\
sage: p.shift(0) \\
x^{100000} + 2^x + 4 \\
sage: p.shift(-1) \\
x^{99999} + 2 \\
sage: p.shift(-100002) \\
0 \\
sage: p.shift(2) \\
x^{100002} + 2^x^3 + 4^x^2
\]

AUTHOR: - David Harvey (2006-08-06)
Polynomials, Release 10.0

**truncate**\((n)\)

Return the polynomial of degree \(< n\) equal to \(self\) modulo \(x^n\).

**EXAMPLES:**

```python
sage: R.<x> = PolynomialRing(ZZ, sparse=True)
sage: (x^11 + x^10 + 1).truncate(11)
x^10 + 1
sage: (x^2^500 + x^2^100 + 1).truncate(2^101)
x^1267650600228229401496763205376 + 1
```

**valuation**\((p=None)\)

Return the valuation of \(self\).

**EXAMPLES:**

```python
sage: R.<w> = PolynomialRing(GF(9, 'a'), sparse=True)
sage: f = w^1997 - w^10000
sage: f.valuation()
1997
sage: R(19).valuation()
0
sage: R(0).valuation()
+Infinity
```

```python

class sage.rings.polynomial.polynomial_element_generic.Polynomial_generic_sparse_cdv(parent, x=None, check=True, is_gen=False, construct=False)

Bases: Polynomial_generic_sparse, Polynomial_generic_cdv

class sage.rings.polynomial.polynomial_element_generic.Polynomial_generic_sparse_cdvf(parent, x=None, check=True, is_gen=False, construct=False)

Bases: Polynomial_generic_sparse_cdv, Polynomial_generic_cdvf

class sage.rings.polynomial.polynomial_element_generic.Polynomial_generic_sparse_cdvr(parent, x=None, check=True, is_gen=False, construct=False)

Bases: Polynomial_generic_sparse_cdvr, Polynomial_generic_cdvr

class sage.rings.polynomial.polynomial_element_generic.Polynomial_generic_sparse_field(parent, x=None, check=True, is_gen=False, construct=False)

Bases: Polynomial_generic_sparse_field, Polynomial_generic_cdvr
```

Chapter 2. Univariate Polynomials
Bases: Polynomial_generic_sparse, Polynomial_generic_field

EXAMPLES:

```python
sage: R.<x> = PolynomialRing(Frac(RR['t']), sparse=True)
sage: f = x^3 - x + 17
sage: type(f)
<class 'sage.rings.polynomial.polynomial_ring.PolynomialRing_field_with_category.element_class'>
sage: loads(f.dumps()) == f
True
```

2.1.5 Univariate Polynomials over GF(2) via NTL's GF2X

AUTHOR: Martin Albrecht (2008-10) initial implementation

sage.rings.polynomial.polynomial_gf2x.GF2X_BuildIrred_list(n)

Return the list of coefficients of the lexicographically smallest irreducible polynomial of degree \(n\) over the field of 2 elements.

EXAMPLES:

```python
sage: from sage.rings.polynomial.polynomial_gf2x import GF2X_BuildIrred_list
sage: GF2X_BuildIrred_list(2)
[1, 1, 1]
sage: GF2X_BuildIrred_list(3)
[1, 1, 0, 1]
sage: GF2X_BuildIrred_list(4)
[1, 1, 0, 0, 1]
sage: GF(2)['x'](GF2X_BuildIrred_list(33))
x^33 + x^6 + x^3 + x + 1
```

sage.rings.polynomial.polynomial_gf2x.GF2X_BuildRandomIrred_list(n)

Return the list of coefficients of an irreducible polynomial of degree \(n\) of minimal weight over the field of 2 elements.

EXAMPLES:

```python
sage: from sage.rings.polynomial.polynomial_gf2x import GF2X_BuildRandomIrred_list
sage: GF2X_BuildRandomIrred_list(2)
[1, 1, 1]
sage: GF2X_BuildRandomIrred_list(3) in [[1, 1, 0, 1], [1, 0, 1, 1]]
True
```

sage.rings.polynomial.polynomial_gf2x.GF2X_BuildSparseIrred_list(n)

Return the list of coefficients of an irreducible polynomial of degree \(n\) of minimal weight over the field of 2 elements.

EXAMPLES:

```python
sage: from sage.rings.polynomial.polynomial_gf2x import GF2X_BuildIrred_list, GF2X_BuildSparseIrred_list
sage: all([GF2X_BuildSparseIrred_list(n) == GF2X_BuildIrred_list(n)
(continues on next page)
..:  for n in range(1,33))
True
sage: GF(2)['x'](GF2X_BuildSparseIrred_list(33))
x^33 + x^10 + 1

class sage.rings.polynomial.polynomial_gf2x.Polynomial_GF2X
Bases: Polynomial_template

Univariate Polynomials over GF(2) via NTL's GF2X.

EXAMPLES:

sage: P.<x> = GF(2)[]
sage: x^3 + x^2 + 1
x^3 + x^2 + 1

is_irreducible()

Return whether this polynomial is irreducible over \( F_2 \).

EXAMPLES:

sage: R.<x> = GF(2)[]
sage: (x^2 + 1).is_irreducible()  
False
sage: (x^3 + x + 1).is_irreducible()  
True

Test that caching works:

sage: R.<x> = GF(2)[]
sage: f = x^2 + 1
sage: f.is_irreducible()  
False
sage: f.is_irreducible.cache  
False

modular_composition(g, h, algorithm=None)

Compute \( f(g) \mod h \).


INPUT:

- \( g \) – a polynomial
- \( h \) – a polynomial
- algorithm – either ‘native’ or ‘ntl’ (default: ‘native’)

EXAMPLES:

sage: P.<x> = GF(2)[]
sage: r = 279
sage: f = x^r + x +1
sage: g = x^r
(continues on next page)
AUTHORS:

- Paul Zimmermann (2008-10) initial implementation
- Martin Albrecht (2008-10) performance improvements

class sage.rings.polynomial.polynomial_gf2x.Polynomial_template

Bases: Polynomial

Template for interfacing to external C / C++ libraries for implementations of polynomials.

AUTHORS:

- Robert Bradshaw (2008-10): original idea for templating
- Martin Albrecht (2008-10): initial implementation

This file implements a simple templating engine for linking univariate polynomials to their C/C++ library implementations. It requires a ‘linkage’ file which implements the `element_` functions (see `sage.libsntl.ntl_GF2X_linkage` for an example). Both parts are then plugged together by inclusion of the linkage file when inheriting from this class. See `sage.rings.polynomial.polynomial_gf2x` for an example.

We illustrate the generic glueing using univariate polynomials over GF(2).

**Note:** Implementations using this template MUST implement coercion from base ring elements and `get_unsafe()`. See `Polynomial_GF2X` for an example.

degree()

EXAMPLES:

```python
sage: P. = GF(2)[]
sage: x.degree()
1
sage: P(1).degree()
0
sage: P(0).degree()
-1
```

gcd(other)

Return the greatest common divisor of self and other.

EXAMPLES:
sage: P.<x> = GF(2)[]
sage: f = x*(x+1)
sage: f.gcd(x+1)
x + 1
sage: f.gcd(x^2)
x

get_cparent()

is_gen()
EXAMPLES:

sage: P.<x> = GF(2)[]
sage: x.is_gen()
True
sage: (x+1).is_gen()
False

is_one()
EXAMPLES:

sage: P.<x> = GF(2)[]
sage: P(1).is_one()
True

is_zero()
EXAMPLES:

sage: P.<x> = GF(2)[]
sage: x.is_zero()
False

list(copy=True)
EXAMPLES:

sage: P.<x> = GF(2)[]
sage: x.list()
[0, 1]
sage: list(x)
[0, 1]

quo_rem(right)
EXAMPLES:

sage: P.<x> = GF(2)[]
sage: f = x^2 + x + 1
sage: f.quo_rem(x + 1)
(x, 1)

shift(n)
EXAMPLES:
```python
sage: P.<x> = GF(2)[]
sage: f = x^3 + x^2 + 1
sage: f.shift(1)
x^4 + x^3 + x
sage: f.shift(-1)
x^2 + x
```

truncaten)

Returns this polynomial mod \(x^n\).

EXAMPLES:
```python
sage: R.<x> =GF(2)[]
sage: f = sum(x^n for n in range(10)); f
x^9 + x^8 + x^7 + x^6 + x^5 + x^4 + x^3 + x^2 + x + 1
sage: f.truncate(6)
x^5 + x^4 + x^3 + x^2 + x + 1
```

If the precision is higher than the degree of the polynomial then the polynomial itself is returned:
```python
sage: f.truncate(10) is f
True
```

If the precision is negative, the zero polynomial is returned:
```python
sage: f.truncate(-1)
0
```

xgcd(other)

Computes extended gcd of self and other.

EXAMPLES:
```python
sage: P.<x> = GF(7)[]
sage: f = x*(x+1)
sage: f.xgcd(x+1)
(x + 1, 0, 1)
sage: f.xgcd(x^2)
(x, 1, 6)
```

```
sage.rings.polynomial.polynomial_gf2x.make_element(parent, args)
```

## 2.1.6 Univariate polynomials over number fields.

AUTHOR:

EXAMPLES:

Define a polynomial over an absolute number field and perform basic operations with them:
```python
sage: N.<a> = NumberField(x^2-2)
sage: K.<x> = N[]
```
sage: \( f = x - a \)
sage: \( g = x^3 - 2^a + 1 \)
sage: \( f*(x + a) \)
x^2 - 2
sage: \( f + g \)
x^3 + x - 3^a + 1
sage: \( g \div f \)
x^2 + a^x + 2
sage: \( g \mod f \)
1
sage: \( \text{factor}(x^3 - 2^a x^2 - 2 x + 4^a) \)
\((x - 2^a) \times (x - a) \times (x + a)\)
sage: \( \text{gcd}(f, x - a) \)
x - a

Polynomials are aware of embeddings of the underlying field:

sage: \( x = \text{var}'(x)' \)
sage: \( Q7 = \text{Qp}(7) \)
sage: \( r1 = Q7(3 + 7 + 2^7^2 + 6^7^3 + 7^4 + 2^7^5 + 7^6 + 2^7^7 + 4^7^8 + \)
\( 6^7^9 + 6^7^10 + 2^7^11 + 7^12 + 7^13 + 2^7^15 + 7^16 + 7^17 + \)
\( 4^7^18 + 6^7^19) \)
sage: \( N.<b> = \text{NumberField}(x^2 - 2, \text{embedding} = r1) \)
sage: \( K.<t> = N[] \)
sage: \( f = t^3 - 2 t + 1 \)
sage: \( f(r1) \)
1 + O(7^20)

We can also construct polynomials over relative number fields:

sage: \( N.<i, s2> = \text{QQ}[I, \text{sqrt}(2)] \)
sage: \( K.<x> = N[] \)
sage: \( f = x - s2 \)
sage: \( g = x^3 - 2i^x^2 + s2^x \)
sage: \( f*(x + s2) \)
x^2 - 2
sage: \( f + g \)
x^3 + (-2I + sqrt2)*x - 2*sqrt2*I + sqrt2 + 2
sage: \( g \div f \)
-4*I + 2*sqrt2 + 2
sage: \( \text{factor}(i^x^4 - 2i^x^2 + 9^i) \)
\((I) \times (x - I + sqrt2) \times (x + I - sqrt2) \times (x - I - sqrt2) \times (x + I + sqrt2)\)
sage: \( \text{gcd}(f, x - i) \)
1

class sage.rings.polynomial.polynomial_number_field.Polynomial_absolute_number_field_dense(parent, x=None, check=True, is_gen=False, construct=False)
Polynomials, Release 10.0

Bases: `Polynomial_generic_dense_field`

Class of dense univariate polynomials over an absolute number field.

```python
gcd(other)
```

Compute the monic gcd of two univariate polynomials using PARI.

**INPUT:**

- `other` – a polynomial with the same parent as `self`.

**OUTPUT:**

- The monic gcd of `self` and `other`.

**EXAMPLES:**

```python
sage: N.<a> = NumberField(x^3-1/2, 'a')
sage: R.<r> = N['r']
sage: f = (5/4*a^2 - 2*a + 4)*r^2 + (5*a^2 - 81/5*a - 17/2)*r + 4/5*a^2 + 24*a → 6
sage: g = (5/4*a^2 - 2*a + 4)*r^2 + (-11*a^2 + 79/5*a - 7/2)*r - 4/5*a^2 - 24*a → 6
sage: gcd(f, g^2)
r - 60808/96625*a^2 - 69936/96625*a - 149212/96625
```

```python
sage: R = QQ[I]['x']
sage: f = R.random_element(2)
sage: g = f + 1
sage: h = R.random_element(2).monic()
sage: f *=h
sage: g *=h
sage: gcd(f, g) - h
0
sage: f.gcd(g) - h
0
```

```python
class sage.rings.polynomial.polynomial_number_field.Polynomial_relative_number_field_dense(parent, x=None, check=True, is_gen=False, construct=False)
```

Bases: `Polynomial_generic_dense_field`

Class of dense univariate polynomials over a relative number field.

```python
gcd(other)
```

Compute the monic gcd of two polynomials.

Currently, the method checks corner cases in which one of the polynomials is zero or a constant. Then, computes an absolute extension and performs the computations there.

**INPUT:**

- `other` – a polynomial with the same parent as `self`.

**OUTPUT:**

- The monic gcd of `self` and `other`. 

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See `Polynomial_absolute_number_field_dense.gcd()` for more details.

**EXAMPLES:**

```python
sage: N = QQ[sqrt(2), sqrt(3)]
sage: s2, s3 = N.gens()
sage: x = polygen(N)
sage: f = x^4 - 5*x^2 +6
sage: g = x^3 + (-2*s2 + s3)*x^2 + (-2*s3*s2 + 2)*x + 2*s3
sage: gcd(f, g)
x^2 + (-sqrt2 + sqrt3)*x - sqrt3*sqrt2
sage: f.gcd(g)
x^2 + (-sqrt2 + sqrt3)*x - sqrt3*sqrt2
```

### 2.1.7 Dense univariate polynomials over \( \mathbb{Z} \), implemented using FLINT

**AUTHORS:**

- David Harvey: rewrote to talk to NTL directly, instead of via ntl.pyx (2007-09); a lot of this was based on Joel Mohler’s recent rewrite of the NTL wrapper
- David Harvey: split off from polynomial_element_generic.py (2007-09)
- Burcin Erocal: rewrote to use FLINT (2008-06-16)

**class** `sage.rings.polynomial.polynomial_integer_dense_flint.Polynomial_integer_dense_flint`

Bases: `Polynomial`

A dense polynomial over the integers, implemented via FLINT.

**_add_(right)**

Returns self plus right.

**EXAMPLES:**

```python
sage: R.<x> = PolynomialRing(ZZ)
sage: f = 2*x + 1
sage: g = -3*x^2 + 6
sage: f + g
-3*x^2 + 2*x + 7
```

**_sub_(right)**

Return self minus right.

**EXAMPLES:**

```python
sage: R.<x> = PolynomialRing(ZZ)
sage: f = 2*x + 1
sage: g = -3*x^2 + 6
sage: f - g
3*x^2 + 2*x - 5
```

**_lmul_(right)**

Returns self multiplied by right, where right is a scalar (integer).

**EXAMPLES:**
Polynomials, Release 10.0

```python
sage: R.<x> = PolynomialRing(ZZ)
sage: x^3
3*x
sage: (2*x^2 + 4)*3
6*x^2 + 12
```

_rmul_(right)

Returns self multiplied by right, where right is a scalar (integer).

EXAMPLES:

```python
sage: R.<x> = PolynomialRing(ZZ)
sage: 3*x
3*x
sage: 3*(2*x^2 + 4)
6*x^2 + 12
```

_mul_(right)

Returns self multiplied by right.

EXAMPLES:

```python
sage: R.<x> = PolynomialRing(ZZ)
sage: (x - 2)*(x^2 - 8*x + 16)
x^3 - 10*x^2 + 32*x - 32
```

_mul_trunc_(right, n)

Truncated multiplication

See also:

_mul_() for standard multiplication

EXAMPLES:

```python
sage: x = polygen(ZZ)
sage: p1 = 1 + x + x^2 + x^4
sage: p2 = -2 + 3*x^2 + 5*x^4
sage: p1._mul_trunc_(p2, 4)
3*x^3 + x^2 - 2*x - 2
sage: (p1*p2).truncate(4)
3*x^3 + x^2 - 2*x - 2
sage: p1._mul_trunc_(p2, 6)
5*x^5 + 6*x^4 + 3*x^3 + x^2 - 2*x - 2
```

content()

Return the greatest common divisor of the coefficients of this polynomial. The sign is the sign of the leading coefficient. The content of the zero polynomial is zero.

EXAMPLES:

```python
sage: R.<x> = PolynomialRing(ZZ)
sage: (2*x^2 - 4*x^4 + 14*x^7).content()
2
sage: x.content()
```

(continues on next page)
1
sage: R(1).content()
1
sage: R(0).content()
@

def degree(gen=None)
    Return the degree of this polynomial.
The zero polynomial has degree -1.

EXAMPLES:
sage: R.<x> = PolynomialRing(ZZ)
sage: x.degree()
1
sage: (x^2).degree()
2
sage: R(1).degree()
0
sage: R(0).degree()
-1

disc(proof=True)
    Return the discriminant of self, which is by definition
    \((-1)^{m(m-1)/2} \text{resultant}(a, a')/\text{lc}(a),\)
    where \(m = \deg(a)\), and \(\text{lc}(a)\) is the leading coefficient of \(a\).
    If \(\text{proof}\) is False (the default is True), then
    this function may use a randomized strategy that errors with probability no more
    than \(2^{-80}\).

EXAMPLES:
sage: R.<x> = ZZ[]
sage: f = 3*x^3 + 2*x + 1
sage: f.discriminant()
-339
sage: f.discriminant(proof=False)
-339

discriminant(proof=True)
    Return the discriminant of self, which is by definition
    \((-1)^{m(m-1)/2} \text{resultant}(a, a')/\text{lc}(a),\)
    where \(m = \deg(a)\), and \(\text{lc}(a)\) is the leading coefficient of \(a\).
    If \(\text{proof}\) is False (the default is True), then
    this function may use a randomized strategy that errors with probability no more
    than \(2^{-80}\).

EXAMPLES:
sage: R.<x> = ZZ[]
sage: f = 3*x^3 + 2*x + 1
sage: f.discriminant()
-339
sage: f.discriminant(proof=False)
-339
factor()

This function overrides the generic polynomial factorization to make a somewhat intelligent decision to use Pari or NTL based on some benchmarking.

Note: This function factors the content of the polynomial, which can take very long if it’s a really big integer. If you do not need the content factored, divide it out of your polynomial before calling this function.

EXAMPLES:

```
sage: R.<x>=ZZ[]
sage: f=x^4-1
sage: f.factor()
(x - 1) * (x + 1) * (x^2 + 1)
sage: f=1-x
sage: f.factor()
(-1) * (x - 1)
sage: f.factor().unit()
-1
sage: f = -30*x; f.factor()
(-1) * 2 * 3 * 5 * x
```

factor_mod(p)

Return the factorization of self modulo the prime p.

INPUT:

• p – prime

OUTPUT:

factorization of self reduced modulo p.

EXAMPLES:

```
sage: R.<x> = ZZ['x']
sage: f = -3*x*(x-2)*(x-9) + x
sage: f.factor_mod(3)
x
sage: f = -3*x*(x-2)*(x-9)
sage: f.factor_mod(3)
Traceback (most recent call last):
... ArithmeticError: factorization of 0 is not defined
sage: f = 2*x*(x-2)*(x-9)
sage: f.factor_mod(7)
(2) * x * (x + 5)^2
```

factor_padic(p, prec=10)

Return p-adic factorization of self to given precision.

INPUT:

• p – prime

• prec – integer; the precision

OUTPUT:

• factorization of self over the completion at p.

2.1. Univariate Polynomials and Polynomial Rings
EXAMPLES:

```python
sage: R.<x> = PolynomialRing(ZZ)
sage: f = x^2 + 1
sage: f.factor_padic(5, 4)
((1 + O(5^4))*x + 2 + 5 + 2*5^2 + 5^3 + O(5^4)) * ((1 + O(5^4))*x + 3 + 3*5 +
→2*5^2 + 3*5^3 + O(5^4))
```

A more difficult example:

```python
sage: f = 100 * (5^x + 1)^2 * (x + 5)^2
sage: f.factor_padic(5, 10)
(4 + O(5^10)) * (5 + O(5^11))^2 * ((1 + O(5^10))*x + 5 + O(5^10))^2 * ((5 + O(5^10))*x + 1 + O(5^10))^2
```

gcd(right)

Return the GCD of self and right. The leading coefficient need not be 1.

EXAMPLES:

```python
sage: R.<x> = PolynomialRing(ZZ)
sage: f = (6*x + 47)*(7*x^2 - 2*x + 38)
sage: g = (6*x + 47)*(3*x^3 + 2*x + 1)
sage: f.gcd(g)
6*x + 47
```

inverse_series_trunc(prec)

Return a polynomial approximation of precision prec of the inverse series of this polynomial.

EXAMPLES:

```python
sage: x = polygen(ZZ)
sage: p = 1+x+2*x^2
sage: q5 = p.inverse_series_trunc(5)
sage: q5
-x^4 + 3*x^3 - x^2 - x + 1
sage: p*q5
-2*x^6 + 5*x^5 + 1
sage: (x-1).inverse_series_trunc(5)
-x^4 - x^3 - x^2 - x - 1
sage: q100 = p.inverse_series_trunc(100)
sage: (q100 * p).truncate(100)
1
```

is_one()

Returns True if self is equal to one.

EXAMPLES:

```python
sage: R.<x> = ZZ[]
sage: R(0).is_one()
False
sage: R(1).is_one()
(True)
```
True
sage: x.is_one()
False

**is_zero()**
Returns True if self is equal to zero.

EXAMPLES:

```python
sage: R.<x> = ZZ[]
sage: R(0).is_zero()
True
sage: R(1).is_zero()
False
sage: x.is_zero()
False
```

**lcm(right)**
Return the LCM of self and right.

EXAMPLES:

```python
sage: R.<x> = PolynomialRing(ZZ)
sage: f = (6*x + 47)*(7*x^2 - 2*x + 38)
sage: g = (6*x + 47)*(3*x^3 + 2*x + 1)
sage: h = f.lcm(g); h
126*x^6 + 951*x^5 + 486*x^4 + 6034*x^3 + 585*x^2 + 3706*x + 1786
sage: h == (6*x + 47)*(7*x^2 - 2*x + 38)*(3*x^3 + 2*x + 1)
True
```

**list(copy=True)**
Return a new copy of the list of the underlying elements of self.

EXAMPLES:

```python
sage: x = PolynomialRing(ZZ, 'x').0
sage: f = x^3 + 3*x - 17
sage: f.list()
[-17, 3, 0, 1]
```

**pseudo_divrem(B)**
Write \( A = \text{self} \). This function computes polynomials \( Q \) and \( R \) and an integer \( d \) such that

\[
\text{lead}(B)^d A = BQ + R
\]

where \( R \) has degree less than that of \( B \).

INPUT:

- \( B \) – a polynomial over \( \mathbb{Z} \)

OUTPUT:
• Q, R – polynomials
• d – nonnegative integer

EXAMPLES:

```python
sage: R.<x> = ZZ['x']
sage: A = R(range(10))
sage: B = 3*R([-1, 0, 1])
sage: Q, R, d = A.pseudo_divrem(B)
sage: Q, R, d
(9*x^7 + 8*x^6 + 16*x^5 + 14*x^4 + 21*x^3 + 18*x^2 + 24*x + 20, 75*x + 60, 1)
sage: B.leading_coefficient()^d * A == B*Q + R
True
```

`quo_rem(right)`
Attempts to divide self by right, and return a quotient and remainder.

EXAMPLES:

```python
sage: R.<x> = PolynomialRing(ZZ)
sage: f = R(range(10)); g = R([-1, 0, 1])
sage: q, r = f.quo_rem(g)
sage: q, r
(9*x^7 + 8*x^6 + 16*x^5 + 14*x^4 + 21*x^3 + 18*x^2 + 24*x + 20, 25*x + 20)
sage: q*g + r == f
True
```

```python
sage: f = x^2
sage: f.quo_rem(0)
Traceback (most recent call last):
... ZeroDivisionError: division by zero polynomial
```

`real_root_intervals()`
Returns isolating intervals for the real roots of this polynomial.

EXAMPLES: We compute the roots of the characteristic polynomial of some Salem numbers:

```python
sage: R.<x> = PolynomialRing(ZZ)
sage: f = 1 - x^2 - x^3 - x^4 + x^6
sage: f.real_root_intervals()
[((1/2, 3/4), 1), ((1, 3/2), 1)]
```

`resultant(other, proof=True)`
Returns the resultant of self and other, which must lie in the same polynomial ring.

If proof = False (the default is proof=True), then this function may use a randomized strategy that errors with probability no more than $2^{-80}$. 

---

Chapter 2. Univariate Polynomials
INPUT:

• other – a polynomial

OUTPUT:

an element of the base ring of the polynomial ring

EXAMPLES:

```python
sage: x = PolynomialRing(ZZ, 'x').0
sage: f = x^3 + x + 1; g = x^3 - x - 1
sage: r = f.resultant(g); r
-8
sage: r.parent() is ZZ
True
```

**reverse**(degree=None)

Return a polynomial with the coefficients of this polynomial reversed.

If an optional degree argument is given the coefficient list will be truncated or zero padded as necessary before computing the reverse.

EXAMPLES:

```python
sage: R.<x> = ZZ[]
sage: p = R([1,2,3,4]); p
4*x^3 + 3*x^2 + 2*x + 1
sage: p.reverse()
x^3 + 2*x^2 + 3*x + 4
sage: p.reverse(degree=6)
x^6 + 2*x^5 + 3*x^4 + 4*x^3
sage: p.reverse(degree=2)
x^2 + 2*x + 3
```

**revert_series**(n)

Return a polynomial \( f \) such that \( f(self(x)) = self(f(x)) = x \mod x^n \).

EXAMPLES:

```python
sage: R.<t> = ZZ[]
sage: f = t - t^3 + t^5
sage: f.revert_series(6)
2*t^5 + t^3 + t
sage: f.revert_series(-1)
Traceback (most recent call last):
... ValueError: argument n must be a non-negative integer, got -1
sage: g = - t^3 + t^5
sage: g.revert_series(6)
Traceback (most recent call last):
... ValueError: self must have constant coefficient 0 and a unit for coefficient t^1
```
**squarefree_decomposition()**

Return the square-free decomposition of self. This is a partial factorization of self into square-free, relatively prime polynomials.

This is a wrapper for the NTL function SquareFreeDecomp.

**EXAMPLES:**

```python
sage: R.<x> = PolynomialRing(ZZ)
sage: p = (x-1)^2 * (x-2)^2 * (x-3)^3 * (x-4)
sage: p.squarefree_decomposition()
(x - 4) * (x^2 - 3*x + 2)^2 * (x - 3)^3
sage: p = 37 * (x-1)^2 * (x-2)^2 * (x-3)^3 * (x-4)
sage: p.squarefree_decomposition()
(37) * (x - 4) * (x^2 - 3*x + 2)^2 * (x - 3)^3
```

**xgcd(right)**

Return a triple \((g, s, t)\) such that \(g = s \cdot \text{self} + t \cdot \text{right}\) and such that \(g\) is the gcd of \text{self} and \text{right} up to a divisor of the resultant of \text{self} and \text{other}.

As integer polynomials do not form a principal ideal domain, it is not always possible given \(a\) and \(b\) to find a pair \(s, t\) such that \(\gcd(a, b) = sa + tb\). Take \(a = x + 2\) and \(b = x + 4\) as an example for which the gcd is 1 but the best you can achieve in the Bezout identity is 2.

If \text{self} and \text{right} are coprime as polynomials over the rationals, then \(g\) is guaranteed to be the resultant of \text{self} and \text{right}, as a constant polynomial.

**EXAMPLES:**

```python
sage: P.<x> = PolynomialRing(ZZ)
sage: (x+2).xgcd(x+4)
(2, -1, 1)
sage: (x+2).resultant(x+4)
2
sage: (x+2).gcd(x+4)
1
sage: F = (x^2 + 2)*x^3; G = (x^2+2)*(x-3)
sage: g, u, v = F.xgcd(G)
sage: g, u, v
(27*x^2 + 54, -432*x + 8208, 432*x^2 + 864*x + 14256)
sage: u*F + v*G
27*x^2 + 54
sage: zero = P(0)
sage: x.xgcd(zero)
(x, 1, 0)
sage: zero.xgcd(x)
(x, 0, 1)
sage: F = (x-3)^3; G = (x-15)^2
sage: g, u, v = F.xgcd(G)
sage: g, u, v
(2985984, -432*x + 8208, 432*x^2 + 864*x + 14256)
```

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2.1.8 Dense univariate polynomials over Z, implemented using NTL.

AUTHORS:
- David Harvey: split off from polynomial_element_generic.py (2007-09)
- David Harvey: rewrote to talk to NTL directly, instead of via ntl.pyx (2007-09); a lot of this was based on Joel Mohler’s recent rewrite of the NTL wrapper

Sage includes two implementations of dense univariate polynomials over Z; this file contains the implementation based on NTL, but there is also an implementation based on FLINT in `sage.rings.polynomial.polynomial_integer_dense_flint`.

The FLINT implementation is preferred (FLINT’s arithmetic operations are generally faster), so it is the default; to use the NTL implementation, you can do:

```python
sage: K.<x> = PolynomialRing(ZZ, implementation='NTL')
sage: K
Univariate Polynomial Ring in x over Integer Ring (using NTL)
```

```python
class sage.rings.polynomial.polynomial_integer_dense_ntl.Polynomial_integer_dense_ntl
    Bases: Polynomial

    A dense polynomial over the integers, implemented via NTL.

    content()
    Return the greatest common divisor of the coefficients of this polynomial. The sign is the sign of the leading coefficient. The content of the zero polynomial is zero.

    EXAMPLES:
    ```
    sage: R.<x> = PolynomialRing(ZZ, implementation='NTL')
    sage: (2*x^2 - 4*x^4 + 14*x^7).content()
    2
    sage: (2*x^2 - 4*x^4 - 14*x^7).content()
    -2
    sage: x.content()
    1
    sage: R(1).content()
    1
    sage: R(0).content()
    0
    ```

    degree(gen=None)
    Return the degree of this polynomial. The zero polynomial has degree -1.

    EXAMPLES:
    ```
    sage: R.<x> = PolynomialRing(ZZ, implementation='NTL')
    sage: x.degree()
    1
    ```
sage: (x^2).degree() 2
sage: R(1).degree() 0
sage: R(0).degree() -1

**discriminant**(proof=True)

Return the discriminant of self, which is by definition

\[ (-1)^{m(m-1)/2} \frac{\text{resultant}(a, a')}{l\text{c}(a)}, \]

where \( m = \text{deg}(a) \), and \( l\text{c}(a) \) is the leading coefficient of \( a \). If \( \text{proof} \) is False (the default is True), then this function may use a randomized strategy that errors with probability no more than \( 2^{-80} \).

**EXAMPLES:**

```
sage: f = ntl.ZZX([1,2,0,3])
sage: f.discriminant() -339
sage: f.discriminant(proof=False) -339
```

**factor()**

This function overrides the generic polynomial factorization to make a somewhat intelligent decision to use Pari or NTL based on some benchmarking.

Note: This function factors the content of the polynomial, which can take very long if it’s a really big integer. If you do not need the content factored, divide it out of your polynomial before calling this function.

**EXAMPLES:**

```
sage: R.<x>=ZZ[]
sage: f=x^4-1
sage: f.factor() (x - 1) * (x + 1) * (x^2 + 1)
sage: f=1-x
sage: f.factor() (-1) * (x - 1)
sage: f.factor().unit() -1
sage: f = -30*x; f.factor() (-1) * 2 * 3 * 5 * x
```

**factor_mod**(p)

Return the factorization of self modulo the prime \( p \).

**INPUT:**

- \( p \) – prime

**OUTPUT:** factorization of self reduced modulo \( p \).

**EXAMPLES:**
sage: R.<x> = PolynomialRing(ZZ, 'x', implementation='NTL')
sage: f = -3*x*(x-2)*(x-9) + x
sage: f.factor_mod(3)
x
sage: f = -3*x*(x-2)*(x-9)
sage: f.factor_mod(3)
Traceback (most recent call last):
...
ArithmeticError: factorization of 0 is not defined

sage: f = 2*x*(x-2)*(x-9)
sage: f.factor_mod(7)
(2) * x * (x + 5)^2

factor_padic(p, prec=10)
Return $p$-adic factorization of self to given precision.

INPUT:

- $p$ – prime
- prec – integer; the precision

OUTPUT:

- factorization of self over the completion at $p$.

EXAMPLES:

sage: R.<x> = PolynomialRing(ZZ, implementation='NTL')
sage: f = x^2 + 1
sage: f.factor_padic(5, 4)
((1 + O(5^4))*x + 2 + 5 + 2*5^2 + 5^3 + O(5^4)) * ((1 + O(5^4))*x + 3 + 3*5 + ...
-2*5^2 + 3*5^3 + O(5^4))

A more difficult example:

sage: f = 100 * (5*x + 1)^2 * (x + 5)^2
sage: f.factor_padic(5, 10)
(4 + O(5^10)) * (5 + O(5^11))^2 * ((1 + O(5^10))^x + 5 + 0(5^10))^2 * ((5 + O(5^10)...
-10))^x + 1 + O(5^10))^2

gcd(right)
Return the GCD of self and right. The leading coefficient need not be 1.

EXAMPLES:

sage: R.<x> = PolynomialRing(ZZ, implementation='NTL')
sage: f = (6*x + 47)*(7*x^2 - 2*x + 38)
sage: g = (6*x + 47)*(3*x^3 + 2*x + 1)
sage: f.gcd(g)
6*x + 47

lcm(right)
Return the LCM of self and right.

EXAMPLES:
sage: R.<x> = PolynomialRing(ZZ, implementation='NTL')
sage: f = (6*x + 47)*(7*x^2 - 2*x + 38)
sage: g = (6*x + 47)*(3*x^3 + 2*x + 1)
sage: h = f.lcm(g); h
126*x^6 + 951*x^5 + 486*x^4 + 6034*x^3 + 585*x^2 + 3706*x + 1786
sage: h == (6*x + 47)*(7*x^2 - 2*x + 38)*(3*x^3 + 2*x + 1)
True

list(copy=True)

Return a new copy of the list of the underlying elements of self.

EXAMPLES:

sage: x = PolynomialRing(ZZ,'x',implementation='NTL').0
sage: f = x^3 + 3*x - 17
sage: f.list()
[-17, 3, 0, 1]
sage: f = PolynomialRing(ZZ,'x',implementation='NTL')(0)
sage: f.list()
[]

quo_rem(right)

Attempts to divide self by right, and return a quotient and remainder.

If right is monic, then it returns (q, r) where self = q * right + r and deg(r) < deg(right).

If right is not monic, then it returns (q, 0) where q = self/right if right exactly divides self, otherwise it raises an exception.

EXAMPLES:

sage: R.<x> = PolynomialRing(ZZ, implementation='NTL')
sage: f = R(range(10)); g = R([-1, 0, 1])
sage: q, r = f.quo_rem(g)
sage: q, r
(9*x^7 + 8*x^6 + 16*x^5 + 14*x^4 + 21*x^3 + 18*x^2 + 24*x + 20, 25*x + 20)
sage: q*g + r == f
True
sage: 0//(2*x)
0
sage: f = x^2
sage: f.quo_rem(0)
Traceback (most recent call last):
  ... ArithmeticError: division by zero polynomial
sage: f = (x^2 + 3) * (2*x - 1)
sage: f.quo_rem(2*x - 1)
(x^2 + 3, 0)
sage: f = x^2
sage: f.quo_rem(2*x - 1)
Traceback (most recent call last):
real_root_intervals()

Returns isolating intervals for the real roots of this polynomial.

EXAMPLES: We compute the roots of the characteristic polynomial of some Salem numbers:

```python
sage: R.<x> = PolynomialRing(ZZ, implementation='NTL')
sage: f = 1 - x^2 - x^3 - x^4 + x^6
sage: f.real_root_intervals()
[((1/2, 3/4), 1), ((1, 3/2), 1)]
```

resultant(other, proof=True)

Returns the resultant of self and other, which must lie in the same polynomial ring.

If proof = False (the default is proof=True), then this function may use a randomized strategy that errors with probability no more than $2^{-80}$.

INPUT:

• other – a polynomial

OUTPUT:

an element of the base ring of the polynomial ring

EXAMPLES:

```python
sage: x = PolynomialRing(ZZ, 'x', implementation='NTL').0
sage: f = x^3 + x + 1; g = x^3 - x - 1
sage: r = f.resultant(g); r
-8
sage: r.parent() is ZZ
True
```

squarefree_decomposition()

Return the square-free decomposition of self. This is a partial factorization of self into square-free, relatively prime polynomials.

This is a wrapper for the NTL function SquareFreeDecomp.

EXAMPLES:

```python
sage: R.<x> = PolynomialRing(ZZ, implementation='NTL')
sage: p = 37 * (x-1)^2 * (x-2)^2 * (x-3)^3 * (x-4)
sage: p.squarefree_decomposition()
(37) * (x - 4) * (x^2 - 3*x + 2)^2 * (x - 3)^3
```

xgcd(right)

This function can’t in general return $(g, s, t)$ as above, since they need not exist. Instead, over the integers, we first multiply $g$ by a divisor of the resultant of $a/g$ and $b/g$, up to sign, and return $g, u, v$ such that $g = s*\text{self} + s*\text{right}$. But note that this $g$ may be a multiple of the gcd.

If self and right are coprime as polynomials over the rationals, then $g$ is guaranteed to be the resultant of self and right, as a constant polynomial.

EXAMPLES:
sage: P.<x> = PolynomialRing(ZZ, implementation='NTL')
sage: F = (x^2 + 2)*x^3; G = (x^2+2)*(x-3)
sage: g, u, v = F.xgcd(G)
sage: g, u, v
(27*x^2 + 54, 1, -x^2 - 3*x - 9)
sage: u*F + v*G
27*x^2 + 54
sage: x.xgcd(P(0))
(x, 1, 0)
sage: f = P(0)
sage: f.xgcd(x)
(x, 0, 1)
sage: F = (x-3)^3; G = (x-15)^2
sage: g, u, v = F.xgcd(G)
sage: g, u, v
(2985984, -432*x + 8208, 432*x^2 + 864*x + 14256)
sage: u*F + v*G
2985984

2.1.9 Univariate polynomials over $\mathbb{Q}$ implemented via FLINT

AUTHOR:

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class sage.rings.polynomial.polynomial_rational_flint.Polynomial_rational_flint

Bases: Polynomial

Univariate polynomials over the rationals, implemented via FLINT.
Internally, we represent rational polynomial as the quotient of an integer polynomial and a positive denominator which is coprime to the content of the numerator.

_add_(right)

Return the sum of two rational polynomials.

EXAMPLES:

sage: R.<t> = QQ[]
sage: f = 2/3 + t + 2*t^3
sage: g = -1 + t/3 - 10/11*t^4
sage: f + g
-10/11*t^4 + 2*t^3 + 4/3*t - 1/3

_sub_(right)

Return the difference of two rational polynomials.

EXAMPLES:

sage: R.<t> = QQ[]
sage: f = -10/11*t^4 + 2*t^3 + 4/3*t - 1/3
sage: g = 2*t^3
sage: f - g
# indirect doctest
-10/11*t^4 + 4/3*t - 1/3
_lmul_(right)
  Return self * right, where right is a rational number.

EXAMPLES:

```
sage: R.<t> = QQ[]
sage: f = 3/2*t^3 - t + 1/3
sage: f * 6  # indirect doctest
9*t^3 - 6*t + 2
```

_rmul_(left)
  Return left * self, where left is a rational number.

EXAMPLES:

```
sage: R.<t> = QQ[]
sage: f = 3/2*t^3 - t + 1/3
sage: 6 * f  # indirect doctest
9*t^3 - 6*t + 2
```

_mul_(right)
  Return the product of self and right.

EXAMPLES:

```
sage: R.<t> = QQ[]
sage: f = -1 + 3*t/2 - t^3
sage: g = 2/3 + 7/3*t + 3*t^2
sage: f * g  # indirect doctest
-3*t^5 - 7/3*t^4 + 23/6*t^3 + 1/2*t^2 - 4/3*t - 2/3
```

_mul_trunc_(right, n)
  Truncated multiplication.

EXAMPLES:

```
sage: x = polygen(QQ)
sage: p1 = 1/2 - 3*x + 2/7*x**3
sage: p2 = x + 2/5*x**5 + x**7
sage: p1._mul_trunc_(p2, 5)
2/7*x^4 - 3*x^2 + 1/2*x
sage: (p1*p2).truncate(5)
2/7*x^4 - 3*x^2 + 1/2*x
sage: p1._mul_trunc_(p2, 1)
0
sage: p1._mul_trunc_(p2, 0)
Traceback (most recent call last):
  ...
ValueError: n must be > 0
```

ALGORITHM:
  Call the FLINT method fmpq_poly_mullow.
**degree()**

Return the degree of self.

By convention, the degree of the zero polynomial is -1.

**EXAMPLES:**
```
sage: R.<t> = QQ[]
sage: f = 1 + t + t^2/2 + t^3/3 + t^4/4
sage: f.degree()
4
sage: g = R(0)
sage: g.degree()
-1
```

**denominator()**

Return the denominator of self.

**EXAMPLES:**
```
sage: R.<t> = QQ[]
sage: f = (3 * t^3 + 1) / -3
sage: f.denominator()
3
```

**disc()**

Return the discriminant of this polynomial.

The discriminant $R_n$ is defined as

$$R_n = a_n^{2n-2} \prod_{1 \leq i < j \leq n} (r_i - r_j)^2,$$

where $n$ is the degree of this polynomial, $a_n$ is the leading coefficient and the roots over $\mathbb{Q}$ are $r_1, \ldots, r_n$.

The discriminant of constant polynomials is defined to be 0.

**OUTPUT:**

- Discriminant, an element of the base ring of the polynomial ring

**Note:** Note the identity $R_n(f) := (-1)^{(n(n-1)/2)} R(f, f') a_n^{n-k-2}$, where $n$ is the degree of this polynomial, $a_n$ is the leading coefficient, $f'$ is the derivative of $f$, and $k$ is the degree of $f'$. Calls **resultant()**.

**ALGORITHM:**

Use PARI.

**EXAMPLES:**

In the case of elliptic curves in special form, the discriminant is easy to calculate:
```
sage: R.<t> = QQ[]
sage: f = t^3 + t + 1
sage: d = f.discriminant(); d
-31
```
(continues on next page)
\begin{verbatim}
sage: d.parent() is QQ True
sage: EllipticCurve([1, 1]).discriminant() / 16
-31

sage: R.<t> = QQ[]
sage: f = 2*t^3 + t + 1
sage: d = f.discriminant(); d
-116

sage: R.<t> = QQ[]
sage: f = t^3 + 3*t - 17
sage: f.discriminant()
-7911
\end{verbatim}

\textbf{discriminant}()

Return the discriminant of this polynomial.

The discriminant $R_n$ is defined as

$$R_n = a_n^{2n-2} \prod_{1 \leq i < j \leq n} (r_i - r_j)^2,$$

where $n$ is the degree of this polynomial, $a_n$ is the leading coefficient and the roots over $\mathbb{Q}$ are $r_1, \ldots, r_n$.

The discriminant of constant polynomials is defined to be 0.

\textbf{OUTPUT:}

- Discriminant, an element of the base ring of the polynomial ring

\textbf{Note:} Note the identity $R_n(f) := (-1)^{n(n-1)/2} R(f, f') a_n^k n - k - 2$), where $n$ is the degree of this polynomial, $a_n$ is the leading coefficient, $f'$ is the derivative of $f$, and $k$ is the degree of $f'$. Calls \texttt{resultant}().

\textbf{ALGORITHM:}

Use PARI.

\textbf{EXAMPLES:}

In the case of elliptic curves in special form, the discriminant is easy to calculate:

\begin{verbatim}
sage: R.<t> = QQ[]
sage: f = t^3 + t + 1
sage: d = f.discriminant(); d
-31
sage: d.parent() is QQ True
sage: EllipticCurve([1, 1]).discriminant() / 16
-31
\end{verbatim}
Polynomials, Release 10.0

sage: d = f.discriminant(); d
-116

sage: R.<t> = QQ[]
sage: f = t^3 + 3*t - 17
sage: f.discriminant()
-7911

**factor_mod(p)**

Return the factorization of self modulo the prime \( p \).

Assumes that the degree of this polynomial is at least one, and raises a \texttt{ValueError} otherwise.

**INPUT:**

\* \( p \) - Prime number

**OUTPUT:**

\* Factorization of this polynomial modulo \( p \)

**EXAMPLES:**

sage: R.<x> = QQ[]
sage: (x^5 + 17*x^3 + x + 3).factor_mod(3)
\( x \* (x^2 + 1)^2 \)
sage: (x^5 + 2).factor_mod(5)
\( (x + 2)^5 \)

Variable names that are reserved in PARI, such as \texttt{zeta}, are supported (see \texttt{github} issue \#20631):

sage: R.<zeta> = QQ[]
sage: (zeta^2 + zeta + 1).factor_mod(7)
\( (zeta + 3) \* (zeta + 5) \)

**factor_padic(p, prec=10)**

Return the \( p \)-adic factorization of this polynomial to the given precision.

**INPUT:**

\* \( p \) - Prime number

\* prec - Integer; the precision

**OUTPUT:**

\* factorization of \self\ viewed as a \( p \)-adic polynomial

**EXAMPLES:**

sage: R.<x> = QQ[]
sage: f = x^3 - 2
sage: f.factor_padic(2)
\( (1 + O(2^{10}))*x^3 + O(2^{10})*x^2 + O(2^{10})*x + 2 + 2^2 + 2^3 + 2^4 + 2^5 + 2^6 + \ldots \rightarrow 2^7 + 2^8 + 2^9 + O(2^{10}) \)
sage: f.factor_padic(3)
\( (1 + O(3^{10}))*x^3 + O(3^{10})*x^2 + O(3^{10})*x + 1 + 2^3 + 2^3*2 + 2^3*3 + 2^3*4 + \ldots \rightarrow 2^3*5 + 2^3*6 + 2^3*7 + 2^3*8 + 2^3*9 + O(3^{10}) \)

(continues on next page)
The input polynomial is considered to have “infinite” precision, therefore the $p$-adic factorization of the polynomial is not the same as first coercing to $\mathbb{Q}_p$ and then factoring (see also github issue #15422):

A more difficult example:

```
sage: f = 100 * (5*x + 1)^2 * (x + 5)^2
sage: f.factor_padic(5, 10)
(4*5^4 + O(5^14)) * ((1 + O(5^9))*x + 5^-1 + O(5^9))^2 * ((1 + O(5^10))*x + 5 + O(5^10))^2
```

Try some bogus inputs:

```
sage: f.factor_padic(3,-1)
Traceback (most recent call last):
  ... ValueError: prec_cap must be non-negative
sage: f.factor_padic(6,10)
Traceback (most recent call last):
  ... ValueError: p must be prime
sage: f.factor_padic('hello', 'world')
Traceback (most recent call last):
  ... TypeError: unable to convert 'hello' to an integer
```

```
galois_group(par=group=False, algorithm='pari')
```

Return the Galois group of this polynomial as a permutation group.

INPUT:

- self - Irreducible polynomial
- pari_group - bool (default: False); if True instead return the Galois group as a PARI group. This has a useful label in it, and may be slightly faster since it doesn't require looking up a group in Gap. To get a permutation group from a PARI group $P$, type $\text{PermutationGroup}(P)$.
- algorithm - 'pari', 'gap', 'kash', 'magma' (default: 'pari', for degrees is at most 11; 'gap', for degrees from 12 to 15; 'kash', for degrees from 16 or more).

OUTPUT:
• Galois group

ALGORITHM:
The Galois group is computed using PARI in C library mode, or possibly GAP, KASH, or MAGMA.

Note: The PARI documentation contains the following warning: The method used is that of resolvent polynomials and is sensitive to the current precision. The precision is updated internally but, in very rare cases, a wrong result may be returned if the initial precision was not sufficient.

GAP uses the “Transitive Groups Libraries” from the “TransGrp” GAP package which comes installed with the “gap” Sage package.

MAGMA does not return a provably correct result. Please see the MAGMA documentation for how to obtain a provably correct result.

EXAMPLES:

```python
sage: R.<x> = QQ[]
sage: f = x^4 - 17*x^3 - 2*x + 1
sage: G = f.galois_group(); G
Transitive group number 5 of degree 4
sage: G.gens()
((1,2), (1,2,3,4))
sage: G.order()
24
```

It is potentially useful to instead obtain the corresponding PARI group, which is little more than a 4-tuple. See the PARI manual for the exact details. (Note that the third entry in the tuple is in the new standard ordering.)

```python
sage: f = x^4 - 17*x^3 - 2*x + 1
sage: G = f.galois_group(pari_group=True); G
PARI group [24, -1, 5, "S4"] of degree 4
sage: PermutationGroup(G)
Transitive group number 5 of degree 4
```

You can use KASH or GAP to compute Galois groups as well. The advantage is that KASH (resp. GAP) can compute Galois groups of fields up to degree 23 (resp. 15), whereas PARI only goes to degree 11. (In my not-so-thorough experiments PARI is faster than KASH.)

```python
sage: f = x^4 - 17*x^3 - 2*x + 1
sage: f.galois_group(algorithm='kash')  # optional - kash
Transitive group number 5 of degree 4
sage: f = x^4 - 17*x^3 - 2*x + 1
sage: f.galois_group(algorithm='gap')
Transitive group number 5 of degree 4
sage: f = x^13 - 17*x^3 - 2*x + 1
sage: f.galois_group(algorithm='gap')
Transitive group number 9 of degree 13
sage: f = x^12 - 2*x^8 - x^7 + 2*x^6 + 4*x^4 - 2*x^3 - x^2 - x + 1
sage: f.galois_group(algorithm='gap')
Transitive group number 183 of degree 12
```
(continues on next page)
**sage**: f.galois_group(algorithm='magma')  # optional - magma

Transitive group number 5 of degree 4

---

**galois_group_davenport_smith_test**

Use the Davenport-Smith test to attempt to certify that \( f \) has Galois group \( A_n \) or \( S_n \).

Return 1 if the Galois group is certified as \( S_n \), 2 if \( A_n \), or 0 if no conclusion is reached.

By default, we first check that \( f \) is irreducible. For extra efficiency, one can override this by specifying `assume_irreducible = True`; this yields undefined results if \( f \) is not irreducible.

A corresponding function in Magma is `IsEasySnAn`.

**EXAMPLES:**

```
sage: P.<x> = QQ[]
sage: u = x^7 + x + 1
sage: u.galois_group_davenport_smith_test()
1
sage: u = x^7 - x^4 - x^3 + 3*x^2 - 1
sage: u.galois_group_davenport_smith_test()
2
sage: u = x^7 - 2
sage: u.galois_group_davenport_smith_test()
0
```

---

**gcd**

Return the (monic) greatest common divisor of self and right.

Corner cases: if self and right are both zero, returns zero. If only one of them is zero, returns the other polynomial, up to normalisation.

**EXAMPLES:**

```
sage: R.<t> = QQ[]
sage: f = -2 + 3*t/2 + 4*t^2/7 - t^3
sage: g = 1/2 + 4*t + 2*t^4/3
sage: f.gcd(g)
1
sage: f = (-3*t + 1/2) * f
sage: g = (-3*t + 1/2) * (4*t^2/3 - 1) * g
sage: f.gcd(g)
t - 1/6
```

---

**hensel_lift**

Assuming that this polynomial factors modulo \( p \) into distinct monic factors, computes the Hensel lifts of these factors modulo \( p^e \). We assume that self has integer coefficients.

Return an empty list if this polynomial has degree less than one.

**INPUT:**

- \( p \) - Prime number; coerceable to Integer
- \( e \) - Exponent; coerceable to Integer

**OUTPUT:**
• Hensel lifts; list of polynomials over $\mathbb{Z}/p^e \mathbb{Z}$

EXAMPLES:

```python
sage: R.<x> = QQ[]
sage: R((x-1)*(x+1)).hensel_lift(7, 2)
[x + 1, x + 48]
```

If the input polynomial $f$ is not monic, we get a factorization of $f/lc(f)$:

```python
sage: R(2*x^2 - 2).hensel_lift(7, 2)
[x + 1, x + 48]
```

**inverse_series_trunc**(prec)

Return a polynomial approximation of precision prec of the inverse series of this polynomial.

EXAMPLES:

```python
sage: x = polygen(QQ)
sage: p = 2 + x - 3/5*x^2
sage: q5 = p.inverse_series_trunc(5)
sage: q5
151/800*x^4 - 17/80*x^3 + 11/40*x^2 - 1/4*x + 1/2
sage: q5 * p
-453/4000*x^6 + 253/800*x^5 + 1
sage: q100 = p.inverse_series_trunc(100)
sage: (q100 * p).truncate(100)
1
```

**is_irreducible()**

Return whether this polynomial is irreducible.

This method computes the primitive part as an element of $\mathbb{Z}[t]$ and calls the method **is_irreducible** for elements of that polynomial ring.

By definition, over any integral domain, an element $r$ is irreducible if and only if it is non-zero, not a unit and whenever $r = ab$ then $a$ or $b$ is a unit.

EXAMPLES:

```python
sage: R.<t> = QQ[]
sage: (t^2 + 2).is_irreducible()
True
sage: (t^2 - 1).is_irreducible()
False
```

**is_one()**

Return whether or not this polynomial is one.

EXAMPLES:

```python
sage: R.<x> = QQ[]
sage: R([0,1]).is_one()
False
sage: R([1]).is_one()
```

(continues on next page)
True
sage: R([0]).is_one()
False
sage: R([-1]).is_one()
False
sage: R([1,1]).is_one()
False

is_zero()
Return whether or not self is the zero polynomial.

EXAMPLES:

sage: R.<t> = QQ[]
sage: f = 1 - t + 1/2*t^2 - 1/3*t^3
sage: f.is_zero()
False
sage: R(0).is_zero()
True

lcm(right)
Return the monic (or zero) least common multiple of self and right.

Corner cases: if either of self and right are zero, returns zero. This behaviour is ensures that the relation \( \text{lcm}(a,b) \text{gcd}(a,b) = a b \) holds up to multiplication by rationals.

EXAMPLES:

sage: R.<t> = QQ[]
sage: f = -2 + 3*t/2 + 4*t^2/7 - t^3
sage: g = 1/2 + 4*t + 2*t^4/3
sage: f.lcm(g)
t^7 - 4/7*t^6 - 3/2*t^5 + 8*t^4 - 75/28*t^3 - 66/7*t^2 + 87/8*t + 3/2
sage: f.lcm(g) * f.gcd(g) // (f * g)
-3/2

list(copy=True)
Return a list with the coefficients of self.

EXAMPLES:

sage: R.<t> = QQ[]
sage: f = 1 + t + t^2/2 + t^3/3 + t^4/4
sage: f.list()
[1, 1, 1/2, 1/3, 1/4]
sage: g = R(0)
sage: g.list()
[]

numerator()
Return the numerator of self.

Representing self as the quotient of an integer polynomial and a positive integer denominator (coprime to the content of the polynomial), returns the integer polynomial.

EXAMPLES:
sage: R.<t> = QQ[]
sage: f = (3 * t^3 + 1) / -3
sage: f.numerator()
-3*t^3 - 1

\textbf{quo\_rem}(right)

Return the quotient and remainder of the Euclidean division of self and right.

Raises a \texttt{ZeroDivisionError} if right is zero.

\textbf{EXAMPLES:}

sage: R.<t> = QQ[]
\texttt{sage: f = R.random\_element(2000)}
\texttt{sage: g = R.random\_element(1000)}
\texttt{sage: q, r = f.quo\_rem(g)}
\texttt{sage: f == q*g + r}
True

\textbf{real\_root\_intervals}()

Return isolating intervals for the real roots of self.

\textbf{EXAMPLES:}

We compute the roots of the characteristic polynomial of some Salem numbers:

sage: R.<t> = QQ[]
\texttt{sage: f = 1 - t^2 - t^3 - t^4 + t^6}
\texttt{sage: f.real\_root\_intervals()}
\begin{verbatim}
[((1/2, 3/4), 1), ((1, 3/2), 1)]
\end{verbatim}

\textbf{resultant}(right)

Return the resultant of self and right.

Enumerating the roots over \emph{Q} as \(r_1, \ldots, r_m\) and \(s_1, \ldots, s_n\) and letting \(x\) and \(y\) denote the leading coefficients of \(f\) and \(g\), the resultant of the two polynomials is defined by

\[
x^{\deg g} y^{\deg f} \prod_{i,j} (r_i - s_j).
\]

Corner cases: if one of the polynomials is zero, the resultant is zero. Note that otherwise if one of the polynomials is constant, the last term in the above is the empty product.

\textbf{EXAMPLES:}

sage: R.<t> = QQ[]
\texttt{sage: f = (t - 2/3) * (t + 4/5) * (t - 1)}
\texttt{sage: g = (t - 1/3) * (t + 1/2) * (t + 1)}
\texttt{sage: f.resultant(g)}
119/1350
\texttt{sage: h = (t - 1/3) * (t + 1/2) * (t - 1)}
\texttt{sage: f.resultant(h)}
\emptyset

\textbf{reverse}(degree=\texttt{None})

Reverse the coefficients of this polynomial (thought of as a polynomial of degree degree).

\textbf{INPUT:}
• degree (None or integral value that fits in an unsigned long, default: degree of self) - if specified, truncate or zero pad the list of coefficients to this degree before reversing it.

EXAMPLES:
We first consider the simplest case, where we reverse all coefficients of a polynomial and obtain a polynomial of the same degree:

\begin{verbatim}
sage: R.<t> = QQ[]
sage: f = 1 + t + t^2 / 2 + t^3 / 3 + t^4 / 4
sage: f.reverse()
t^4 + t^3 + 1/2*t^2 + 1/3*t + 1/4
\end{verbatim}

Next, an example we the returned polynomial has lower degree because the original polynomial has low coefficients equal to zero:

\begin{verbatim}
sage: R.<t> = QQ[]
sage: f = 3/4*t^2 + 6*t^7
sage: f.reverse()
3/4*t^5 + 6
\end{verbatim}

The next example illustrates the passing of a value for degree less than the length of self, notationally resulting in truncation prior to reversing:

\begin{verbatim}
sage: R.<t> = QQ[]
sage: f = 1 + t + t^2 / 2 + t^3 / 3 + t^4 / 4
sage: f.reverse(2)
t^2 + t + 1/2
\end{verbatim}

Now we illustrate the passing of a value for degree greater than the length of self, notationally resulting in zero padding at the top end prior to reversing:

\begin{verbatim}
sage: R.<t> = QQ[]
sage: f = 1 + t + t^2 / 2 + t^3 / 3
sage: f.reverse(4)
t^4 + t^3 + 1/2*t^2 + 1/3*t
\end{verbatim}

\texttt{revert\_series}(n)
Return a polynomial \( f \) such that \( f(self(x)) = self(f(x)) = x \mod x^n \).

EXAMPLES:

\begin{verbatim}
sage: R.<t> = QQ[]
sage: f = t - t^3/6 + t^5/120
sage: f.revert_series(6)
3/40*t^5 + 1/6*t^3 + t
\end{verbatim}

\begin{verbatim}
sage: f.revert_series(-1)
Traceback (most recent call last):
  ... ValueError: argument n must be a non-negative integer, got -1
\end{verbatim}

\begin{verbatim}
sage: g = - t^3/3 + t^5/5
sage: g.revert_series(6)
Traceback (most recent call last):
  ... ValueError: self must have constant coefficient 0 and a unit for coefficient t^1
\end{verbatim}
The `truncate(n)` function

- **Return self truncated modulo \( t^n \).**

**INPUT:**

- \( n \) - The power of \( t \) modulo which self is truncated

**EXAMPLES:**

```sage
sage: R.<t> = QQ[]
sage: f = 1 - t + 1/2*t^2 - 1/3*t^3
sage: f.truncate(0)
0
sage: f.truncate(2)
-t + 1
```

The `xgcd(right)` function

- **Return polynomials \( d, s, \) and \( t \) such that \( d = s \times \text{self} + t \times \text{right} \), where \( d \) is the (monic) greatest common divisor of \( \text{self} \) and \( \text{right} \). The choice of \( s \) and \( t \) is not specified any further.**

**Corner cases:** if \( \text{self} \) and \( \text{right} \) are zero, returns zero polynomials. Otherwise, if only \( \text{self} \) is zero, returns \( (d, s, t) = (\text{right}, 0, 1) \) up to normalisation, and similarly if only \( \text{right} \) is zero.

**EXAMPLES:**

```sage
sage: R.<t> = QQ[]
sage: f = 2/3 + 3/4 * t - t^2
sage: g = -3 + 1/7 * t
sage: f.xgcd(g)
(1, -12/5095, -84/5095*t - 1701/5095)
```

### 2.1.10 Dense univariate polynomials over \( \mathbb{Z}/n\mathbb{Z} \), implemented using FLINT

This module gives a fast implementation of \((\mathbb{Z}/n\mathbb{Z})[x] \) whenever \( n \) is at most `sys.maxsize`. We use it by default in preference to NTL when the modulus is small, falling back to NTL if the modulus is too large, as in the example below.

**EXAMPLES:**

```sage
sage: R.<a> = PolynomialRing(Integers(100))
sage: type(a)
<class 'sage.rings.polynomial.polynomial_zmod_flint.Polynomial_zmod_flint'>
sage: R.<a> = PolynomialRing(Integers(5*2^64))
sage: type(a)
<class 'sage.rings.polynomial.polynomial_modn_dense_ntl.Polynomial_dense_modn_ZZ'>
sage: R.<a> = PolynomialRing(Integers(5*2^64), implementation="FLINT")
Traceback (most recent call last):
  ... ValueError: FLINT does not support modulus 92233720368547758080
```

**AUTHORS:**

- Burcin Erocal (2008-11) initial implementation
- Martin Albrecht (2009-01) another initial implementation
class sage.rings.polynomial.polynomial_zmod_flint.Polynomial_template

Bases: Polynomial

Template for interfacing to external C / C++ libraries for implementations of polynomials.

AUTHORS:

• Robert Bradshaw (2008-10): original idea for templating
• Martin Albrecht (2008-10): initial implementation

This file implements a simple templating engine for linking univariate polynomials to their C/C++ library implementations. It requires a 'linkage' file which implements the \texttt{celement_} functions (see \texttt{sage.libs.ntlntl_GF2X_linkage} for an example). Both parts are then plugged together by inclusion of the linkage file when inheriting from this class. See \texttt{sage.rings.polynomial.polynomial_gf2x} for an example.

We illustrate the generic glueing using univariate polynomials over GF(2).

\textbf{Note:} Implementations using this template MUST implement coercion from base ring elements and \texttt{get_unsafe().} See \texttt{Polynomial_GF2X} for an example.

\begin{Verbatim}
\textbf{degree()}
\end{Verbatim}

EXAMPLES:

\begin{verbatim}
sage: P.<x> = GF(2)[]
sage: x.degree()
1
sage: P(1).degree()
0
sage: P(0).degree()
-1
\end{verbatim}

\begin{Verbatim}
\textbf{gcd(other)}
\end{Verbatim}

Return the greatest common divisor of self and other.

EXAMPLES:

\begin{verbatim}
sage: P.<x> = GF(2)[]
sage: f = x*(x+1)
sage: f.gcd(x+1)
x + 1
sage: f.gcd(x^2)
x
\end{verbatim}

\begin{Verbatim}
\textbf{get_cparent()}
\end{Verbatim}

\begin{Verbatim}
\textbf{is_gen()}
\end{Verbatim}

EXAMPLES:

\begin{verbatim}
sage: P.<x> = GF(2)[]
sage: x.is_gen()
True
sage: (x+1).is_gen()
False
\end{verbatim}
is_one()

EXAMPLES:

```
sage: P.<x> = GF(2)[]
sage: P(1).is_one()
True
```

is_zero()

EXAMPLES:

```
sage: P.<x> = GF(2)[]
sage: x.is_zero()
False
```

list(copy=True)

EXAMPLES:

```
sage: P.<x> = GF(2)[]
sage: x.list()
[0, 1]
sage: list(x)
[0, 1]
```

quo_rem(right)

EXAMPLES:

```
sage: P.<x> = GF(2)[]
sage: f = x^2 + x + 1
sage: f.quo_rem(x + 1)
(x, 1)
```

shift(n)

EXAMPLES:

```
sage: P.<x> = GF(2)[]
sage: f = x^3 + x^2 + 1
sage: f.shift(1)
x^4 + x^3 + x
sage: f.shift(-1)
x^2 + x
```

truncate(n)

Returns this polynomial mod $x^n$.

EXAMPLES:

```
sage: R.<x> =GF(2)[]
sage: f = sum(x^n for n in range(10)); f
x^9 + x^8 + x^7 + x^6 + x^5 + x^4 + x^3 + x^2 + x + 1
sage: f.truncate(6)
x^5 + x^4 + x^3 + x^2 + x + 1
```

If the precision is higher than the degree of the polynomial then the polynomial itself is returned:
sage: f.truncate(10) is f
True

If the precision is negative, the zero polynomial is returned:

sage: f.truncate(-1)
0

\textbf{xgcd}(\textit{other})

Computes extended gcd of self and other.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: P.<x> = GF(7)[]
sage: f = x*(x+1)
sage: f.xgcd(x+1)
(x + 1, 0, 1)
sage: f.xgcd(x^2)
(x, 1, 6)
\end{verbatim}

\textbf{class} \texttt{sage.rings.polynomial.polynomial_zmod_flint.Polynomial_zmod_flint}

\textbf{Bases:} \texttt{Polynomial_template}

Polynomial on \(\mathbb{Z}/n\mathbb{Z}\) implemented via FLINT.

\textbf{\_add\_}(\textit{right})

\textbf{EXAMPLES:}

\begin{verbatim}
sage: P.<x> = GF(2)[]
sage: x + 1
x + 1
\end{verbatim}

\textbf{\_sub\_}(\textit{right})

\textbf{EXAMPLES:}

\begin{verbatim}
sage: P.<x> = GF(2)[]
sage: x - 1
x + 1
\end{verbatim}

\textbf{\_lmul\_}(\textit{left})

\textbf{EXAMPLES:}

\begin{verbatim}
sage: P.<x> = GF(2)[]
sage: t = x^2 + x + 1
sage: 0*t
0
sage: 1*t
x^2 + x + 1
sage: R.<y> = GF(5)[]
sage: u = y^2 + y + 1
sage: 3*u
3*y^2 + 3*y + 3
sage: 5*u
0
\end{verbatim}

(continues on next page)
sage: \((2^81)*u\)
\(2^8y^2 + 2^8y + 2\)
sage: \((-2^81)*u\)
\(3^8y^2 + 3^8y + 3\)

sage: \(P.<x> = \text{GF}(2)[\]
\(t = x^2 + x + 1\)
sage: \(t*0\)
\(0\)
sage: \(t*1\)
\(x^2 + x + 1\)

sage: \(R.<y> = \text{GF}(5)[\]
\(u = y^2 + y + 1\)
sage: \(u*3\)
\(3^3y^2 + 3^3y + 3\)
sage: \(u*5\)
\(0\)

\_rmul\_ (right)
Multiply self on the right by a scalar.

EXAMPLES:

sage: \(R.<x> = \text{ZZ}[\]
\(f = (x^3 + x + 5)\)
sage: \(f._\text{rmul}\_ (7)\)
\(7^3x^3 + 7^3x + 35\)
sage: \(f*7\)
\(7^3x^3 + 7^3x + 35\)

\_mul\_ (right)

EXAMPLES:

sage: \(P.<x> = \text{GF}(2)[\]
\(x*(x+1)\)
\(x^2 + x\)

\_mul\_ trunc\_ (right, n)
Return the product of this polynomial and other truncated to the given length \(n\).

This function is usually more efficient than simply doing the multiplication and then truncating. The function is tuned for length \(n\) about half the length of a full product.

EXAMPLES:

sage: \(P.<a> = \text{GF}(7)[\]
\(a = \text{P}(\text{range}(10)); b = \text{P}(\text{range}(5, 15))\)
sage: \(a._\text{mul\_trunc}\_ (b, 5)\)
\(4^a^4 + 6^a^3 + 2^a^2 + 5^a\)

\factor\()
Returns the factorization of the polynomial.
EXAMPLES:

```python
sage: R.<x> = GF(5)[]
sage: (x^2 + 1).factor()
(x + 2) * (x + 3)
```

It also works for prime-power moduli:

```python
sage: R.<x> = Zmod(23^5)[]
sage: (x^3 + 1).factor()
(x + 1) * (x^2 + 6436342*x + 1)
```

`is_irreducible()`

Return whether this polynomial is irreducible.

EXAMPLES:

```python
sage: R.<x> = GF(5)[]
sage: (x^2 + 1).is_irreducible()
False
sage: (x^3 + x + 1).is_irreducible()
True
```

Not implemented when the base ring is not a field:

```python
sage: S.<s> = Zmod(10)[]
sage: (s^2).is_irreducible()
Traceback (most recent call last):
... NotImplementedError: checking irreducibility of polynomials over rings with composite characteristic is not implemented
```

`minpoly_mod(other)`

Thin wrapper for `sage.rings.polynomial.polynomial_modn_dense_ntl.Polynomial_dense_mod_n.minpoly_mod()`.

EXAMPLES:

```python
sage: R.<x> = GF(127)[]
sage: type(x)
<class 'sage.rings.polynomial.polynomial_zmod_flint.Polynomial_zmod_flint'>
sage: (x^5-3).minpoly_mod(x^3+5*x-1)
x^3 + 34*x^2 + 125*x + 95
```

`monic()`

Return this polynomial divided by its leading coefficient.

Raises ValueError if the leading coefficient is not invertible in the base ring.

EXAMPLES:

```python
sage: R.<x> = GF(5)[]
sage: (2*x^2+1).monic()
x^2 + 3
```
rational_reconstruct(*args, **kwds)

Deprecated: Use rational_reconstruction() instead. See github issue #12696 for details.

rational_reconstruction(m, n_deg=0, d_deg=0)

Construct a rational function n/d such that p * d is equivalent to n modulo m where p is this polynomial.

EXAMPLES:

```
sage: P.<x> = GF(5)[]
sage: p = 4*x^5 + 3*x^4 + 2*x^3 + 2*x^2 + 4*x + 2
sage: n, d = p.rational_reconstruction(x^9, 4, 4); n, d
(3*x^4 + 2*x^3 + x^2 + 2*x, x^4 + 3*x^3 + x^2 + x)
sage: (p*d % x^9) == n
True
```

resultant(other)

Returns the resultant of self and other, which must lie in the same polynomial ring.

INPUT:

• other – a polynomial

OUTPUT: an element of the base ring of the polynomial ring

EXAMPLES:

```
sage: R.<x> = GF(19)['
x']
sage: f = x^3 + x + 1; g = x^3 - x - 1
sage: r = f.resultant(g); r
11
sage: r.parent() is GF(19)
True
```

The following example shows that github issue #11782 has been fixed:

```
sage: R.<x> = ZZ.quo(9)['
x']
sage: f = 2*x^3 + x^2 + x; g = 6*x^2 + 2*x + 1
sage: f.resultant(g)
5
```

reverse(degree=None)

Return a polynomial with the coefficients of this polynomial reversed.

If an optional degree argument is given the coefficient list will be truncated or zero padded as necessary before computing the reverse.

EXAMPLES:

```
sage: R.<x> = GF(5)[]
sage: p = R([1,2,3,4]); p
4*x^3 + 3*x^2 + 2*x + 1
sage: p.reverse()
x^3 + 2*x^2 + 3*x + 4
sage: p.reverse(degree=6)
x^6 + 2*x^5 + 3*x^4 + 4*x^3
sage: p.reverse(degree=2)
x^2 + 2*x + 3
```

(continues on next page)
sage: R.<x> = GF(101)[]
sage: f = x^3 - x + 2; f
x^3 + 100*x + 2
sage: f.reverse()
2*x^3 + 100*x^2 + 1
sage: f.reverse() == f(1/x) * x^f.degree()
True

Note that if \( f \) has zero constant coefficient, its reverse will have lower degree.

sage: f = x^3 + 2*x
sage: f.reverse()
2*x^2 + 1

In this case, reverse is not an involution unless we explicitly specify a degree.

sage: f = x^3 + 2*x
sage: f.reverse().reverse()
x^2 + 2
sage: f.reverse(5).reverse(5)
x^3 + 2*x

revert_series(n)
Return a polynomial \( f \) such that \( f(self(x)) = self(f(x)) = x \mod x^n \).

EXAMPLES:

sage: R.<t> = GF(5)[]
sage: f = t + 2*t^2 - t^3 - 3*t^4
sage: f.revert_series(5)
3*t^4 + 4*t^3 + 3*t^2 + t
sage: f.revert_series(-1)
Traceback (most recent call last):
  ... ValueError: argument n must be a non-negative integer, got -1
sage: g = - t^3 + t^5
sage: g.revert_series(6)
Traceback (most recent call last):
  ... ValueError: self must have constant coefficient \( 0 \) and a unit for coefficient \( t^1 \)

2.1. Univariate Polynomials and Polynomial Rings

small_roots(*args, **kwds)
See `sage.rings.polynomial.polynomial_modn_dense_ntl.small_roots()` for the documentation of this function.

**EXAMPLES:**

```python
sage: N = 10001
sage: K = Zmod(10001)
sage: P.<x> = PolynomialRing(K)
sage: f = x^3 + 10*x^2 + 5000*x - 222
sage: f.small_roots()
[4]
```

`sage.rings.polynomial.polynomial_modn_dense_ntl.squarefree_decomposition()`

Returns the squarefree decomposition of this polynomial.

**EXAMPLES:**

```python
sage: R.<x> = GF(5)[]
sage: ((x+1)*(x^2+1)^2*x^3).squarefree_decomposition()
(x + 1) * (x^2 + 1)^2 * x^3
```

`sage.rings.polynomial.polynomial_modn_dense_ntl.make_element(parent, args)`

### 2.1.11 Dense univariate polynomials over \(\mathbb{Z}/n\mathbb{Z}\), implemented using NTL

This implementation is generally slower than the FLINT implementation in `polynomial_zmod_flint`, so we use FLINT by default when the modulus is small enough; but NTL does not require that \(n\) be int-sized, so we use it as default when \(n\) is too large for FLINT.

Note that the classes `Polynomial_dense_modn_ntl ZZ` and `Polynomial_dense_modn_ntl ZZ` are different; the former is limited to moduli less than a certain bound, while the latter supports arbitrarily large moduli.

**AUTHORS:**

- Robert Bradshaw: Split off from polynomial_element_generic.py (2007-09)
- Robert Bradshaw: Major rewrite to use NTL directly (2007-09)

**class** `sage.rings.polynomial.polynomial_modn_dense_ntl.Polynomial_dense_mod_n`

Bases: `Polynomial`

A dense polynomial over the integers modulo \(n\), where \(n\) is composite, with the underlying arithmetic done using NTL.

**EXAMPLES:**

```python
sage: R.<x> = PolynomialRing(Integers(16), implementation='NTL')
sage: f = x^3 - x + 17
sage: f^2
x^6 + 14*x^4 + 2*x^3 + x^2 + 14*x + 1
sage: loads(f.dumps()) == f
True
sage: R.<x> = PolynomialRing(Integers(100), implementation='NTL')
sage: p = 3*x
sage: q = 7*x
```
sage: p+q
10*x
sage: R.<x> = PolynomialRing(Integers(8), implementation='NTL')
sage: parent(p)
Univariate Polynomial Ring in x over Ring of integers modulo 100 (using NTL)
sage: p + q
10*x
sage: R({10:-1})
7*x^10

def(gen=None)

Return the degree of this polynomial.

The zero polynomial has degree -1.

EXAMPLES:

sage: R.<x> = PolynomialRing(Integers(100), implementation='NTL')
sage: (x^3 + 3*x - 17).degree()
3
sage: R.zero().degree()
-1

int_list()

list(copy=True)

Return a new copy of the list of the underlying elements of self.

EXAMPLES:

sage: R.<x> = PolynomialRing(Integers(100), implementation='NTL')
sage: f = x^3 + 3*x - 17
sage: f.list()
[83, 3, 0, 1]

minpoly_mod(other)

Compute the minimal polynomial of this polynomial modulo another polynomial in the same ring.

ALGORITHM:

NTL's MinPolyMod(), which uses Shoup's algorithm [Sho1999].

EXAMPLES:

sage: R.<x> = PolynomialRing(GF(101), implementation='NTL')
sage: f = x^17 + x^2 - 1
sage: (x^2).minpoly_mod(f)
x^17 + 100*x^2 + 2*x + 100

ntl_ZZ_pX()

Return underlying NTL representation of this polynomial. Additional "bonus" functionality is available through this function.

**Warning:** You must call ntl.set_modulus(ntl.ZZ(n)) before doing arithmetic with this object!
**ntl_set_directly(v)**

Set the value of this polynomial directly from a vector or string.

Polynomials over the integers modulo \( n \) are stored internally using NTL's \texttt{ZZ\_pX} class. Use this function to set the value of this polynomial using the NTL constructor, which is potentially very fast. The input \( v \) is either a vector of ints or a string of the form \([ n1 \ n2 \ n3 \ ... \] where the \( n \) are integers and there are no commas between them. The optimal input format is the string format, since that's what NTL uses by default.

**EXAMPLES:**

```python
sage: R.<x> = PolynomialRing(Integers(100), implementation='NTL')
sage: from sage.rings.polynomial.polynomial_modn_dense_ntl import Polynomial_˓→dense_mod_n as poly_modn_dense
sage: poly_modn_dense(R, ([1,-2,3]))
3*x^2 + 98*x + 1
sage: f = poly_modn_dense(R, 0)
sage: f.ntl_set_directly([1,-2,3])
sage: f
3*x^2 + 98*x + 1
sage: f.ntl_set_directly([1 -2 3 4])
sage: f
4*x^3 + 3*x^2 + 98*x + 1
```

**quo_rem(right)**

Returns a tuple (quotient, remainder) where self = quotient*other + remainder.

**shift(n)**

Returns this polynomial multiplied by the power \( x^n \). If \( n \) is negative, terms below \( x^n \) will be discarded. Does not change this polynomial.

**EXAMPLES:**

```python
sage: R.<x> = PolynomialRing(Integers(12345678901234567890), implementation='NTL')
sage: p = x^2 + 2*x + 4
sage: p.shift(0)
x^2 + 2*x + 4
sage: p.shift(-1)
x + 2
sage: p.shift(-5)
0
sage: p.shift(2)
x^4 + 2*x^3 + 4*x^2
```

**small_roots(*args, **kwds)**

See `sage.rings.polynomial.polynomial_modn_dense_ntl.small_roots()` for the documentation of this function.

**EXAMPLES:**
```python
sage: N = 10001
sage: K = Zmod(10001)
sage: P.<x> = PolynomialRing(K, implementation='NTL')
sage: f = x^3 + 10*x^2 + 5000*x - 222
sage: f.small_roots()
[4]
```

class sage.rings.polynomial.polynomial_modn_dense_ntl.Polynomial_dense_mod_p

Bases: Polynomial_dense_mod_n

A dense polynomial over the integers modulo p, where p is prime.

discriminant()

EXAMPLES:
```python
sage: _.<x> = PolynomialRing(GF(19),implementation='NTL')
sage: f = x^3 + 3*x - 17
sage: f.discriminant()
12
```
gcd(right)

Return the greatest common divisor of this polynomial and other, as a monic polynomial.

INPUT:

- `other` – a polynomial defined over the same ring as `self`

EXAMPLES:
```python
sage: R.<x> = PolynomialRing(GF(3),implementation="NTL")
sage: f,g = x + 2, x^2 - 1
sage: f.gcd(g)
x + 2
```

resultant(other)

Returns the resultant of self and other, which must lie in the same polynomial ring.

INPUT:

- `other` – a polynomial

OUTPUT: an element of the base ring of the polynomial ring

EXAMPLES:
```python
sage: R.<x> = PolynomialRing(GF(19),implementation='NTL')
sage: f = x^3 + x + 1; g = x^3 - x - 1
sage: r = f.resultant(g); r
11
sage: r.parent() is GF(19)
True
```
xgcd(other)

Compute the extended gcd of this element and other.

INPUT:

- `other` – an element in the same polynomial ring
OUTPUT:

A tuple \((r, s, t)\) of elements in the polynomial ring such that \(r = s*\text{self} + t*\text{other}\).

EXAMPLES:

```
sage: R.<x> = PolynomialRing(GF(3), implementation='NTL')
sage: x.xgcd(x)
(x, 0, 1)
sage: (x^2 - 1).xgcd(x - 1)
(x + 2, 0, 1)
sage: R.zero().xgcd(R.one())
(1, 0, 1)
sage: (x^3 - 1).xgcd((x - 1)^2)
(x^2 + x + 1, 0, 1)
sage: ((x - 1)*(x + 1)).xgcd(x*(x - 1))
(x + 2, 1, 2)
```

class sage.rings.polynomial.polynomial_modn_dense_ntl.Polynomial_dense_modn_ntl_ZZ

Bases: Polynomial_dense_mod_n

degree()

EXAMPLES:

```
sage: R.<x> = PolynomialRing(Integers(14^34), implementation='NTL')
sage: f = x^4 - x - 1
sage: f.degree()
4
sage: f = 14^43*x + 1
sage: f.degree()
0
```

is_gen()

list(copy=True)

quo_rem(right)

Returns \(q\) and \(r\), with the degree of \(r\) less than the degree of \(right\), such that \(q*right + r = self\).

EXAMPLES:

```
sage: R.<x> = PolynomialRing(Integers(10^30), implementation='NTL')
sage: f = x^5+1; g = (x+1)^2
sage: q, r = f.quo_rem(g)
sage: q
x^3 + 999999999999999999999999999998*x^2 + 3*x + 999999999999999999999999999996
sage: r
5*x + 5
sage: q*g + r
x^5 + 1
```

reverse(degree=None)

Return the reverse of the input polynomial thought as a polynomial of degree degree.

If \(f\) is a degree-\(d\) polynomial, its reverse is \(x^d f(1/x)\).

INPUT:
• degree (None or an integer) - if specified, truncate or zero pad the list of coefficients to this degree before reversing it.

EXAMPLES:

```
sage: R.<x> = PolynomialRing(Integers(12^29), implementation='NTL')
sage: f = x^4 + 2*x + 5
sage: f.reverse()
5*x^4 + 2*x^3 + 1
sage: f = x^3 + x
sage: f.reverse()
x^2 + 1
sage: f.reverse(1)
1
sage: f.reverse(5)
x^4 + x^2
```

**shift(n)**

Shift self to left by \( n \), which is multiplication by \( x^n \), truncating if \( n \) is negative.

EXAMPLES:

```
sage: R.<x> = PolynomialRing(Integers(12^30), implementation='NTL')
sage: f = x^7 + x + 1
sage: f.shift(1)
x^8 + x^2 + x
sage: f.shift(-1)
x^6 + 1
sage: f.shift(10).shift(-10) == f
True
```

**truncate(n)**

Returns this polynomial mod \( x^n \).

EXAMPLES:

```
sage: R.<x> = PolynomialRing(Integers(15^30), implementation='NTL')
sage: f = sum(x^n for n in range(10)); f
x^9 + x^8 + x^7 + x^6 + x^5 + x^4 + x^3 + x^2 + x + 1
sage: f.truncate(6)
x^5 + x^4 + x^3 + x^2 + x + 1
```

**valuation()**

Returns the valuation of self, that is, the power of the lowest non-zero monomial of self.

EXAMPLES:

```
sage: R.<x> = PolynomialRing(Integers(10^50), implementation='NTL')
sage: x.valuation()
1
sage: f = x-3; f.valuation()
0
sage: f = x^99; f.valuation()
99
sage: f = x-x; f.valuation()
+Infinity
```
class sage.rings.polynomial.polynomial_modn_dense_ntl.Polynomial_dense_modn_ntl_zz

    Bases: Polynomial_dense_mod_n

Polynomial on \(\mathbb{Z}/n\mathbb{Z}\) implemented via NTL.

_add_(right)

_sub_(right)

_lmul_(c)

_rmul_(c)

_mul_(right)

_mul_trunc_(right, n)

Return the product of self and right truncated to the given length \(n\)

EXAMPLES:

```
sage: R.<x> = PolynomialRing(Integers(100), implementation="NTL")
sage: f = x - 2
sage: g = x^2 - 8*x + 16
sage: f*g
x^3 + 90*x^2 + 32*x + 68
sage: f._mul_trunc_(g, 42)
x^3 + 90*x^2 + 32*x + 68
sage: f._mul_trunc_(g, 3)
90*x^2 + 32*x + 68
sage: f._mul_trunc_(g, 2)
32*x + 68
sage: f._mul_trunc_(g, 1)
68
sage: f._mul_trunc_(g, 0)
0
sage: f = x^2 - 8*x + 16
sage: f._mul_trunc_(f, 2)
44*x + 56
```

degree()

EXAMPLES:

```
sage: R.<x> = PolynomialRing(Integers(77), implementation='NTL')
sage: f = x^4 - x - 1
sage: f.degree()
4
sage: f = 77*x + 1
sage: f.degree()
0
```

int_list()

Returns the coefficients of self as efficiently as possible as a list of python ints.

EXAMPLES:
```python
sage: R.<x> = PolynomialRing(Integers(100), implementation='NTL')
sage: from sage.rings.polynomial.polynomial_modn_dense_ntl import Polynomial_dense_mod_n as poly_modn_dense
sage: f = poly_modn_dense(R,[5,0,0,1])
sage: f.int_list()
[5, 0, 0, 1]
sage: [type(a) for a in f.int_list()]
[<... 'int'>, <... 'int'>, <... 'int'>, <... 'int'>]
```

```python
is_gen()
```

```python
ntl_set_directly(v)
```

```python
quo_rem(right)
Returns q and r, with the degree of r less than the degree of right, such that q * right + r = self.
EXAMPLES:
```
```python
sage: R.<x> = PolynomialRing(Integers(125), implementation='NTL')
sage: f = x^5+1; g = (x+1)^2
sage: q, r = f.quo_rem(g)
sage: q
x^3 + 123*x^2 + 3*x + 121
sage: r
5*x + 5
```

```python
reverse(degree=None)
Return the reverse of the input polynomial thought as a polynomial of degree degree.
If f is a degree-d polynomial, its reverse is x^d*f(1/x).
INPUT:
  • degree (None or an integer) - if specified, truncate or zero pad the list of coefficients to this degree before reversing it.
EXAMPLES:
```
```python
sage: R.<x> = PolynomialRing(Integers(77), implementation='NTL')
sage: f = x^4 - x - 1
sage: f.reverse()
76*x^4 + 76*x^3 + 1
sage: f.reverse(2)
76*x^2 + 76*x
sage: f.reverse(5)
76*x^5 + 76*x^4 + x
sage: g = x^3 - x
sage: g.reverse()
76*x^2 + 1
```

```python
shift(n)
Shift self to left by n, which is multiplication by x^n, truncating if n is negative.
EXAMPLES:
```
```
Polynomials, Release 10.0

```python
sage: R.<x> = PolynomialRing(Integers(77), implementation='NTL')
sage: f = x^7 + x + 1
sage: f.shift(1)
x^8 + x^2 + x
sage: f.shift(-1)
x^6 + 1
sage: f.shift(10).shift(-10) == f
True
```

**truncate**\(n\)

Returns this polynomial mod \(x^n\).

EXAMPLES:

```python
sage: R.<x> = PolynomialRing(Integers(77), implementation='NTL')
sage: f = sum(x^n for n in range(10)); f
x^9 + x^8 + x^7 + x^6 + x^5 + x^4 + x^3 + x^2 + x + 1
sage: f.truncate(6)
x^5 + x^4 + x^3 + x^2 + x + 1
```

**valuation**

Returns the valuation of self, that is, the power of the lowest non-zero monomial of self.

EXAMPLES:

```python
sage: R.<x> = PolynomialRing(Integers(10), implementation='NTL')
sage: x.valuation()
1
sage: f = x-3; f.valuation()
0
sage: f = x^99; f.valuation()
99
sage: f = x-x; f.valuation()
+Infinity
```

Let \(N\) be the characteristic of the base ring this polynomial is defined over: \(N = \text{self.base_ring().characteristic()}\). This method returns small roots of this polynomial modulo some factor \(b\) of \(N\) with the constraint that \(b \geq N^\beta\). Small in this context means that if \(x\) is a root of \(f\) modulo \(b\) then \(|x| < X\). This \(X\) is either provided by the user or the maximum \(X\) is chosen such that this algorithm terminates in polynomial time. If \(X\) is chosen automatically it is \(X = \text{ceil}(1/2N^{\beta^2/\delta-\epsilon})\). The algorithm may also return some roots which are larger than \(X\). ‘This algorithm’ in this context means Coppersmith’s algorithm for finding small roots using the LLL algorithm. The implementation of this algorithm follows Alexander May’s PhD thesis referenced below.

INPUT:

- \(X\) – an absolute bound for the root (default: see above)
- \(beta\) – compute a root mod \(b\) where \(b\) is a factor of \(N\) and \(b \geq N^\beta\). (Default: 1.0, so \(b = N\).)
- \(epsilon\) – the parameter \(\epsilon\) described above. (Default: \(\beta/8\))
- **kwds** – passed through to method \(\text{Matrix_integer_dense.LLL()}\).
EXAMPLES:

First consider a small example:

```
sage: N = 10001
sage: K = Zmod(10001)
sage: P.<x> = PolynomialRing(K, implementation='NTL')
sage: f = x^3 + 10*x^2 + 5000*x - 222
```

This polynomial has no roots without modular reduction (i.e. over \(\mathbb{Z}\)):
```
sage: f.change_ring(ZZ).roots()
[]
```

To compute its roots we need to factor the modulus \(N\) and use the Chinese remainder theorem:
```
sage: p,q = N.prime_divisors()
sage: f.change_ring(GF(p)).roots()
[(4, 1)]
sage: f.change_ring(GF(q)).roots()
[(4, 1)]
sage: crt(4, 4, p, q)
4
```

This root is quite small compared to \(N\), so we can attempt to recover it without factoring \(N\) using Coppersmith's small root method:
```
sage: f.small_roots()
[4]
```

An application of this method is to consider RSA. We are using 512-bit RSA with public exponent \(e = 3\) to encrypt a 56-bit DES key. Because it would be easy to attack this setting if no padding was used we pad the key \(K\) with 1s to get a large number:

```
sage: Nbits, Kbits = 512, 56
sage: e = 3
```

We choose two primes of size 256-bit each:
```
sage: p = 2^256 + 2^8 + 2^5 + 2^3 + 1
sage: q = 2^256 + 2^8 + 2^5 + 2^3 + 2^2 + 1
sage: N = p*q
sage: ZmodN = Zmod( N )
```

We choose a random key:
```
sage: K = ZZ.random_element(0, 2^Kbits)
```

and pad it with 512-56=456 1s:
```
sage: Kdigits = K.digits(2)
sage: M = [0]*Kbits + [1]*(Nbits-Kbits)
sage: for i in range(len(Kdigits)): M[i] = Kdigits[i]
sage: M = ZZ(M, 2)
```
Now we encrypt the resulting message:

```
sage: C = ZmodN(M)^e
```

To recover $K$ we consider the following polynomial modulo $N$:

```
sage: P.<x> = PolynomialRing(ZmodN, implementation='NTL')
sage: f = (2^Nbits - 2^Kbits + x)^e - C
```

and recover its small roots:

```
sage: Kbar = f.small_roots()[0]
sage: K == Kbar
True
```

The same algorithm can be used to factor $N = pq$ if partial knowledge about $q$ is available. This example is from the Magma handbook:

First, we set up $p$, $q$ and $N$:

```
sage: length = 512
sage: hidden = 110
sage: p = next_prime(2^int(round(length/2)))
sage: q = next_prime( round(pi.n()*p) )
sage: N = p*q
```

Now we disturb the low 110 bits of $q$:

```
sage: qbar = q + ZZ.random_element(0,2^hidden-1)
```

And try to recover $q$ from it:

```
sage: F.<x> = PolynomialRing(Zmod(N), implementation='NTL')
sage: f = x - qbar
```

We know that the error is $\leq 2^{\text{hidden}} - 1$ and that the modulus we are looking for is $\geq \sqrt{N}$:

```
sage: from sage.misc.verbose import set_verbose
sage: set_verbose(2)
sage: d = f.small_roots(X=2^hidden-1, beta=0.5)[0]  # time random
verbose 2 (<module>) m = 4
verbose 2 (<module>) t = 4
verbose 2 (<module>) X = 1298074214633706907132624082305023
verbose 1 (<module>) LLL of 8x8 matrix (algorithm fpLLL:wrapper)
verbose 1 (<module>) LLL finished (time = 0.006998)
sage: q == qbar - d
True
```

REFERENCES:


2.1.12 Dense univariate polynomials over \( \mathbb{R} \), implemented using MPFR

```python
class sage.rings.polynomial.polynomial_real_mpfr_dense.PolynomialRealDense
    Bases: Polynomial

change_ring(R)
    EXAMPLES:

        sage: from sage.rings.polynomial.polynomial_real_mpfr_dense import PolynomialRealDense
        sage: f = PolynomialRealDense(RR['x'], [-2, 0, 1.5])
        sage: f.change_ring(QQ)
        3/2*x^2 - 2
        sage: f.change_ring(RealField(10))
        1.5*x^2 - 2.0
        sage: f.change_ring(RealField(100))
        1.5000000000000000000000000000*x^2 - 2.0000000000000000000000000000

degree()
    Return the degree of the polynomial.
    EXAMPLES:

        sage: from sage.rings.polynomial.polynomial_real_mpfr_dense import PolynomialRealDense
        sage: f = PolynomialRealDense(RR['x'], [1, 2, 3]); f
        3.00000000000000*x^2 + 2.00000000000000*x + 1.00000000000000
        sage: f.degree()
        2

integral()
    EXAMPLES:

        sage: from sage.rings.polynomial.polynomial_real_mpfr_dense import PolynomialRealDense
        sage: f = PolynomialRealDense(RR['x'], [3, pi, 1])
        sage: f.integral()
        0.333333333333333*x^3 + 1.57079632679490*x^2 + 3.00000000000000*x

list(copy=True)
    EXAMPLES:

        sage: from sage.rings.polynomial.polynomial_real_mpfr_dense import PolynomialRealDense
        sage: f = PolynomialRealDense(RR['x'], [1, 0, -2]); f
        -2.00000000000000*x^2 + 1.00000000000000
        sage: f.list()
        [1.00000000000000, 0.000000000000000, -2.00000000000000]

quo_rem(other)
    Return the quotient with remainder of self by other.
    EXAMPLES:
```
sage: from sage.rings.polynomial.polynomial_real_mpfr_dense import PolynomialRealDense
sage: f = PolynomialRealDense(RR['x'], [-2, 0, 1])
sage: g = PolynomialRealDense(RR['x'], [5, 1])
sage: q, r = f.quo_rem(g)
sage: q
x - 5.00000000000000
sage: r
23.0000000000000
sage: q*g + r == f
True
sage: fg = f*g
sage: fg.quo_rem(f)
(x + 5.00000000000000, 0)
sage: fg.quo_rem(g)
(x^2 - 2.00000000000000, 0)

reverse(degree=None)

Return reverse of the input polynomial thought as a polynomial of degree degree.

If \( f \) is a degree-\( d \) polynomial, its reverse is \( x^d f(1/x) \).

INPUT:

- degree (None or an integer) - if specified, truncate or zero pad the list of coefficients to this degree before reversing it.

EXAMPLES:

sage: f = RR['x']([-3, pi, 0, 1])
sage: f.reverse()
-3.00000000000000*x^3 + 3.14159265358979*x^2 + 1.00000000000000
sage: f.reverse(2)
-3.00000000000000*x^2 + 3.14159265358979*x
sage: f.reverse(5)
-3.00000000000000*x^5 + 3.14159265358979*x^4 + x^2

shift(n)

Returns this polynomial multiplied by the power \( x^n \). If \( n \) is negative, terms below \( x^n \) will be discarded. Does not change this polynomial.

EXAMPLES:

(continues on next page)
sage: f.shift(-1)
3.00000000000000*x + 2.00000000000000
sage: f.shift(-10)
0

\textbf{truncate}(n)

Returns the polynomial of degree \(< n\) which is equivalent to self modulo \(x^n\).

\textbf{EXAMPLES:}

\begin{verbatim}
sage: from sage.rings.polynomial.polynomial_real_mpfr_dense import PolynomialRealDense
sage: f = PolynomialRealDense(RealField(10)[]}x], [1, 2, 4, 8])
sage: f.truncate(3)
4.0*x^2 + 2.0*x + 1.0
sage: f.truncate(100)
8.0*x^3 + 4.0*x^2 + 2.0*x + 1.0
sage: f.truncate(1)
1.0
sage: f.truncate(0)
0
\end{verbatim}

\textbf{truncate\_abs}(\text{bound})

Truncate all high order coefficients below bound.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: from sage.rings.polynomial.polynomial_real_mpfr_dense import PolynomialRealDense
sage: f = PolynomialRealDense(RealField(10)[]}x], [10^-k for k in range(10)])
sage: f
1.0e-9*x^9 + 1.0e-8*x^8 + 1.0e-7*x^7 + 1.0e-6*x^6 + 0.000010*x^5 + 0.00010*x^4 + 0.0010*x^3 + 0.010*x^2 + 0.10*x + 1.0
sage: f.truncate_abs(0.5e-6)
1.0e-6*x^6 + 0.000010*x^5 + 0.00010*x^4 + 0.0010*x^3 + 0.010*x^2 + 0.10*x + 1.0
sage: f.truncate_abs(10.0)
0
sage: f.truncate_abs(1e-100) == f
True
\end{verbatim}

\textbf{sage.rings.polynomial.polynomial_real_mpfr_dense.make\_PolynomialRealDense}(parent, data)

\textbf{EXAMPLES:}

\begin{verbatim}
sage: from sage.rings.polynomial.polynomial_real_mpfr_dense import make_PolynomialRealDense
sage: make_PolynomialRealDense(RR[]}x], [1,2,3])
3.00000000000000*x^2 + 2.00000000000000*x + 1.00000000000000
\end{verbatim}
2.1.13 Polynomial Interfaces to Singular

AUTHORS:

- Martin Albrecht <malb@informatik.uni-bremen.de> (2006-04-21)
- Robert Bradshaw: Re-factor to avoid multiple inheritance vs. Cython (2007-09)
- Syed Ahmad Lavasani: Added function field to _singular_init_ (2011-12-16)
  Added non-prime finite fields to _singular_init_ (2012-1-22)

```python
class sage.rings.polynomial.polynomial_singular_interface.PolynomialRing_singular_repr
Bases: object
Implements methods to convert polynomial rings to Singular.
This class is a base class for all univariate and multivariate polynomial rings which support conversion from and to Singular rings.

class sage.rings.polynomial.polynomial_singular_interface.Polynomial_singular_repr
Bases: object
Implements coercion of polynomials to Singular polynomials.
This class is a base class for all (univariate and multivariate) polynomial classes which support conversion from and to Singular polynomials.
Due to the incompatibility of Python extension classes and multiple inheritance, this just defers to module-level functions.
```

```python
sage.rings.polynomial.polynomial_singular_interface.can_convert_to_singular(R)
Return True if this ring’s base field or ring can be represented in Singular, and the polynomial ring has at least one generator.
The following base rings are supported: finite fields, rationals, number fields, and real and complex fields.
```

EXAMPLES:

```python
sage: from sage.rings.polynomial.polynomial_singular_interface import can_convert_to_singular
sage: can_convert_to_singular(PolynomialRing(QQ, names=['x']))
True
sage: can_convert_to_singular(PolynomialRing(ZZ, names=['x']))
True
sage: can_convert_to_singular(PolynomialRing(QQ, names=[]))
False
```

2.1.14 Base class for generic $p$-adic polynomials

This provides common functionality for all $p$-adic polynomials, such as printing and factoring.

AUTHORS:

- Jeroen Demeyer (2013-11-22): initial version, split off from other files, made Polynomial_padic the common base class for all $p$-adic polynomials.

```python
class sage.rings.polynomial.padics.polynomial_padic.Polynomial_padic
  parent, x=None, check=True, is_gen=False, construct=False)
```

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\textbf{content()}

Compute the content of this polynomial.

\textbf{OUTPUT:}

If this is the zero polynomial, return the constant coefficient. Otherwise, since the content is only defined up to a unit, return the content as $\pi^k$ with maximal precision where $k$ is the minimal valuation of any of the coefficients.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: K = Zp(13,7)
sage: R.<t> = K[]
sage: f = 13^7*t^3 + K(169,4)*t - 13^4
sage: f.content()
13^2 + O(13^9)
sage: R(0).content()
0
sage: f = R(K(0,3)); f
O(13^3)
sage: f.content()
O(13^3)

sage: P.<x> = ZZ[]
sage: f = x + 2
sage: f.content()
1
sage: fp = f.change_ring(pAdicRing(2, 10))
sage: fp
(1 + O(2^10))*x + 2 + O(2^11)
sage: fp.content()
1 + O(2^10)
sage: (2*fp).content()
2 + O(2^11)
\end{verbatim}

Over a field it would be sufficient to return only zero or one, as the content is only defined up to multiplication with a unit. However, we return $\pi^k$ where $k$ is the minimal valuation of any coefficient:

\begin{verbatim}
sage: K = Qp(13,7)
sage: R.<t> = K[]
sage: f = 13^7*t^3 + K(169,4)*t - 13^-4
sage: f.content()
13^-4 + O(13^3)
sage: f = R.zero()
sage: f.content()
0
sage: f = 13*t^3 + K(0,1)*t
sage: f.content()
13 + O(13^8)
\end{verbatim}
factor()

Return the factorization of this polynomial.

EXAMPLES:

```
sage: R.<t> = PolynomialRing(Qp(3,3,print_mode='terse',print_pos=False))
sage: pol = t^8 - 1
sage: for p,e in pol.factor():
....:     print(f"{e} {}", end='\n')
1 (1 + O(3^3))*t + 1 + O(3^3)
1 (1 + O(3^3))*t - 1 + O(3^3)
1 (1 + O(3^3))*t^2 + (5 + O(3^3))*t - 1 + O(3^3)
1 (1 + O(3^3))*t^2 + (-5 + O(3^3))*t - 1 + O(3^3)
1 (1 + O(3^3))*t^2 + O(3^3)*t + 1 + O(3^3)
```

```
sage: R.<t> = PolynomialRing(Qp(5,6,print_mode='terse',print_pos=False))
sage: pol = 100 * (5*t - 1) * (t - 5)
sage: pol
(500 + O(5^9))*t^2 + (-2600 + O(5^8))*t + 500 + O(5^9)
sage: pol.factor()
(500 + O(5^9)) * ((1 + O(5^5))*t - 1/5 + O(5^5)) * ((1 + O(5^6))*t - 5 + O(5^6))
sage: pol.factor().value()
(500 + O(5^8))*t^2 + (-2600 + O(5^8))*t + 500 + O(5^8)
```

The same factorization over \(\mathbb{Z}_p\). In this case, the “unit” part is a \(p\)-adic unit and the power of \(p\) is considered to be a factor:

```
sage: R.<t> = PolynomialRing(Zp(5,6,print_mode='terse',print_pos=False))
sage: pol = 100 * (5*t - 1) * (t - 5)
sage: pol
(500 + O(5^9))*t^2 + (-2600 + O(5^8))*t + 500 + O(5^9)
sage: pol.factor()
(4 + O(5^6)) * (5 + O(5^7))^2 * ((1 + O(5^6))*t - 5 + O(5^6)) * ((5 + O(5^6))*t - 1 + O(5^6))
sage: pol.factor().value()
(500 + O(5^8))*t^2 + (-2600 + O(5^8))*t + 500 + O(5^8)
```

In the following example, the discriminant is zero, so the \(p\)-adic factorization is not well defined:

```
sage: factor(t^2)
Traceback (most recent call last):
...
PrecisionError: p-adic factorization not well-defined since the discriminant is zero up to the request \(p\)-adic precision
```

An example of factoring a constant polynomial (see github issue #26669):

```
sage: R.<x> = Qp(5)[]
sage: R(2).factor()
2 + O(5^20)
```

More examples over \(\mathbb{Z}_p\):
sage: f = w^5 - 1
sage: f.factor()
((1 + O(5^6))*w + 3124 + O(5^6)) * ((1 + O(5^6))*w^4 + (12501 + O(5^6))*w^3 +
→ (9376 + O(5^6))*w^2 + (6251 + O(5^6))*w + 3126 + O(5^6))

See github issue #4038:

sage: E = EllipticCurve('37a1')
sage: K = Qp(7,10)
sage: EK = E.base_extend(K)
sage: E = EllipticCurve('37a1')
sage: K = Qp(7,10)
sage: EK = E.base_extend(K)
sage: g = EK.division_polynomial_0(3)
sage: g.factor()
(3 + O(7^10)) * ((1 + O(7^10))*x + 1 + 2*7 + 4*7^2 + 2*7^3 + 5*7^4 + 7*5 + 5*7^6 + 6 + 3*7^8 + 3*7^9 + O(7^10)) * ((1 + O(7^10))*x^3 + (6 + 4*7 + 2*7^2 + 5*7^3 + 5*7^4 + 7^5 + 5*7^6 + 6 + 3*7^8 + 3*7^9 + O(7^10))*x^2 + (6 + 3*7 + 5*7^2 + 2*7^4 + 7^5 + 7^6 + 2*7^8 + 3*7^9 + O(7^10))*x + 2 + 5*7 + 4*7^2 + 2*7^3 + 6*7^4 + 3*7^5 + 7^6 + 4*7^7 + O(7^10))

root_field(names, check_irreducible=True, **kwds)

Return the p-adic extension field generated by the roots of the irreducible polynomial self.

INPUT:

• names – name of the generator of the extension

• check_irreducible – check whether the polynomial is irreducible

• kwds – see sage.ring.padics.padic_generic.pAdicGeneric.extension()

EXAMPLES:

sage: R.<x> = Qp(3,5,print_mode='digits')[]
sage: f = x^2 - 3
sage: f.root_field('x')
3-adic Eisenstein Extension Field in x defined by x^2 - 3

sage: R.<x> = Qp(5,5,print_mode='digits')[]
sage: f = x^2 - 3
sage: f.root_field('x', print_mode='bars')
5-adic Unramified Extension Field in x defined by x^2 - 3

sage: R.<x> = Qp(11,5,print_mode='digits')[]
sage: f = x^2 - 3
sage: f.root_field('x', print_mode='bars')
Traceback (most recent call last):
...
ValueError: polynomial must be irreducible
2.1.15 p-adic Capped Relative Dense Polynomials

class sage.rings.polynomial.padics.polynomial_padic_capped_relative_dense.Polynomial_padic_capped_relative_dense

Bases: Polynomial_generic_cdv, Polynomial_padic
degree(secure=False)

Return the degree of self.

INPUT:

• secure – a boolean (default: False)

If secure is True and the degree of this polynomial is not determined (because the leading coefficient is indistinguishable from 0), an error is raised.

If secure is False, the returned value is the largest n so that the coefficient of \(x^n\) does not compare equal to 0.

EXAMPLES:

sage: K = Qp(3,10)
sage: R.<T> = K[

sage: f = T + 2; f
(1 + O(3^10))*T + 2 + O(3^10)
sage: f.degree()
1
sage: (f-T).degree()
0
sage: (f-T).degree(secure=True)
Traceback (most recent call last):
... PrecisionError: the leading coefficient is indistinguishable from 0

sage: x = 0(3^5)
sage: li = [3^i * x for i in range(0,5)]; li
[0(3^5), 0(3^6), 0(3^7), 0(3^8), 0(3^9)]
sage: f = R(li); f
0(3^9)*T^4 + 0(3^8)*T^3 + 0(3^7)*T^2 + 0(3^6)*T + 0(3^5)
sage: f.degree(secure=True)
-1
sage: f.degree(secure=True)
Traceback (most recent call last):
... PrecisionError: the leading coefficient is indistinguishable from 0

disc()
factor_mod()
Return the factorization of \texttt{self} modulo \( p \).

is_eisenstein(secure=False)
Return \texttt{True} if this polynomial is an Eisenstein polynomial.

EXAMPLES:

\[
\begin{align*}
sage: & K = \text{Qp}(5) \\
sage: & R.<t> = K[] \\
sage: & f = 5 + 5^*t + t^4 \\
sage: & f.is_eisenstein() \\
& \text{True}
\end{align*}
\]

AUTHOR:
• Xavier Caruso (2013-03)

lift()
Return an integer polynomial congruent to this one modulo the precision of each coefficient.

Note: The lift that is returned will not necessarily be the same for polynomials with the same coefficients (i.e. same values and precisions): it will depend on how the polynomials are created.

EXAMPLES:

\[
\begin{align*}
sage: & K = \text{Qp}(13,7) \\
sage: & R.<t> = K[] \\
sage: & a = 13^7*t^3 + K(169,4)*t - 13^4 \\
sage: & a.lift() \\
& 62748517*t^3 + 169*t - 28561
\end{align*}
\]

list(\texttt{copy=\texttt{True}})
Return a list of coefficients of \texttt{self}.

Note: The length of the list returned may be greater than expected since it includes any leading zeros that have finite absolute precision.

EXAMPLES:

\[
\begin{align*}
sage: & K = \text{Qp}(13,7) \\
sage: & R.<t> = K[] \\
sage: & a = 2*t^3 + 169*t - 1 \\
sage: & a \\
& (2 + 0(13^7))*t^3 + (13^2 + 0(13^9))*t + 12 + 12*13 + 12*13^2 + 12*13^3 + 12*13^4 + 12*13^5 + 12*13^6 + 0(13^7) \\
sage: & a.list() \\
& [12 + 12*13 + 12*13^2 + 12*13^3 + 12*13^4 + 12*13^5 + 12*13^6 + 0(13^7), \\
& 13^2 + 0(13^9), \\
& 0, \\
& 2 + 0(13^7)]
\end{align*}
\]
lshift_coeffs(shift, no_list=False)

Return a new polynomials whose coefficients are multiplied by p^shift.

EXAMPLES:

```python
sage: K = Qp(13, 4)
sage: R.<t> = K[]
sage: a = t + 52
sage: a.lshift_coeffs(3)
(13^3 + O(13^7))*t + 4*13^4 + O(13^8)
```

class newton_polygon()

Return the Newton polygon of this polynomial.

**Note:** If some coefficients have not enough precision an error is raised.

OUTPUT:

• a Newton polygon

EXAMPLES:

```python
sage: K = Qp(2, prec=5)
sage: P.<x> = K[]
sage: f = x^4 + 2^3*x^3 + 2^13*x^2 + 2^21*x + 2^37
sage: f.newton_polygon()
Finite Newton polygon with 4 vertices: (0, 37), (1, 21), (3, 3), (4, 0)
```

Here is an example where the computation fails because precision is not sufficient:

```python
sage: g = f + K(0,0)*t^4; g
(5^2 + O(5^22))*t^10 + O(5^0)*t^4 + (3 + O(5^20))*t + 5 + O(5^21)
sage: g.newton_polygon()
Traceback (most recent call last):
...
PrecisionError: The coefficient of t^4 has not enough precision
```

AUTHOR:

• Xavier Caruso (2013-03-20)

newton_slopes(repetition=True)

Return a list of the Newton slopes of this polynomial.

These are the valuations of the roots of this polynomial.

If repetition is True, each slope is repeated a number of times equal to its multiplicity. Otherwise it appears only one time.

INPUT:
• repetition – boolean (default True)

OUTPUT:

• a list of rationals

EXAMPLES:

```python
sage: K = Qp(5)
sage: R.<t> = K[]
sage: f = 5 + 3^t + t^4 + 25*t^10
sage: f.newton_polygon()
Finite Newton polygon with 4 vertices: (0, 1), (1, 0), (4, 0), (10, 2)
sage: f.newton_slopes()
[1, 0, 0, 0, -1/3, -1/3, -1/3, -1/3, -1/3, -1/3]
sage: f.newton_slopes(repetition=False)
[1, 0, -1/3]
```

AUTHOR:

• Xavier Caruso (2013-03-20)

**prec_degree()**

Return the largest $n$ so that precision information is stored about the coefficient of $x^n$.

Always greater than or equal to degree.

EXAMPLES:

```python
sage: K = Qp(3,10)
sage: R.<T> = K[]
sage: f = T + 2; f
(1 + O(3^10))*T + 2 + O(3^10)
sage: f.prec_degree()
1
```

**precision_absolute(n=None)**

Return absolute precision information about self.

INPUT:

self – a p-adic polynomial

n – None or an integer (default None).

OUTPUT:

If $n = None$, returns a list of absolute precisions of coefficients. Otherwise, returns the absolute precision of the coefficient of $x^n$.

EXAMPLES:

```python
sage: K = Qp(3,10)
sage: R.<T> = K[]
sage: f = T + 2; f
(1 + O(3^10))*T + 2 + O(3^10)
sage: f.prec_degree()
[10, 10]
```

2.1. Univariate Polynomials and Polynomial Rings
**precision_relative**(*n=None*)

Return relative precision information about `self`.

**INPUT:**

`self` – a p-adic polynomial

`n` – `None` or an integer (default `None`).

**OUTPUT:**

If `n == None`, returns a list of relative precisions of coefficients. Otherwise, returns the relative precision of the coefficient of `x^n`.

**EXAMPLES:**

```python
sage: K = Qp(3,10)
sage: R.<T> = K[]
sage: f = T + 2; f
(1 + O(3^10))*T + 2 + O(3^10)
sage: f.precision_relative()
[10, 10]
```

**quo_rem**(*right*, *secure=False*)

Return the quotient and remainder in division of `self` by `right`.

**EXAMPLES:**

```python
sage: K = Qp(3,10)
sage: R.<T> = K[]
sage: f = T + 2
sage: g = T**4 + 3*T+22
sage: g.quo_rem(f)
((1 + O(3^10))*T^3 + (1 + 2*3 + 2*3^2 + 2*3^3 + 2*3^4 + 2*3^5 + 2*3^6 + 2*3^7 + O(3^10))*T^2 + (1 + 3 + O(3^10))*T + 1 + 3 + 2*3^2 + 2*3^3 + 2*3^4 + 2*3^5 + 2*3^6 + 2*3^7 + O(3^10), 2 + 3 + 3*3 + O(3^10))
```

**rescale**(*a*)

Return `f(a*X)`

**Todo:** Need to write this function for integer polynomials before this works.

**EXAMPLES:**

```python
sage: K = Zp(13, 5)
sage: R.<t> = K[]
sage: f = t^3 + K(13, 3) * t
sage: f.rescale(2) # not implemented
```

**reverse**(*degree=None*)

Return the reverse of the input polynomial, thought as a polynomial of degree `degree`.

If `f` is a degree-`d` polynomial, its reverse is `x^d f(1/x)`.

**INPUT:**

...
• degree (None or an integer) - if specified, truncate or zero pad the list of coefficients to this degree before reversing it.

EXAMPLES:

```python
sage: K = Qp(13,7)
sage: R.<t> = K[]
sage: f = t^3 + 4*t; f
     (1 + O(13^7))*t^3 + (4 + O(13^7))*t
sage: f.reverse()
     0*t^3 + (4 + O(13^7))*t^2 + 1 + O(13^7)
sage: f.reverse(3)
     0*t^3 + (4 + O(13^7))*t^2 + 1 + O(13^7)
sage: f.reverse(2)
     0*t^2 + (4 + O(13^7))*t
sage: f.reverse(4)
     0*t^4 + (4 + O(13^7))*t^3 + (1 + O(13^7))*t
sage: f.reverse(6)
     0*t^6 + (4 + O(13^7))*t^5 + (1 + O(13^7))*t^3
```

`rshift_coeffs(shift, no_list=False)`

Return a new polynomial whose coefficients are p-adically shifted to the right by `shift`.

**Note:** Type `Qp(5)(0).__rshift__?` for more information.

EXAMPLES:

```python
sage: K = Zp(13, 4)
sage: R.<t> = K[]
sage: a = t^2 + K(13,3)*t + 169; a
     (1 + O(13^4))*t^2 + (13 + O(13^3))*t + 13^2 + O(13^6)
sage: b = a.rshift_coeffs(1); b
     O(13^3)*t^2 + (1 + O(13^2))*t + 13 + O(13^5)
sage: b.list()
[13 + O(13^5), 1 + O(13^2), 0(13^3)]
sage: b = a.rshift_coeffs(2); b
     O(13^2)*t^2 + 0(13)*t + 1 + O(13^4)
sage: b.list()
[1 + O(13^4), 0(13), 0(13^2)]
```

`valuation(val_of_var=None)`

Return the valuation of `self`.

**INPUT:**

- `self` – a p-adic polynomial
- `val_of_var` – None or a rational (default None).

**OUTPUT:**

If `val_of_var == None`, returns the largest power of the variable dividing `self`. Otherwise, returns the valuation of `self` where the variable is assigned valuation `val_of_var`.

EXAMPLES:
.. code-block:: python

    sage: K = Qp(3,10)
    sage: R.<T> = K[]
    sage: f = T + 2; f
    (1 + O(3^10))*T + 2 + O(3^10)
    sage: f.valuation()
    0

valuation_of_coefficient(n=None)

Return valuation information about self’s coefficients.

INPUT:

self – a p-adic polynomial

n – None or an integer (default None).

OUTPUT:

If n == None, returns a list of valuations of coefficients. Otherwise, returns the valuation of the coefficient of x^n.

EXAMPLES:

.. code-block:: python

    sage: K = Qp(3,10)
    sage: R.<T> = K[]
    sage: f = T + 2; f
    (1 + O(3^10))*T + 2 + O(3^10)
    sage: f.valuation_of_coefficient(1)
    0

sage.rings.polynomial.padics.polynomial_padic_capped_relative_dense.make_padic_poly(parent, x, version)

2.1.16 p-adic Flat Polynomials

class sage.rings.polynomial.padics.polynomial_padic_flat.Polynomial_padic_flat(parent, x=None, check=True, is_gen=False, construct=False, absprec=None)

Bases: Polynomial_generic_dense, Polynomial_padic
2.1.17 Univariate Polynomials over GF(p^e) via NTL’s ZZ_pEX

AUTHOR:

• Yann Laigle-Chapuy (2010-01) initial implementation
• Lorenz Panny (2023-01): minpoly_mod()

class sage.rings.polynomial.polynomial_zz_pex.Polynomial_ZZ_pEX

Bases: Polynomial_template

Univariate Polynomials over GF(p^n) via NTL’s ZZ_pEX.

EXAMPLES:

```
sage: K.<a>=GF(next_prime(2**60)**3)
sage: R.<x> = PolynomialRing(K, implementation='NTL')
sage: (x^3 + a*x^2 + 1) * (x + a)
x^4 + 2*a*x^3 + a^2*x^2 + x + a
```

**is_irreducible**(algorithm='fast_when_false', iter=1)

Returns True precisely when self is irreducible over its base ring.

INPUT:

Parameters

• algorithm – a string (default “fast_when_false”), there are 3 available algorithms: “fast_when_true”, “fast_when_false” and “probabilistic”.

• iter – (default: 1) if the algorithm is “probabilistic” defines the number of iterations. The error probability is bounded by \(q^{-\text{iter}}\) for polynomials in \(GF(q)[x]\).

EXAMPLES:

```
sage: K.<a>=GF(next_prime(2**60)**3)
sage: R.<x> = PolynomialRing(K, implementation='NTL')
sage: P = x^3+(2-a)*x+1
sage: P.is_irreducible(algorithm='fast_when_false')
True
sage: P.is_irreducible(algorithm='fast_when_true')
True
sage: P.is_irreducible(algorithm='probabilistic')
True
sage: Q = (x^2+a)*(x+a^3)
sage: Q.is_irreducible(algorithm='fast_when_false')
False
sage: Q.is_irreducible(algorithm='fast_when_true')
False
sage: Q.is_irreducible(algorithm='probabilistic')
False
```

**list**(copy=True)

Return the list of coefficients.

EXAMPLES:

Polynomials, Release 10.0

```
sage: K.<a> = GF(5^3)
sage: P = PolynomialRing(K, 'x')
sage: f = P.random_element(100)
sage: f.list() == [f[i] for i in range(f.degree()+1)]
True
sage: P.0.list()
[0, 1]
```

**minpoly_mod**(other)

Compute the minimal polynomial of this polynomial modulo another polynomial in the same ring.

**ALGORITHM:**

NTL's MinPolyMod(), which uses Shoup's algorithm [Sho1999].

**EXAMPLES:**

```
sage: R.<x> = GF(101^2)[]
sage: f = x^17 + x^2 - 1
sage: (x^2).minpoly_mod(f)
x^17 + 100*x^2 + 2*x + 100
```

**resultant**(other)

Returns the resultant of self and other, which must lie in the same polynomial ring.

**INPUT:**

- **other** – a polynomial

**OUTPUT:** an element of the base ring of the polynomial ring

**EXAMPLES:**

```
sage: K.<a>=GF(next_prime(2**60)**3)
sage: R.<x> = PolynomialRing(K,implementation='NTL')
sage: f=(x-a)*(x-a^2)*(x+1)
sage: g=(x-a^3)*(x-a^4)*(x+a)
sage: r = f.resultant(g)
sage: r == prod(u-v for (u,eu) in f.roots() for (v,ev) in g.roots())
True
```

**shift**(n)

**EXAMPLES:**

```
sage: K.<a>=GF(next_prime(2**60)**3)
sage: R.<x> = PolynomialRing(K,implementation='NTL')
sage: f = x^3 + x^2 + 1
sage: f.shift(1)
x^4 + x^3 + x
sage: f.shift(-1)
x^2 + x
```

**class** sage.rings.polynomial.polynomial_zz_pex.Polynomial_ZZ_pX

Bases: Polynomial_template
class sage.rings.polynomial.polynomial_zz_pex.Polynomial_template

Bases: Polynomial

Template for interfacing to external C / C++ libraries for implementations of polynomials.

AUTHORS:
  • Robert Bradshaw (2008-10): original idea for templating
  • Martin Albrecht (2008-10): initial implementation

This file implements a simple templating engine for linking univariate polynomials to their C/C++ library implementations. It requires a ‘linkage’ file which implements the celement_ functions (see sage.libsntl.ntl_GF2X_linkage for an example). Both parts are then plugged together by inclusion of the linkage file when inheriting from this class. See sage.rings.polynomial.polynomial_gf2x for an example.

We illustrate the generic glueing using univariate polynomials over GF(2).

Note: Implementations using this template MUST implement coercion from base ring elements and get_unsafe(). See Polynomial_GF2X for an example.

degree()

EXAMPLES:

```
sage: P.<x> = GF(2)[]
sage: x.degree()
1
sage: P(1).degree()
0
sage: P(0).degree()
-1
```

gcd(other)

Return the greatest common divisor of self and other.

EXAMPLES:

```
sage: P.<x> = GF(2)[]
sage: f = x*(x+1)
sage: f.gcd(x+1)
x + 1
sage: f.gcd(x^2)
x
```

get_cparent()


is_gen()

EXAMPLES:

```
sage: P.<x> = GF(2)[]
sage: x.is_gen()
True
sage: (x+1).is_gen()
False
```
is_one()
EXAMAPLES:

```
sage: P.<x> = GF(2)[]
sage: P(1).is_one()
True
```

is_zero()

EXAMAPLES:

```
sage: P.<x> = GF(2)[]
sage: x.is_zero()
False
```

list(copy=True)

EXAMAPLES:

```
sage: P.<x> = GF(2)[]
sage: x.list()
[0, 1]
sage: list(x)
[0, 1]
```

quo_rem(right)

EXAMAPLES:

```
sage: P.<x> = GF(2)[]
sage: f = x^2 + x + 1
sage: f.quo_rem(x + 1)
(x, 1)
```

shift(n)

EXAMAPLES:

```
sage: P.<x> = GF(2)[]
sage: f = x^3 + x^2 + 1
sage: f.shift(1)
x^4 + x^3 + x
sage: f.shift(-1)
x^2 + x
```

truncate(n)

Returns this polynomial mod \(x^n\).

EXAMAPLES:

```
sage: R.<x> =GF(2)[]
sage: f = sum(x^n for n in range(10)); f
x^9 + x^8 + x^7 + x^6 + x^5 + x^4 + x^3 + x^2 + x + 1
sage: f.truncate(6)
x^5 + x^4 + x^3 + x^2 + x + 1
```

If the precision is higher than the degree of the polynomial then the polynomial itself is returned:
sage: f.truncate(10) is f
True

If the precision is negative, the zero polynomial is returned:

sage: f.truncate(-1)
0

\textbf{xgcd}(\text{other})

Computes extended gcd of self and other.

\textbf{EXAMPLES:}

```
sage: P.<x> = GF(7)[]
sage: f = x*(x+1)
sage: f.xgcd(x+1)
(x + 1, 0, 1)
sage: f.xgcd(x^2)
(x, 1, 6)
```

\textbf{sage.rings.polynomial.polynomial_zz_pex.make_element}(parent, args)

### 2.1.18 Isolate Real Roots of Real Polynomials

\textbf{AUTHOR:}

• Carl Witty (2007-09-19): initial version

This is an implementation of real root isolation. That is, given a polynomial with exact real coefficients, we compute isolating intervals for the real roots of the polynomial. (Polynomials with integer, rational, or algebraic real coefficients are supported.)

We convert the polynomials into the Bernstein basis, and then use de Casteljau’s algorithm and Descartes’ rule of signs on the Bernstein basis polynomial (using interval arithmetic) to locate the roots. The algorithm is similar to that in “A Descartes Algorithm for Polynomials with Bit-Stream Coefficients”, by Eigenwillig, Kettner, Krandick, Mehlhorn, Schmitt, and Wolpert, but has three crucial optimizations over the algorithm in that paper:

• Precision reduction: at certain points in the computation, we discard the low-order bits of the coefficients, widening the intervals.

• Degree reduction: at certain points in the computation, we find lower-degree polynomials that are approximately equal to our high-degree polynomial over the region of interest.

• When the intervals are too wide to continue (either because of a too-low initial precision, or because of precision or degree reduction), and we need to restart with higher precision, we recall which regions have already been proven not to have any roots and do not examine them again.

The best description of the algorithms used (other than this source code itself) is in the slides for my Sage Days 4 talk, currently available from https://wiki.sagemath.org/days4schedule .

\textbf{exception} sage.rings.polynomial.real_roots.PrecisionError

\textbf{Bases:} ValueError

\textbf{sage.rings.polynomial.real_roots.bernstein_down}(d1, d2, s)

Given polynomial degrees d1 and d2 (where d1 < d2), and a number of samples s, computes a matrix bd.

If you have a Bernstein polynomial of formal degree d2, and select s of its coefficients (according to subsample_vec), and multiply the resulting vector by bd, then you get the coefficients of a Bernstein polynomial of...
formal degree $d_1$, where this second polynomial is a good approximation to the first polynomial over the region of the Bernstein basis.

**EXAMPLES:**

```python
sage: from sage.rings.polynomial.real_roots import *
sage: bernstein_down(3, 8, 5)
[ 612/245 -348/245 -37/49 338/245 -172/245]
[-724/441 132/49 395/441 -290/147 452/441]
[ 452/441 -290/147 395/441 132/49 -724/441]
[-172/245 338/245 -37/49 -348/245 612/245]
```

`sage.rings.polynomial.real_roots.bernstein_expand(c, d2)`

Given an integer vector representing a Bernstein polynomial $p$, and a degree $d_2$, compute the representation of $p$ as a Bernstein polynomial of formal degree $d_2$.

This is similar to multiplying by the result of `bernstein_up`, but should be faster for large $d_2$ (this has about the same number of multiplies, but in this version all the multiplies are by single machine words).

Returns a pair consisting of the expanded polynomial, and the maximum error $E$. (So if an element of the returned polynomial is $a$, and the true value of that coefficient is $b$, then $a \leq b < a + E$.)

**EXAMPLES:**

```python
sage: from sage.rings.polynomial.real_roots import *
sage: c = vector(ZZ, [1000, 2000, -3000])
sage: bernstein_expand(c, 3)
((1000, 1666, 333, -3000), 1)
sage: bernstein_expand(c, 4)
((1000, 1500, 1000, -500, -3000), 1)
sage: bernstein_expand(c, 20)
((1000, 1100, 1168, 1205, 1210, 1184, 1126, 1036, 915, 763, 578, 363, 115, -474, -816, -1190, -2032, -2500, -3000), 1)
```

**class** `sage.rings.polynomial.real_roots.bernstein_polynomial_factory`

Bases: `object`

An abstract base class for `bernstein_polynomial` factories. That is, elements of subclasses represent Bernstein polynomials (exactly), and are responsible for creating `interval_bernstein_polynomial_integer` approximations at arbitrary precision.

Supports four methods, `coeffs_bitsize()`, `bernstein_polynomial()`, `lsign()`, and `usign()`. The `coeffs_bitsize()` method gives an integer approximation to the log2 of the max of the absolute values of the Bernstein coefficients. The `bernstein_polynomial(scale_log2)` method gives an approximation where the maximum coefficient has approximately `coeffs_bitsize()` - `scale_log2` bits. The `lsign()` and `usign()` methods give the (exact) sign of the first and last coefficient, respectively.

- **lsign()**
  Returns the sign of the first coefficient of this Bernstein polynomial.

- **usign()**
  Returns the sign of the last coefficient of this Bernstein polynomial.

**class** `sage.rings.polynomial.real_roots.bernstein_polynomial_factory_ar(poly, neg)`

Bases: `bernstein_polynomial_factory`

This class holds an exact Bernstein polynomial (represented as a list of algebraic real coefficients), and returns arbitrarily-precise interval approximations of this polynomial on demand.
bernstein_polynomial\((scale\_log2)\)

Compute an interval_bernstein_polynomial_integer that approximates this polynomial, using the given scale_log2. (Smaller scale_log2 values give more accurate approximations.)

EXAMPLES:

```
sage: from sage.rings.polynomial.real_roots import *
sage: x = polygen(AA)
sage: p = (x - 1) * (x - sqrt(AA(2))) * (x - 2)
sage: bpf = bernstein_polynomial_factory_ar(p, False)
sage: print(bpf.bernstein_polynomial(0))
degree 3 IBP with 2-bit coefficients
sage: bpf.bernstein_polynomial(-20)
<IBP: ((-2965821, 2181961, -1542880, 1048576) + [0 .. 1)) * 2^-20>
sage: bpf = bernstein_polynomial_factory_ar(p, True)
sage: bpf.bernstein_polynomial(-20)
<IBP: ((-2965821, -2181962, -1542880, -1048576) + [0 .. 1)) * 2^-20>
sage: p = x^2 - 1
sage: bpf = bernstein_polynomial_factory_ar(p, False)
sage: bpf.bernstein_polynomial(-10)
<IBP: ((-1024, 0, 1024) + [0 .. 1)) * 2^-10>
```
**coeffs_bitsize()**

Computes the approximate log2 of the maximum of the absolute values of the coefficients.

**EXAMPLES:**

```python
sage: from sage.rings.polynomial.real_roots import *
sage: bernstein_polynomial_factory_intlist([1, 2, 3, -60000]).coeffs_bitsize()
16
```

**class sage.rings.polynomial.real_roots.bernstein_polynomial_factory_ratlist(coeffs)**

Bases: `bernstein_polynomial_factory`

This class holds an exact Bernstein polynomial (represented as a list of rational coefficients), and returns arbitrarily-precise interval approximations of this polynomial on demand.

**bernstein_polynomial(scale_log2)**

Compute an interval_bernstein_polynomial_integer that approximates this polynomial, using the given scale_log2. (Smaller scale_log2 values give more accurate approximations.)

**EXAMPLES:**

```python
sage: from sage.rings.polynomial.real_roots import *
sage: bpf = bernstein_polynomial_factory_ratlist([1/3, -22/7, 193/71, -140/99])
sage: print(bpf.bernstein_polynomial(0))
degree 3 IBP with 3-bit coefficients
sage: bpf.bernstein_polynomial(20)
<IBP: ((0, -1, 0, -1) + [0 .. 1)) * 2^20; lsign 1>
sage: bpf.bernstein_polynomial(0)
<IBP: (0, -4, 2, -2) + [0 .. 1); lsign 1>
sage: bpf.bernstein_polynomial(-20)
<IBP: ((349525, -3295525, 2850354, -1482835) + [0 .. 1)) * 2^-20>
```

**coeffs_bitsize()**

Computes the approximate log2 of the maximum of the absolute values of the coefficients.

**EXAMPLES:**

```python
sage: from sage.rings.polynomial.real_roots import *
sage: bernstein_polynomial_factory_ratlist([1, 2, 3, -60000]).coeffs_bitsize()
15
sage: bernstein_polynomial_factory_ratlist([65535/65536]).coeffs_bitsize()
-1
sage: bernstein_polynomial_factory_ratlist([65536/65535]).coeffs_bitsize()
1
```

**sage.rings.polynomial.real_roots.bernstein_up(d1, d2, s=\texttt{None})**

Given polynomial degrees \( d1 \) and \( d2 \), where \( d1 < d2 \), compute a matrix \( \mathbf{bu} \).

If you have a Bernstein polynomial of formal degree \( d1 \), and multiply its coefficient vector by \( \mathbf{bu} \), then the result is the coefficient vector of the same polynomial represented as a Bernstein polynomial of formal degree \( d2 \).

If \( s \) is not None, then it represents a number of samples; then the product only gives \( s \) of the coefficients of the new Bernstein polynomial, selected according to subsample_vec.

**EXAMPLES:**
sage: from sage.rings.polynomial.real_roots import *
sage: bernstein_down(3, 7, 4)
[ 12/5 -4 3 -2/5]
[ -13/15 16/3 -4 8/15]
[ 8/15 -4 16/3 -13/15]
[ -2/5 3 -4 12/5]

sage.rings.polynomial.real_roots.bitsize_doctest(n)

sage.rings.polynomial.real_roots.cl_maximum_root(cl)

Given a polynomial represented by a list of its coefficients (as RealIntervalFieldElements), compute an upper bound on its largest real root.

Uses two algorithms of Akritas, Strzeboński, and Vigklas, and picks the better result.

EXAMPLES:

sage: from sage.rings.polynomial.real_roots import *
sage: cl_maximum_root([RIF(-1), RIF(0), RIF(1)])
1.00000000000000

sage.rings.polynomial.real_roots.cl_maximum_root_first_lambda(cl)

Given a polynomial represented by a list of its coefficients (as RealIntervalFieldElements), compute an upper bound on its largest real root.


EXAMPLES:

sage: from sage.rings.polynomial.real_roots import *
sage: cl_maximum_root_first_lambda([RIF(-1), RIF(0), RIF(1)])
1.00000000000000

sage.rings.polynomial.real_roots.cl_maximum_root_local_max(cl)

Given a polynomial represented by a list of its coefficients (as RealIntervalFieldElements), compute an upper bound on its largest real root.


EXAMPLES:

sage: from sage.rings.polynomial.real_roots import *
sage: cl_maximum_root_local_max([RIF(-1), RIF(0), RIF(1)])
1.41421356237310

class sage.rings.polynomial.real_roots.context

Bases: object

A simple context class, which is passed through parts of the real root isolation algorithm to avoid global variables.

Holds logging information, a random number generator, and the target machine wordsize.

get_be_log()

get_dc_log()
sage.rings.polynomial.real_roots.de_casteljau_doublevec(c, x)

Given a polynomial in Bernstein form with floating-point coefficients over the region [0 .. 1], and a split point x, use de Casteljau's algorithm to give polynomials in Bernstein form over [0 .. x] and [x .. 1].

This function will work for an arbitrary rational split point x, as long as 0 < x < 1; but it has a specialized code path for x==1/2.

INPUT:
- c – vector of coefficients of polynomial in Bernstein form
- x – rational splitting point; 0 < x < 1

OUTPUT:
- c1 – coefficients of polynomial over range [0 .. x]
- c2 – coefficients of polynomial over range [x .. 1]
- err_inc – number of half-ulps by which error intervals widened

EXAMPLES:

```
sage: from sage.rings.polynomial.real_roots import *
sage: c = vector(RDF, [0.7, 0, 0, 0, 0, 0])
sage: de_casteljau_doublevec(c, 1/2)
((0.7, 0.35, 0.175, 0.0875, 0.04375, 0.021875), (0.021875, 0.0, 0.0, 0.0, 0.0, 0.0), 5)
sage: de_casteljau_doublevec(c, 1/3) # rel tol
((0.7, 0.4666666666666667, 0.3111111111111111, 0.20740740740740746, 0.13827160493827165, 0.09218106995884777), (0.09218106995884777, 0.0, 0.0, 0.0, 0.0, 0.0), 15)
sage: de_casteljau_doublevec(c, 7/22) # rel tol
((0.7, 0.4772727272727273, 0.3254132231404959, 0.22187265214124724, 0.15127680827812312, 0.10314327837144759), (0.10314327837144759, 0.0, 0.0, 0.0, 0.0, 0.0), 15)
```

sage.rings.polynomial.real_roots.de_casteljau_intvec(c, c_bitsize, x, use_ints)

Given a polynomial in Bernstein form with integer coefficients over the region [0 .. 1], and a split point x, use de Casteljau's algorithm to give polynomials in Bernstein form over [0 .. x] and [x .. 1].

This function will work for an arbitrary rational split point x, as long as 0 < x < 1; but it has specialized code paths that make some values of x faster than others. If x == a/(a + b), there are special efficient cases for a==1, b==1, a+b fits in a machine word, a+b is a power of 2, a fits in a machine word, b fits in a machine word. The most efficient case is x==1/2.

Given split points x == a/(a + b) and y == c/(c + d), where min(a, b) and min(c, d) fit in the same number of machine words and a+b and c+d are both powers of two, then x and y should be equally fast split points.

If use_ints is nonzero, then instead of checking whether numerators and denominators fit in machine words, we check whether they fit in ints (32 bits, even on 64-bit machines). This slows things down, but allows for identical results across machines.

INPUT:
- c – vector of coefficients of polynomial in Bernstein form
- c_bitsize – approximate size of coefficients in c (in bits)
- x – rational splitting point; 0 < x < 1

OUTPUT:
• `c1` – coefficients of polynomial over range `[0 .. x]`
• `c2` – coefficients of polynomial over range `[x .. 1]`
• `err_inc` – amount by which error intervals widened

**EXAMPLES:**

```python
sage: from sage.rings.polynomial.real_roots import *
sage: c = vector(ZZ, [1048576, 0, 0, 0, 0, 0])
sage: de_casteljau_intvec(c, 20, 1/2, 1)
((1048576, 524288, 262144, 131072, 65536, 32768), (32768, 0, 0, 0, 0, 0), 1)
sage: de_casteljau_intvec(c, 20, 1/3, 1)
((1048576, 699050, 466033, 310689, 207126, 138084), (138084, 0, 0, 0, 0, 0), 1)
sage: de_casteljau_intvec(c, 20, 7/22, 1)
((1048576, 714938, 487457, 332357, 226607, 154505), (154505, 0, 0, 0, 0, 0), 1)
```

sage.rings.polynomial.real_roots.**degree_reduction_next_size**(n)

Given n (a polynomial degree), returns either a smaller integer or None. This defines the sequence of degrees followed by our degree reduction implementation.

**EXAMPLES:**

```python
sage: from sage.rings.polynomial.real_roots import *
sage: degree_reduction_next_size(1000)
30
sage: degree_reduction_next_size(20)
15
sage: degree_reduction_next_size(3)
2
sage: degree_reduction_next_size(2) is None
True
```

sage.rings.polynomial.real_roots.**dprod_imatrow_vec**(m, v, k)

Computes the dot product of row k of the matrix m with the vector v (that is, compute one element of the product m*v).

If v has more elements than m has columns, then elements of v are selected using subsample_vec.

**EXAMPLES:**

```python
sage: from sage.rings.polynomial.real_roots import *
sage: m = matrix(3, range(9))
sage: dprod_imatrow_vec(m, vector(ZZ, [1, 0, 0, 0]), 1)
0
sage: dprod_imatrow_vec(m, vector(ZZ, [0, 1, 0, 0]), 1)
3
sage: dprod_imatrow_vec(m, vector(ZZ, [0, 0, 1, 0]), 1)
4
sage: dprod_imatrow_vec(m, vector(ZZ, [0, 0, 0, 1]), 1)
5
sage: dprod_imatrow_vec(m, vector(ZZ, [1, 0, 0]), 1)
3
sage: dprod_imatrow_vec(m, vector(ZZ, [0, 1, 0]), 1)
4
sage: dprod_imatrow_vec(m, vector(ZZ, [0, 0, 1]), 1)
(continues on next page)
```
sage.rings.polynomial.real_roots.get_realfield_rndu(n)

A simple cache for RealField fields (with rounding set to round-to-positive-infinity).

EXAMPLES:

sage: from sage.rings.polynomial.real_roots import *
sage: get_realfield_rndu(20)
Real Field with 20 bits of precision and rounding RNDU
sage: get_realfield_rndu(53)
Real Field with 53 bits of precision and rounding RNDU
sage: get_realfield_rndu(20)
Real Field with 20 bits of precision and rounding RNDU

class sage.rings.polynomial.real_roots.interval_bernstein_polynomial

Bases: object

An interval_bernstein_polynomial is an approximation to an exact polynomial. This approximation is in the form of a Bernstein polynomial (a polynomial given as coefficients over a Bernstein basis) with interval coefficients.

The Bernstein basis of degree n over the region [a .. b] is the set of polynomials
\[
\binom{n}{k} (x - a)^k (b - x)^{n-k} / (b - a)^n
\]
for 0 \leq k \leq n.

A degree-n interval Bernstein polynomial P with its region [a .. b] can represent an exact polynomial p in two different ways: it can “contain” the polynomial or it can “bound” the polynomial.

We say that P contains p if, when p is represented as a degree-n Bernstein polynomial over [a .. b], its coefficients are contained in the corresponding interval coefficients of P. For instance, [0.9 .. 1.1]*x^2 (which is a degree-2 interval Bernstein polynomial over [0 .. 1]) contains x^2.

We say that P bounds p if, for all a <= x <= b, there exists a polynomial p' contained in P such that p(x) == p'(x). For instance, [0 .. 1]*x is a degree-1 interval Bernstein polynomial which bounds x^2 over [0 .. 1].

If P contains p, then P bounds p; but the converse is not necessarily true. In particular, if n < m, it is possible for a degree-n interval Bernstein polynomial to bound a degree-m polynomial; but it cannot contain the polynomial.

In the case where P bounds p, we maintain extra information, the “slope error”. We say that P (over [a .. b]) bounds p with a slope error of E (where E is an interval) if there is a polynomial p' contained in P such that the derivative of (p - p') is bounded by E in the range [a .. b]. If P bounds p with a slope error of 0 then P contains p.

(Note that “contains” and “bounds” are not standard terminology; I just made them up.)

Interval Bernstein polynomials are useful in finding real roots because of the following properties:

• Given an exact real polynomial p, we can compute an interval Bernstein polynomial over an arbitrary region containing p.

• Given an interval Bernstein polynomial P over [a .. c], where a < b < c, we can compute interval Bernstein polynomials P1 over [a .. b] and P2 over [b .. c], where P1 and P2 contain (or bound) all polynomials that P contains (or bounds).

• Given a degree-n interval Bernstein polynomial P over [a .. b], and m < n, we can compute a degree-m interval Bernstein polynomial P' over [a .. b] that bounds all polynomials that P bounds.
• It is sometimes possible to prove that no polynomial bounded by \( P \) over \([a .. b]\) has any roots in \([a .. b]\).
  (Roughly, this is possible when no polynomial contained by \( P \) has any complex roots near the line segment \([a .. b]\), where “near” is defined relative to the length \( b-a \).)

• It is sometimes possible to prove that every polynomial bounded by \( P \) over \([a .. b]\) with slope error \( E \) has exactly one root in \([a .. b]\). (Roughly, this is possible when every polynomial contained by \( P \) over \([a .. b]\) has exactly one root in \([a .. b]\), there are no other complex roots near the line segment \([a .. b]\), and every polynomial contained in \( P \) has a derivative which is bounded away from zero over \([a .. b]\) by an amount which is large relative to \( E \).)

• Starting from a sufficiently precise interval Bernstein polynomial, it is always possible to split it into polynomials which provably have 0 or 1 roots (as long as your original polynomial has no multiple real roots).

So a rough outline of a family of algorithms would be:

• Given a polynomial \( p \), compute a region \([a .. b]\) in which any real roots must lie.

• Compute an interval Bernstein polynomial \( P \) containing \( p \) over \([a .. b]\).

• Keep splitting \( P \) until you have isolated all the roots. Optionally, reduce the degree or the precision of the interval Bernstein polynomials at intermediate stages (to reduce computation time). If this seems not to be working, go back and try again with higher precision.

Obviously, there are many details to be worked out to turn this into a full algorithm, like:

• What initial precision is selected for computing \( P \)?

• How do you decide when to reduce the degree of intermediate polynomials?

• How do you decide when to reduce the precision of intermediate polynomials?

• How do you decide where to split the interval Bernstein polynomial regions?

• How do you decide when to give up and start over with higher precision?

Each set of answers to these questions gives a different algorithm (potentially with very different performance characteristics), but all of them can use this \( \text{interval\_bernstein\_polynomial} \) class as their basic building block.

To save computation time, all coefficients in an \( \text{interval\_bernstein\_polynomial} \) share the same interval width. (There is one exception: when creating an \( \text{interval\_bernstein\_polynomial} \), the first and last coefficients can be marked as “known positive” or “known negative”. This has some of the same effect as having a (potentially) smaller interval width for these two coefficients, although it does not affect de Casteljau splitting.) To allow for widely varying coefficient magnitudes, all coefficients in an \( \text{interval\_bernstein\_polynomial} \) are scaled by \( 2^n \) (where \( n \) may be positive, negative, or zero).

There are two representations for \( \text{interval\_bernstein\_polynomials} \), integer and floating-point. These are the two subclasses of this class; \( \text{interval\_bernstein\_polynomial} \) itself is an abstract class.

\( \text{interval\_bernstein\_polynomial} \) and its subclasses are not expected to be used outside this file.

\( \text{region()} \)

\( \text{region\_width()} \)

\( \text{try\_rand\_split}(\text{ctx, logging\_note}) \)
  Compute a random split point \( r \) (using the random number generator embedded in \( \text{ctx} \)). We require \( 1/4 <= r < 3/4 \) (to ensure that recursive algorithms make progress).

  Then, try doing a de Casteljau split of this polynomial at \( r \), resulting in polynomials \( p1 \) and \( p2 \). If we see that the sign of this polynomial is determined at \( r \), then return \( (p1, p2, r) \); otherwise, return None.

EXAMPLES:
try_split(ctx, logging_note)

Try doing a de Casteljau split of this polynomial at 1/2, resulting in polynomials p1 and p2. If we see that
the sign of this polynomial is determined at 1/2, then return (p1, p2, 1/2); otherwise, return None.

EXAMPLES:

sage: from sage.rings.polynomial.real_roots import *
sage: bp = mk_ibpi([50, 20, -90, -70, 200], error=5)
sage: bp1, bp2, _ = bp.try_split(mk_context(), None)
sage: bp1
<IBP: (50, 35, 0, -29, -31) + [0 .. 6) over [0 .. 1/2]>
sage: bp2
<IBP: (-31, -33, -8, 65, 200) + [0 .. 6) over [1/2 .. 1]>
sage: bp = mk_ibpf([0.5, 0.2, -0.9, -0.7, 0.99], neg_err=-0.1, pos_err=0.01)
sage: bp1, bp2, _ = bp.try_split(mk_context(), None)
sage: bp1
<IBP: (0.5, 0.35, 0.0, -0.2875, -0.369375) + [-0.10000000000000023 .. 0.010000000000000226] over [0 .. 1/2]>
sage: bp2
<IBP: (-0.369375, -0.45125, -0.3275, 0.14500000000000002, 0.99) + [-0.10000000000000023 .. 0.010000000000000226] over [1/2 .. 1]>

variations()

Consider a polynomial (written in either the normal power basis or the Bernstein basis). Take its list of
coefficients, omitting zeroes. Count the number of positions in the list where the sign of one coefficient is
opposite the sign of the next coefficient.

This count is the number of sign variations of the polynomial. According to Descartes’ rule of signs, the
number of real roots of the polynomial (counted with multiplicity) in a certain interval is always less than
or equal to the number of sign variations, and the difference is always even. (If the polynomial is written
in the power basis, the region is the positive reals; if the polynomial is written in the Bernstein basis over a
particular region, then we count roots in that region.)
In particular, a polynomial with no sign variations has no real roots in the region, and a polynomial with one sign variation has one real root in the region.

In an interval Bernstein polynomial, we do not necessarily know the signs of the coefficients (if some of the coefficient intervals contain zero), so the polynomials contained by this interval polynomial may not all have the same number of sign variations. However, we can compute a range of possible numbers of sign variations.

This function returns the range, as a 2-tuple of integers.

class sage.rings.polynomial.real_roots.interval_bernstein_polynomial_float

Bases: interval_bernstein_polynomial

This is the subclass of interval_bernstein_polynomial where polynomial coefficients are represented using floating-point numbers.

In the floating-point representation, each coefficient is represented as an IEEE double-precision float A, and the (shared) lower and upper interval widths E1 and E2. These represent the coefficients \( (A+E1) \cdot 2^n \leq c \leq (A+E2) \cdot 2^n \).

Note that we always have \( E1 \leq 0 \leq E2 \). Also, each floating-point coefficient has absolute value less than one.

(Note that mk_ibpf is a simple helper function for creating elements of interval_bernstein_polynomial_float in doctests.)

EXAMPLES:

```
sage: from sage.rings.polynomial.real_roots import *
sage: bp = mk_ibpf([0.1, 0.2, 0.3], pos_err=0.5); print(bp)
degree 2 IBP with floating-point coefficients
sage: bp
<IBP: (0.1, 0.2, 0.3) + [0.0 .. 0.5]>
sage: bp.variations()
(0, 0)
sage: bp = mk_ibpf([-0.3, -0.1, 0.1, -0.1, -0.3, -0.1], lower=1, upper=5/4, usign=1, pos_err=0.2, scale_log2=-3, level=2, slope_err=RIF(pi)); print(bp)
degree 5 IBP with floating-point coefficients
sage: bp
<IBP: ((-0.3, -0.1, 0.1, -0.1, -0.3, -0.1) + [0.0 .. 0.2]) * 2^-3 over [1 .. 5/4]; usign 1; level 2; slope_err 3.141592653589794?>
sage: bp.variations()
(3, 3)
```

as_float()

decasteljau(ctx, mid, msign=0)

Uses de Casteljau’s algorithm to compute the representation of this polynomial in a Bernstein basis over new regions.

INPUT:

- **mid** – where to split the Bernstein basis region; \( 0 < \text{mid} < 1 \)
- **msign** – default 0 (unknown); the sign of this polynomial at \( \text{mid} \)

OUTPUT:

- **bp1, bp2** – the new interval Bernstein polynomials
- **ok** – a boolean; True if the sign of the original polynomial at \( \text{mid} \) is known
EXAMPLES:

```python
sage: from sage.rings.polynomial.real_roots import *
sage: ctx = mk_context()
sage: bp = mk_ibpf([0.5, 0.2, -0.9, -0.7, 0.99], neg_err=-0.1, pos_err=0.01)
sage: bp1, bp2, ok = bp.de_casteljau(ctx, 1/2)
sage: bp1
<IBP: (0.5, 0.35, 0.0, -0.2875, -0.369375) + [-0.10000000000000023 .. 0.010000000000000226] over [0 .. 1/2]>
sage: bp2
<IBP: (-0.369375, -0.45125, -0.3275, 0.14500000000000002, 0.99) + [-0.10000000000000023 .. 0.010000000000000226] over [1/2 .. 1]>
sage: bp1, bp2, ok = bp.de_casteljau(ctx, 2/3)
sage: bp1
# rel tol 2e-16
<IBP: (0.5, 0.30000000000000004, -0.2555555555555555, -0.5444444444444444, -0.32172839506172846) + [-0.10000000000000069 .. 0.010000000000000677] over [0 .. 2/3]>
sage: bp2
# rel tol 3e-15
<IBP: (-0.32172839506172846, -0.21037037037037046, 0.028888888888888897, 0.04266666666666666, 0.99) + [-0.10000000000000069 .. 0.010000000000000677] over [2/3 .. 1]>
sage: bp1, bp2, ok = bp.de_casteljau(ctx, 7/39)
sage: bp1
# rel tol
<IBP: (0.5, 0.4461538461538461, 0.36653517422748183, 0.27328680523946786, 0.39666666666666666) + [-0.10000000000000069 .. 0.010000000000000677] over [0 .. 7/39]>
sage: bp2
# rel tol
<IBP: (0.39666666666666666, -0.265568003047927313, -0.7802038132807364, -0.3606666666666666, 0.99) + [-0.10000000000000069 .. 0.010000000000000677] over [7/39 .. 1]>
```

**get_msb_bit()**

Returns an approximation of the log2 of the maximum of the absolute values of the coefficients, as an integer.

**slope_range()**

Compute a bound on the derivative of this polynomial, over its region.

EXAMPLES:

```python
sage: from sage.rings.polynomial.real_roots import *
sage: bp = mk_ibpf([0.5, 0.2, -0.9, -0.7, 0.99], neg_err=-0.1, pos_err=0.01)
sage: bp.slope_range().str(style='brackets')
'[-4.8400000000000017 .. 7.2000000000000011]'
```

**class** `sage.rings.polynomial.real_roots.interval_bernstein_polynomial_integer`

Bases: `interval_bernstein_polynomial`

This is the subclass of `interval_bernstein_polynomial` where polynomial coefficients are represented using integers.

In this integer representation, each coefficient is represented by a GMP arbitrary-precision integer A, and a (shared) interval width E (which is a machine integer). These represent the coefficients A*2^n <= c < (A+E)*2^n.

(Note that `mk_ibpi` is a simple helper function for creating elements of `interval_bernstein_polynomial_integer` in doctests.)
EXAMPLES:

```sage
def from sage.rings.polynomial.real_roots import *

sage: bp = mk_ibpi([1, 2, 3], error=5)
degree 2 IBP with 2-bit coefficients
sage: print(bp)
<IBP: (1, 2, 3) + [0 .. 5)>

sage: bp.variations()
(0, 0)

sage: bp = mk_ibpi([-3, -1, 1, -1, -3, -1], lower=1, upper=5/4, usign=1, error=2,
    scale_log2=-3, level=2, slope_err=RIF(pi)); print(bp)
degree 5 IBP with 2-bit coefficients
sage: print(bp)
<IBP: ((-3, -1, 1, -1, -3, -1) + [0 .. 2)) * 2^-3 over [1 .. 5/4); usign 1; level 2;
    slope_err 3.141592653589794?>

sage: bp.variations()
(3, 3)
```

**as_float()**

Compute an interval_bernstein_polynomial_float which contains (or bounds) all the polynomials this interval polynomial contains (or bounds).

EXAMPLES:

```sage
def from sage.rings.polynomial.real_roots import *

sage: bp = mk_ibpi([50, 20, -90, -70, 200], error=5)

sage: print(bp.as_float())
degree 4 IBP with floating-point coefficients
sage: print(bp.as_float())
<IBP: ((0.1953125, 0.078125, -0.3515625, -0.2734375, 0.78125) + [-1...
```

**de_casteljau(ctx, mid, msign=0)**

Uses de Casteljau’s algorithm to compute the representation of this polynomial in a Bernstein basis over new regions.

INPUT:

- mid – where to split the Bernstein basis region; 0 < mid < 1
- msign – default 0 (unknown); the sign of this polynomial at mid

OUTPUT:

- bp1, bp2 – the new interval Bernstein polynomials
- ok – a boolean; True if the sign of the original polynomial at mid is known

EXAMPLES:

```sage
def from sage.rings.polynomial.real_roots import *

sage: ctx = mk_context()
sage: bp1, bp2, ok = bp.de_casteljau(ctx, 1/2)
sage: bp1
<IBP: (50, 35, 0, -29, -31) + [0 .. 6) over [0 .. 1/2]>
sage: bp2
```
\[ \text{down\_degree}(ctx, \text{max\_err}, \text{exp\_err\_shift}) \]

Compute an interval Bernstein polynomial integer which bounds all the polynomials this interval polynomial bounds, but is of lesser degree.

During the computation, we find an “expected error” expected_err, which is the error inherent in our approach (this depends on the degrees involved, and is proportional to the error of the current polynomial).

We require that the error of the new interval polynomial be bounded both by max_err, and by expected_err \(< \text{exp\_err\_shift}. \) If we find such a polynomial p, then we return a pair of p and some debugging/logging information. Otherwise, we return the pair (None, None).

If the resulting polynomial would have error more than \(2^{17}\), then it is downscaled before returning.

EXAMPLES:

```
sage: from sage.rings.polynomial.real_roots import *
sage: bp = mk_ibpi([0, 100, 400, 903], error=2)
sage: ctx = mk_context()
sage: bp
<IBP: (0, 100, 400, 903) + [0 .. 2)>
sage: dbp, _ = bp.down_degree(ctx, 10, 32)
sage: dbp
<IBP: (-1, 148, 901) + [0 .. 4); level 1; slope_err 0.7e2>
```

down\_degree\_iter(ctx, max\_scale)

Compute a degree-reduced version of this interval polynomial, by iterating down\_degree.

We stop when degree reduction would give a polynomial which is too inaccurate, meaning that either we think the current polynomial may have more roots in its region than the degree of the reduced polynomial, or that the least significant accurate bit in the result (on the absolute scale) would be larger than \(1 \ll \text{max\_scale}\).

EXAMPLES:

```
sage: from sage.rings.polynomial.real_roots import *
sage: bp = mk_ibpi([0, 100, 400, 903, 1600, 2500], error=2)
sage: ctx = mk_context()
sage: bp
<IBP: (0, 100, 400, 903, 1600, 2500) + [0 .. 2)>
sage: rbp = bp.down_degree_iter(ctx, 6)
sage: rbp
<IBP: (-4, 249, 2497) + [0 .. 9); level 2; slope_err 0.7e3>
```
**downscale**(bits)
Compute an interval_bernstein_polynomial_integer which contains (or bounds) all the polynomials this
interval polynomial contains (or bounds), but uses “bits” fewer bits.

EXAMPLES:
```
sage: from sage.rings.polynomial.real_roots import *
sage: bp = mk_ibpi([0, 100, 400, 903], error=2)
sage: bp.downscale(5)
<IBP: ((0, 3, 12, 28) + [0 .. 1)) * 2^5>
```

**get_msb_bit()**
Returns an approximation of the log2 of the maximum of the absolute values of the coefficients, as an
integer.

**slope_range()**
Compute a bound on the derivative of this polynomial, over its region.

EXAMPLES:
```
sage: from sage.rings.polynomial.real_roots import *
sage: bp = mk_ibpi([0, 100, 400, 903], error=2)
sage: bp.slope_range().str(style='brackets')
'[(294.0000000000000 .. 1515.0000000000000]
```

sage.rings.polynomial.real_roots.intvec_to_doublevec(b, err)
Given a vector of integers A = [a1, ..., an], and an integer error bound E, returns a vector of floating-point
numbers B = [b1, ..., bn], lower and upper error bounds F1 and F2, and a scaling factor d, such that

\[(bk + F1) \times 2^d \leq ak\]

and

\[ak + E \leq (bk + F2) \times 2^d\]

If bj is the element of B with largest absolute value, then 0.5 <= abs(bj) < 1.0.

EXAMPLES:
```
sage: from sage.rings.polynomial.real_roots import *
sage: intvec_to_doublevec(vector(ZZ, [1, 2, 3, 4, 5]), 3)
(0.125, 0.25, 0.375, 0.5, 0.625), -1.1275702593849246e-16, 0.37500000000000017, 3)
```

**class** sage.rings.polynomial.real_roots.island
Bases: object

This implements the island portion of my ocean-island root isolation algorithm. See the documentation for class
ocean, for more information on the overall algorithm.

Island root refinement starts with a Bernstein polynomial whose region is the whole island (or perhaps slightly
more than the island in certain cases). There are two subalgorithms; one when looking at a Bernstein polynomial
covering a whole island (so we know that there are gaps on the left and right), and one when looking at a Bernstein
polynomial covering the left segment of an island (so we know that there is a gap on the left, but the right is in
the middle of an island). An important invariant of the left-segment subalgorithm over the region [l .. r] is that
it always finds a gap [r0 .. r] ending at its right endpoint.

Ignoring degree reduction, downscaling (precision reduction), and failures to split, the algorithm is roughly:

Whole island:
1. If the island definitely has exactly one root, then return.
2. Split the island in (approximately) half.
3. If both halves definitely have no roots, then remove this island from its doubly-linked list (merging its left and right gaps) and return.
4. If either half definitely has no roots, then discard that half and call the whole-island algorithm with the other half, then return.
5. If both halves may have roots, then call the left-segment algorithm on the left half.
6. We now know that there is a gap immediately to the left of the right half, so call the whole-island algorithm on the right half, then return.

Left segment:
1. Split the left segment in (approximately) half.
2. If both halves definitely have no roots, then extend the left gap over the segment and return.
3. If the left half definitely has no roots, then extend the left gap over this half and call the left-segment algorithm on the right half, then return.
4. If the right half definitely has no roots, then split the island in two, creating a new gap. Call the whole-island algorithm on the left half, then return.
5. Both halves may have roots. Call the left-segment algorithm on the left half.
6. We now know that there is a gap immediately to the left of the right half, so call the left-segment algorithm on the right half, then return.

Degree reduction complicates this picture only slightly. Basically, we use heuristics to decide when degree reduction might be likely to succeed and be helpful; whenever this is the case, we attempt degree reduction.

Precision reduction and split failure add more complications. The algorithm maintains a stack of different-precision representations of the interval Bernstein polynomial. The base of the stack is at the highest (currently known) precision; each stack entry has approximately half the precision of the entry below it. When we do a split, we pop off the top of the stack, split it, then push whichever half we’re interested in back on the stack (so the different Bernstein polynomials may be over different regions). When we push a polynomial onto the stack, we may heuristically decide to push further lower-precision versions of the same polynomial onto the stack.

In the algorithm above, whenever we say “split in (approximately) half”, we attempt to split the top-of-stack polynomial using try_split() and try_rand_split(). However, these will fail if the sign of the polynomial at the chosen split point is unknown (if the polynomial is not known to high enough precision, or if the chosen split point actually happens to be a root of the polynomial). If this fails, then we discard the top-of-stack polynomial, and try again with the next polynomial down (which has approximately twice the precision). This next polynomial may not be over the same region; if not, we split it using de Casteljau’s algorithm to get a polynomial over (approximately) the same region first.

If we run out of higher-precision polynomials (if we empty out the entire stack), then we give up on root refinement for this island. The ocean class will notice this, provide the island with a higher-precision polynomial, and restart root refinement. Basically the only information kept in that case is the lower and upper bounds on the island. Since these are updated whenever we discover a “half” (of an island or a segment) that definitely contains no roots, we never need to re-examine these gaps. (We could keep more information. For example, we could keep a record of split points that succeeded and failed. However, a split point that failed at lower precision is likely to succeed at higher precision, so it’s not worth avoiding. It could be useful to select split points that are known to succeed, but starting from a new Bernstein polynomial over a slightly different region, hitting such split points would require de Casteljau splits with non-power-of-two denominators, which are much much slower.)
bp_done(bp)
Examine the given Bernstein polynomial to see if it is known to have exactly one root in its region. (In
addition, we require that the polynomial region not include 0 or 1. This makes things work if the user gives
explicit bounds to real_roots(), where the lower or upper bound is a root of the polynomial. real_roots()
deals with this by explicitly detecting it, dividing out the appropriate linear polynomial, and adding the root
to the returned list of roots; but then if the island considers itself “done” with a region including 0 or 1, the
returned root regions can overlap with each other.)

done(ctx)
Check to see if the island is known to contain zero roots or is known to contain one root.

has_root()
Assuming that the island is done (has either 0 or 1 roots), reports whether the island has a root.

less_bits(ancestors, bp)
Heuristically pushes lower-precision polynomials on the polynomial stack. See the class documentation for
class island for more information.

more_bits(ctx, ancestors, bp, rightmost)
Find a Bernstein polynomial on the “ancestors” stack with more precision than bp; if it is over a different
region, then shrink its region to (approximately) match that of bp. (If this is rightmost – if bp covers the
whole island – then we only require that the new region cover the whole island fairly tightly; if this is not
rightmost, then the new region will have exactly the same right boundary as bp, although the left boundary
may vary slightly.)

refine(ctx)
Attempts to shrink and/or split this island into sub-island that each definitely contain exactly one root.

refine_recurse(ctx, bp, ancestors, history, rightmost)
This implements the root isolation algorithm described in the class documentation for class island. This is
the implementation of both the whole-island and the left-segment algorithms; if the flag rightmost is True,
then it is the whole-island algorithm, otherwise the left-segment algorithm.

The precision-reduction stack is (ancestors + [bp]); that is, the top-of-stack is maintained separately.

reset_root_width(target_width)
Modify the criteria for this island to require that it is not “done” until its width is less than or equal to
target_width.

shrink_bp(ctx)
If the island’s Bernstein polynomial covers a region much larger than the island itself (in particular, if either
the island’s left gap or right gap are totally contained in the polynomial’s region) then shrink the polynomial
down to cover the island more tightly.

class sage.rings.polynomial.real_roots.linear_map(lower, upper)
Bases: object
A simple class to map linearly between original coordinates (ranging from [lower .. upper]) and ocean coordinates
(ranging from [0 .. 1]).

from_ocean(region)
to_ocean(region)

sage.rings.polynomial.real_roots.max_abs_doublevec(c)
Given a floating-point vector, return the maximum of the absolute values of its elements.

EXAMPLES:
Given a polynomial with real coefficients, computes an upper bound on its largest real root.

This is using the first-lambda algorithm from “Implementations of a New Theorem for Computing Bounds for Positive Roots of Polynomials”, by Akritas, Strzeboński, and Vigklas.

EXAMPLES:

```python
sage: from sage.rings.polynomial.real_roots import *
sage: x = polygen(ZZ)
sage: maximum_root_first_lambda((x-1)*(x-2)*(x-3))
6.00000000000001
sage: maximum_root_first_lambda((x+1)*(x+2)*(x+3))
0.000000000000000
sage: maximum_root_first_lambda(x^2 - 1)
1.41421356237310
```

sage.rings.polynomial.real_roots.maximum_root_local_max(p)

Given a polynomial with real coefficients, computes an upper bound on its largest real root, using the local-max algorithm from “Implementations of a New Theorem for Computing Bounds for Positive Roots of Polynomials”, by Akritas, Strzeboński, and Vigklas.

EXAMPLES:

```python
sage: from sage.rings.polynomial.real_roots import *
sage: x = polygen(ZZ)
sage: maximum_root_local_max((x-1)*(x-2)*(x-3))
12.00000000000001
sage: maximum_root_local_max((x+1)*(x+2)*(x+3))
0.000000000000000
sage: maximum_root_local_max(x^2 - 1)
1.41421356237310
```

sage.rings.polynomial.real_roots.min_max_delta_intvec(a, b)

Given two integer vectors a and b (of equal, nonzero length), return a pair of the minimum and maximum values taken on by a[i] - b[i].

EXAMPLES:

```python
sage: from sage.rings.polynomial.real_roots import *
sage: a = vector(ZZ, [10, -30])
sage: b = vector(ZZ, [15, -60])
sage: min_max_delta_intvec(a, b)
(30, -5)
```

sage.rings.polynomial.real_roots.min_max_diff_doublevec(c)

Given a floating-point vector b = (b0, ..., bn), compute the minimum and maximum values of b_[j+1] - b_j.

EXAMPLES:
sage: from sage.rings.polynomial.real_roots import *
sage: min_max_diff_doublevec(vector(RDF, [1, 7, -2]))
(-9.0, 6.0)

sage.rings.polynomial.real_roots.min_max_diff_intvec(b)
Given an integer vector b = (b0, ..., bn), compute the minimum and maximum values of b_{j+1} - b_j.

EXAMPLES:

sage: from sage.rings.polynomial.real_roots import *
sage: min_max_diff_intvec(vector(ZZ, [1, 7, -2]))
(-9, 6)

sage.rings.polynomial.real_roots.mk_context(do_logging=False, seed=0, wordsize=32)
A simple wrapper for creating context objects with coercions, defaults, etc.
For use in doctests.

EXAMPLES:

sage: from sage.rings.polynomial.real_roots import *
sage: mk_context(do_logging=True, seed=3, wordsize=64)
root isolation context: seed=3; do_logging=True; wordsize=64

sage.rings.polynomial.real_roots.mk_ibpf(coeffs, lower=0, upper=1, lsign=0, usign=0, neg_err=0, pos_err=0, scale_log2=0, level=0, slope_err=None)
A simple wrapper for creating interval_bernstein_polynomial_float objects with coercions, defaults, etc.
For use in doctests.

EXAMPLES:

sage: from sage.rings.polynomial.real_roots import *
sage: print(mk_ibpf([0.5, 0.2, -0.9, -0.7, 0.99], pos_err=0.1, neg_err=-0.01))
degree 4 IBP with floating-point coefficients

sage.rings.polynomial.real_roots.mk_ibpi(coeffs, lower=0, upper=1, lsign=0, usign=0, error=1, scale_log2=0, level=0, slope_err=None)
A simple wrapper for creating interval_bernstein_polynomial_integer objects with coercions, defaults, etc.
For use in doctests.

EXAMPLES:

sage: from sage.rings.polynomial.real_roots import *
sage: print(mk_ibpi([50, 20, -90, -70, 200], error=5))
degree 4 IBP with 8-bit coefficients

class sage.rings.polynomial.real_roots.ocean
Bases: object

Given the tools we’ve defined so far, there are many possible root isolation algorithms that differ on where to select split points, what precision to work at when, and when to attempt degree reduction.

Here we implement one particular algorithm, which I call the ocean-island algorithm. We start with an interval Bernstein polynomial defined over the region [0 .. 1]. This region is the “ocean”. Using de Casteljau’s algorithm and Descartes’ rule of signs, we divide this region into subregions which may contain roots, and subregions
which are guaranteed not to contain roots. Subregions which may contain roots are “islands”; subregions known
not to contain roots are “gaps”.

All the real root isolation work happens in class island. See the documentation of that class for more information.
An island can be told to refine itself until it contains only a single root. This may not succeed, if the island’s
interval Bernstein polynomial does not have enough precision. The ocean basically loops, refining each of its
islands, then increasing the precision of islands which did not succeed in isolating a single root; until all islands
are done.

Increasing the precision of unsuccessful islands is done in a single pass using split_for_target(); this means it is
possible to share work among multiple islands.

**all_done()**

Returns true iff all islands are known to contain exactly one root.

**EXAMPLES:**

```python
sage: from sage.rings.polynomial.real_roots import *
sage: oc = ocean(mk_context(), bernstein_polynomial_factory_ratlist([1/3, -22/7,
₁₉₃/₇₁, -₁₄₀/₉₉]), lmap)
sage: oc.all_done()
False
sage: oc.find_roots()
sage: oc.all_done()
True
```

**approx_bp(scale_log2)**

Returns an approximation to our Bernstein polynomial with the given scale_log2.

**EXAMPLES:**

```python
sage: from sage.rings.polynomial.real_roots import *
sage: oc = ocean(mk_context(), bernstein_polynomial_factory_ratlist([1/3, -22/7,
₁₉₃/₇₁, -₁₄₀/₉₉]), lmap)
sage: oc.approx_bp(0)
<IBP: (0, -4, 2, -2) + [0 .. 1); lsign 1>
sage: oc.approx_bp(-20)
<IBP: ((349525, -3295525, 2850354, -1482835) + [0 .. 1)) * 2^-20>
```

**find_roots()**

Isolate all roots in this ocean.

**EXAMPLES:**

```python
sage: from sage.rings.polynomial.real_roots import *
sage: oc = ocean(mk_context(), bernstein_polynomial_factory_ratlist([1/3, -22/7,
₁₉₃/₇₁, -₁₄₀/₉₉]), lmap)
sage: oc
ocean with precision 120 and 1 island(s)
sage: oc.find_roots()
sage: oc
ocean with precision 120 and 3 island(s)
sage: oc = ocean(mk_context(), bernstein_polynomial_factory_ratlist([1, 0,
₁₁₁/₂, 0, ₁₁₁₀₈₈₈₉₉₉₄, 0, 0, 0, 0, -1]), lmap)
sage: oc.find_roots()
```
increase_precision()

Increase the precision of the interval Bernstein polynomial held by any islands which are not done. (In normal use, calls to this function are separated by calls to self.refine_all().)

EXAMPLES:

```
sage: oc = ocean(mk_context(), bernstein_polynomial_factory_ratlist([1/3, -22/7, 193/71, -140/99]), lmap)
sage: oc
ocean with precision 120 and 1 island(s)
```

refine_all()

Refine all islands which are not done (which are not known to contain exactly one root).

EXAMPLES:

```
sage: from sage.rings.polynomial.real_roots import *
sage: oc = ocean(mk_context(), bernstein_polynomial_factory_ratlist([-1, 1]), lmap)
sage: oc
ocean with precision 120 and 3 island(s)
```

reset_root_width(isle_num, target_width)

Require that the isle_num island have a width at most target_width.
If this is followed by a call to find_roots(), then the corresponding root will be refined to the specified width.

EXAMPLES:

```
sage: from sage.rings.polynomial.real_roots import *
sage: oc = ocean(mk_context(), bernstein_polynomial_factory_ratlist([-1, -1, 1]), lmap)
```

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roots()
      Return the locations of all islands in this ocean. (If run after find_roots(), this is the location of all roots in the ocean.)
      EXAMPLES:
      sage: from sage.rings.polynomial.real_roots import *
      sage: oc = ocean(mk_context(), bernstein_polynomial_factory_ratlist([1/3, -22/7, → 193/71, -140/99]), lmap)
      sage: oc.find_roots()
      sage: oc.roots()
      [(1/32, 1/16), (1/2, 5/8), (3/4, 7/8)]
      sage: oc = ocean(mk_context(), bernstein_polynomial_factory_ratlist([1, 0, - →1111/2, 0, 11108889/14, 0, 0, 0, 0, -1]), lmap)
      sage: oc.find_roots()
      sage: oc.roots()
      [(95761241267509487747625/9671406556917033397649408, 191522482605387719863145/ →19342813113834066795298816), (1496269390434373736805/151115727451828646838272, →374067366568272936175/37778931862957161709568), (31/32, 63/64)]

sage.rings.polynomial.real_roots.precompute_degree_reduction_cache(n)
      Compute and cache the matrices used for degree reduction, starting from degree n.
      EXAMPLES:
      sage: from sage.rings.polynomial.real_roots import *
      sage: precompute_degree_reduction_cache(5)
      sage: dr_cache[5]
      (\[121/126 8/63 -1/9 -2/63 11/126 -2/63\]
      \[-3/7 37/42 16/21 1/21 -3/7 1/6\]
      \[ 1/6 -3/7 1/21 16/21 37/42 -3/7\]
      3, \[-2/63 11/126 -2/63 -1/9 8/63 121/126\], 2,
      (\[121 16 -14 -4 11 -4\]
      \[-54 111 96 6 -54 21\]
      \[21 -54 6 96 111 -54\]
      \[-4 11 -4 -14 16 121\], 126)

sage.rings.polynomial.real_roots.pseudoinverse(m)

sage.rings.polynomial.real_roots.rational_root_bounds(p)
      Given a polynomial p with real coefficients, computes rationals a and b, such that for every real root r of p, a < r < b. We try to find rationals which bound the roots somewhat tightly, yet are simple (have small numerators and denominators).
      EXAMPLES:
      sage: from sage.rings.polynomial.real_roots import *
      sage: x = polygen(ZZ)
      sage: rational_root_bounds((x-1)*(x-2)*(x-3))
      (0, 7)
      sage: rational_root_bounds(x^2)
      (-1/2, 1/2)
sage: rational_root_bounds(x*(x+1))
(-3/2, 1/2)
sage: rational_root_bounds((x+2)*(x-3))
(-3, 6)
sage: rational_root_bounds(x^995 * (x^2 - 9999) - 1)
(-100, 1000/7)
sage: rational_root_bounds(x^995 * (x^2 - 9999) + 1)
(-142, 213/2)

If we can see that the polynomial has no real roots, return None.
sage: rational_root_bounds(x^2 + 7) is None
True

sage: rational_root_bounds(x^2 + 7)

sage.rings.polynomial.real_roots.real_roots(p, bounds=None, seed=None, skip_squarefree=False, do_logging=False, wordsize=32, retval='rational', strategy=None, max_diameter=None)

Compute the real roots of a given polynomial with exact coefficients (integer, rational, and algebraic real coefficients are supported). Returns a list of pairs of a root and its multiplicity.

The root itself can be returned in one of three different ways. If retval=='rational', then it is returned as a pair of rationals that define a region that includes exactly one root. If retval=='interval', then it is returned as a RealIntervalFieldElement that includes exactly one root. If retval=='algebraic_real', then it is returned as an AlgebraicReal. In the former two cases, all the intervals are disjoint.

An alternate high-level algorithm can be used by selecting strategy='warp'. This affects the conversion into Bernstein polynomial form, but still uses the same ocean-island algorithm as the default algorithm. The 'warp' algorithm performs the conversion into Bernstein polynomial form much more quickly, but performs the rest of the computation slightly slower in some benchmarks. The ‘warp’ algorithm is particularly likely to be helpful for low-degree polynomials.

Part of the algorithm is randomized; the seed parameter gives a seed for the random number generator. (By default, the same seed is used for every call, so that results are repeatable.) The random seed may affect the running time, or the exact intervals returned, but the results are correct regardless of the seed used.

The bounds parameter lets you find roots in some proper subinterval of the reals; it takes a pair of a rational lower and upper bound and only roots within this bound will be found. Currently, specifying bounds does not work if you select strategy='warp', or if you use a polynomial with algebraic real coefficients.

By default, the algorithm will do a squarefree decomposition to get squarefree polynomials. The skip_squarefree parameter lets you skip this step. (If this step is skipped, and the polynomial has a repeated real root, then the algorithm will loop forever! However, repeated non-real roots are not a problem.)

For integer and rational coefficients, the squarefree decomposition is very fast, but it may be slow for algebraic reals. (It may trigger exact computation, so it might be arbitrarily slow. The only other way that this algorithm might trigger exact computation on algebraic real coefficients is that it checks the constant term of the input polynomial for equality with zero.)

Part of the algorithm works (approximately) by splitting numbers into word-size pieces (that is, pieces that fit into a machine word). For portability, this defaults to always selecting pieces suitable for a 32-bit machine; the wordsize parameter lets you make choices suitable for a 64-bit machine instead. (This affects the running time, and the exact intervals returned, but the results are correct on both 32- and 64-bit machines even if the wordsize is chosen “wrong”.)

The precision of the results can be improved (at the expense of time, of course) by specifying the max_diameter parameter. If specified, this sets the maximum diameter() of the intervals returned. (Sage defines diameter() to be the relative diameter for intervals that do not contain 0, and the absolute diameter for intervals containing 0.) This directly affects the results in rational or interval return mode; in algebraic_real mode, it increases the
precision of the intervals passed to the algebraic number package, which may speed up some operations on that algebraic real.

Some logging can be enabled with do_logging=True. If logging is enabled, then the normal values are not returned; instead, a pair of the internal context object and a list of all the roots in their internal form is returned.

ALGORITHM: We convert the polynomial into the Bernstein basis, and then use de Casteljau’s algorithm and Descartes’ rule of signs (using interval arithmetic) to locate the roots.

EXAMPLES:

```python
sage: from sage.rings.polynomial.real_roots import *
sage: x = polygen(ZZ)
sage: real_roots(x^3 - x^2 - x - 1)
[((7/4, 19/8), 1)]
sage: real_roots((x-1)*(x-2)*(x-3)*(x-5)*(x-8)*(x-13)*(x-21)*(x-34))
[((11/16, 33/32), 1), ((11/8, 33/16), 1), ((11/4, 55/16), 1), ((77/16, 165/32), 1), ((11/2, 33/4), 1), ((11/5, 55/4), 1), ((165/8, 341/16), 1), (22, 44), 1]]
sage: real_roots(x^5 * (x^2 - 9999)^2 - 1)
[((-2927449638111/9007199254740992, 419601125186091/2251799813685248), 1), ((2126658450145849539106165441515324959/21266747932558563966649601926485513264, 42533190727313001885395339616127199492535295865117307932921825928971026432), 1),..., (1086329366279326983230456482242756608, 531664613453865869670144520163085456545353/516911983139663491615228241121378304), 1)]
sage: real_roots(x^5 * (x^2 - 9999)^2 - 1, seed=42)
[((-123196838480288/18014398509481984, 293964743458749/9007199254740992), 1), ((83072597397955190784169638196376143/830764979736557242056487941267521536, 1661519150981033789137940787475325503/1661534994713114484112975882535043072), 1),..., (519203723562592617581615249797433455/51922968583482762853049639229200969, 6044326892408166806312183/604462909807314587353088), 1)]
sage: real_roots(x^5 * (x^2 - 9999)^2 - 1, wordsize=64)
[((-62866503803202151050003/193428131138340666795298816, 90186554512564177624143/4835703278458516698247904), 1), ((54442456323733731521499987922809050110157/544451780707350154154393718908291383296, 108884912769660194637118845654929064385439/1088890357414700030803827987437816582766592), 1),..., (272225893536750770076699685945145691648/136106141275823501959100399337685485662633, 13611294676837538353834984297270782485824), 1)]
sage: real_roots(x)
[((-47/256, 81/512), 1)]
sage: real_roots(x + (x-1))
[((-47/256, 81/512), 1), ((1/2, 1201/1024), 1)]
sage: real_roots(x-1)
[((209/256, 593/512), 1)]
sage: real_roots(x*(x-1)*(x-2), bounds=(0, 2))
[((0, 0), 1), ((1, 2), 1)]
sage: real_roots(x*(x-1), bounds=(0, 2), retval='algebraic_real')
[[(0, 1), (1, 2), (2, 1)], ((0, 1), (1, 2), (2, 1))]
sage: v = 2^40
sage: real_roots((x^2-1)^2 * (x^2 - (v+1)/v))
[((-12855504354077682108858019021174120740504020581912910106032383/12855504354077682108858019021174120740504020581912910106032383, -12855504354077682108858019021174120740504020581912910106032383))
```

sage: real_roots(x^2 - 2)
[(-2.?, 1), (2.?, 1)]

sage: v = 2^60
sage: real_roots((x-1) * (x-(v+1)/v), strategy='warp')
[(-499/525, 1173/875), 1], ((337/175, 849/175), 1)]

sage: real_roots((x-1) * (x-2), strategy='warp')
[(-1713/335, -689/335), 1], ((-2067/2029, -689/1359), 1), (((0, 0), 1), ((499/525, -1173/875), 1), ((337/175, 849/175), 1))]
sage: real_roots((x+3)*(x+1)*x*(x-1)*(x-2), strategy='warp', retval='algebraic_real')
[(-3.000000000000000?, 1), (-1.000000000000000?, 1), (0, 1), (1.00000000000000007?, 1), (2.0000000000000000?, 1)]
sage: ar_rts = real_roots(x-1, retval='algebraic_real')
sage: ar_rts[0][0] == 1
True
If the polynomial has no real roots, we get an empty list.

sage: (x^2 + 1).real_root_intervals()
[]
We can compute Conway’s constant (see http://mathworld.wolfram.com/ConwaysConstant.html) to arbitrary precision.

sage: p = x^71 - x^69 - 2*x^68 - x^67 + 2*x^66 + 2*x^65 + x^64 - x^63 - x^62 - x^61...
˓→- x^60 - x^59 + 2*x^58 + 5*x^57 - 3*x^56 - 2*x^55 + 10*x^54 - 3*x^53 - 2*x^52 +...
˓→- 6*x^51 + 6*x^50 + x^49 + 9*x^48 - 3*x^47 - 7*x^46 - 8*x^45 - 8*x^44 + 10*x^43 +...
˓→- 6*x^42 + 8*x^41 - 5*x^40 - 12*x^39 + 7*x^38 - 7*x^37 + 7*x^36 + x^35 - 3*x^34 +...
˓→- 10*x^33 + x^32 - 6*x^31 - 2*x^30 - 10*x^29 + 3*x^28 + 2*x^27 + 9*x^26 - 3*x^25 +...
˓→- 14*x^24 - 8*x^23 - 7*x^21 + 9*x^20 - 4*x^18 - 10*x^17 - 7*x^16 + 12*x^15...
˓→+ 7*x^14 + 2*x^13 - 12*x^12 - 4*x^11 - 2*x^10 + 5*x^9 + x^7 - 7*x^6 + 7*x^5 - 4*x^...
˓→+ 4 + 12*x^3 - 6*x^2 + 3*x - 6
sage: cc = real_roots(p, retval='algebraic_real')[2][0]  # long time
sage: RealField(180)(cc)  # long time
1.3035772690342963912570991121525518907307025046594049
Now we play with algebraic real coefficients.

sage: x = polygen(AA)
sage: p = (x - 1) * (x - sqrt(AA(2))) * (x - 2)
sage: real_roots(p)
[((499/525, 2171/1925), 1), ((1173/875, 2521/1575), 1), ((337/175, 849/175), 1)]
sage: ar_rts = real_roots(p, retval='algebraic_real'); ar_rts
[(1.000000000000000?, 1), (1.414213562373095?, 1), (2.000000000000000?, 1)]
sage: ar_rts[1][0]^2 == 2
True
sage: ar_rts = real_roots(x*(x-1), retval='algebraic_real')
sage: ar_rts[0][0] == 0
True
sage: p2 = p * (p - 1/100); p2
x^6 - 8.82842712474619759*x^5 + 31.97056274847714272*x^4 - 60.77955262170047353*x^3 + 63.
˓→- 9852676327580179632*x^2 - 35.37613490585595570*x + 8.02828427124746267
sage: real_roots(p2, retval='interval')
[((1.007, 1), (1.17, 1), (1.387, 1), (1.57, 1), (2.007, 1), (2.17, 1)]
sage: p = (x - 1) * (x - sqrt(AA(2)))^2 * (x - 2)
sage: real_roots(p, retval='interval')
[((1.0000000000000000000, 1), (1.4142135623730950000, 1), (2.00000000000000000000000000000, 3)]
• \((bl, bh)\) – pair of rationals

OUTPUT:

• \((cl, ch)\) – pair of rationals

Computes the linear transformation that maps \((al, ah)\) to \((0, 1)\); then applies this transformation to \((bl, bh)\) and returns the result.

EXAMPLES:

```python
sage: from sage.rings.polynomial.real_roots import *
sage: relative_bounds((1/7, 1/4), (1/6, 1/5))
(2/9, 8/15)
```

`sage.rings.polynomial.real_roots.reverse_intvec(c)`

Given a vector of integers, reverse the vector (like the reverse() method on lists).

Modifies the input vector; has no return value.

EXAMPLES:

```python
sage: from sage.rings.polynomial.real_roots import *
sage: v = vector(ZZ, [1, 2, 3, 4]); v
(1, 2, 3, 4)
sage: reverse_intvec(v)
sage: v
(4, 3, 2, 1)
```

`sage.rings.polynomial.real_roots.root_bounds(p)`

Given a polynomial with real coefficients, computes a lower and upper bound on its real roots. Uses algorithms of Akritas, Strzeboński, and Vigklas.

EXAMPLES:

```python
sage: from sage.rings.polynomial.real_roots import *
sage: x = polygen(ZZ)
sage: root_bounds((x-1)*(x-2)*(x-3))
(0.545454545454545, 6.00000000000001)
sage: root_bounds(x^2)
(0.000000000000000, 0.000000000000000)
sage: root_bounds(x*(x+1))
(-1.000000000000000, 0.000000000000000)
sage: root_bounds((x+2)*(x-3))
(-2.44948974278317, 3.46410161513776)
sage: root_bounds(x^995 * (x^2 - 9999) - 1)
(-99.9949998749937, 141.414284992713)
sage: root_bounds(x^995 * (x^2 - 9999) + 1)
(-141.414284992712, 99.9949998749938)
```

If we can see that the polynomial has no real roots, return None.

```python
sage: root_bounds(x^2 + 1) is None
True
```

`class sage.rings.polynomial.real_roots.rr_gap`

Bases: object
A simple class representing the gaps between islands, in my ocean-island root isolation algorithm. Named “rr_gap” for “real roots gap”, because “gap” seemed too short and generic.

\texttt{region()}

\texttt{sage.rings.polynomial.real_roots.scale_intvec_var(c, k)}

Given a vector of integers \(c\) of length \(n+1\), and a rational \(k = \frac{kn}{kd}\), multiplies each element \(c[i]\) by \((kd^i) \cdot (kn^{n-i})\).

Modifies the input vector; has no return value.

\textbf{EXAMPLES:}

\begin{verbatim}
  sage: from sage.rings.polynomial.real_roots import *
  sage: v = vector(ZZ, [1, 1, 1, 1])
  sage: scale_intvec_var(v, 3/4)
  sage: v
  (64, 48, 36, 27)
\end{verbatim}

\texttt{sage.rings.polynomial.real_roots.split_for_targets(ctx, bp, target_list, precise=False)}

Given an interval Bernstein polynomial over a particular region (assumed to be a (not necessarily proper) sub-region of \([0 .. 1]\)), and a list of targets, uses de Casteljau’s method to compute representations of the Bernstein polynomial over each target. Uses degree reduction as often as possible while maintaining the requested precision.

Each target is of the form \((\text{lgap}, \text{ugap}, b)\). Suppose \text{lgap.region()} is \((l_1, l_2)\), and \text{ugap.region()} is \((u_1, u_2)\). Then we will compute an interval Bernstein polynomial over a region \([l .. u]\), where \(l_1 <= l <= l_2\) and \(u_1 <= u <= u_2\). (\text{split_for_targets()} is free to select arbitrary region endpoints within these bounds; it picks endpoints which make the computation easier.) The third component of the target, \(b\), is the maximum allowed scale_{\text{log2}} of the result; this is used to decide when degree reduction is allowed.

The pair \((l_1, l_2)\) can be replaced by None, meaning \([-\infty .. 0]\); or, \((u_1, u_2)\) can be replaced by None, meaning \([1 .. \infty]\).

There is another constraint on the region endpoints selected by \text{split_for_targets()} for a target \(((l_1, l_2), (u_1, u_2), b)\). We set a size goal \(g\), such that \((u - l) <= g \cdot (u_1 - l_2)\). Normally \(g\) is 256/255, but if \text{precise} is True, then \(g\) is 65536/65535.

\textbf{EXAMPLES:}

\begin{verbatim}
  sage: from sage.rings.polynomial.real_roots import *
  sage: bp = mk_ibpi([1000000, -2000000, 3000000, -4000000, -5000000, -6000000])
  sage: ctx = mk_context()
  sage: bps = split_for_targets(ctx, bp, [(rr_gap(1/1234567893, 1/1234567892, 1), rr_gap(1/1234567891, 1/1234567890, 1), 12), (rr_gap(1/3, 1/2, -1), rr_gap(2/3, 3/4, -1), 6)])
  sage: bps[0]
  <IBP: (999992, 999992, 999992) + [0 .. 15) over [8613397477114467984778830327/\ldots10633823966279326983230456482242756608 .. 591986168025934394813836527495938294787/\ldots7308750818665451459101842416358141509827966271488]; level 2; slope_err 0.?e12>
  sage: bps[1]
  <IBP: (-1562500, -1875001, -222222, -2592593, -2969137, -3337450) + [0 .. 4) over [1/2 .. 2863311531/4294967296]>}
\end{verbatim}

\texttt{sage.rings.polynomial.real_roots.subsample_vec_doctest(a, slen, llen)}
Polynomials, Release 10.0

```
sage.rings.polynomial.real_roots.taylor_shift1_intvec(c)

Given a vector of integers c of length d+1, representing the coefficients of a degree-d polynomial p, modify the vector to perform a Taylor shift by 1 (that is, p becomes p(x+1)).

This is the straightforward algorithm, which is not asymptotically optimal.

Modifies the input vector; has no return value.

EXAMPLES:
```
sage: from sage.rings.polynomial.real_roots import *
sage: x = polygen(ZZ)
sage: p = (x-1)*(x-2)*(x-3)
sage: v = vector(ZZ, p.list())
sage: p, v
(x^3 - 6*x^2 + 11*x - 6, (-6, 11, -6, 1))
sage: taylor_shift1_intvec(v)
sage: p(x+1), v
(x^3 - 3*x^2 + 2*x, (0, 2, -3, 1))
```

```
sage.rings.polynomial.real_roots.to_bernstein(p, low=0, high=1, degree=None)

Given a polynomial p with integer coefficients, and rational bounds low and high, compute the exact rational Bernstein coefficients of p over the region [low .. high]. The optional parameter degree can be used to give a formal degree higher than the actual degree.

The return value is a pair (c, scale); c represents the same polynomial as p*scale. (If you only care about the roots of the polynomial, then of course scale can be ignored.)

EXAMPLES:
```
sage: from sage.rings.polynomial.real_roots import *
sage: x = polygen(ZZ)
sage: to_bernstein(x)
([0, 1], 1)
sage: to_bernstein(x, degree=5)
([0, 1/5, 2/5, 3/5, 4/5, 1], 1)
sage: to_bernstein(x^3 + x^2 - x - 1, low=-3, high=3)
([-16, 24, -32, 32], 1)
sage: to_bernstein(x^3 + x^2 - x - 1, low=3, high=22/7)
([[296352, 310464, 325206, 340605], 9261]
```

```
sage.rings.polynomial.real_roots.to_bernstein_warp(p)

Given a polynomial p with rational coefficients, compute the exact rational Bernstein coefficients of p(x/(x+1)).

EXAMPLES:
```
sage: from sage.rings.polynomial.real_roots import *
sage: x = polygen(ZZ)
sage: to_bernstein_warp(1 + x + x^2 + x^3 + x^4 + x^5)
[1, 1/5, 1/10, 1/10, 1/5, 1]
```

```
class sage.rings.polynomial.real_roots.warp_map(neg)

Bases: object

A class to map between original coordinates and ocean coordinates. If neg is False, then the original->ocean transform is x -> x/(x+1), and the ocean->original transform is x/(1-x); this maps between [0 .. infinity] and [0
```

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If neg is True, then the original-ocean transform is \( x \rightarrow -x/(1-x) \), and the ocean-original transform is the same thing: \( -x/(1-x) \). This maps between \([0 \ldots -\infty]\) and \([0 \ldots 1]\).

```python
from ocean(region)
```

```python
to ocean(region)
```

```python
sage.rings.polynomial.real_roots.wordsize_rational(a, b, wordsize)
```

Given rationals \( a \) and \( b \), selects a de Casteljau split point \( r \) between \( a \) and \( b \). An attempt is made to select an efficient split point (according to the criteria mentioned in the documentation for `de_casteljau_intvec`), with a bias towards split points near \( a \).

In full detail:

Takes as input two rationals, \( a \) and \( b \), such that \( 0 \leq a \leq 1 \), \( 0 \leq b \leq 1 \), and \( a \neq b \). Returns rational \( r \), such that \( a \leq r \leq b \) or \( b \leq r \leq a \). The denominator of \( r \) is a power of 2. Let \( m \) be \( \min(r, 1-r) \), \( nm \) be numerator(m), and \( dml \) be \( \log_2(\text{denominator}(m)) \). The return value \( r \) is taken from the first of the following classes to have any members between \( a \) and \( b \) (except that if \( a \leq 1/8 \), or \( 7/8 \leq a \), then class 2 is preferred to class 1).

1. \( dml < \text{wordsize} \)
2. \( \text{bitsize}(nm) \leq \text{wordsize} \)
3. \( \text{bitsize}(nm) \leq 2*\text{wordsize} \)
4. \( \text{bitsize}(nm) \leq 3*\text{wordsize} \)
   ...
   k. \( \text{bitsize}(nm) \leq (k-1)\text{wordsize} \)

From the first class to have members between \( a \) and \( b \), \( r \) is chosen as the element of the class which is closest to \( a \).

EXAMPLES:

```output
sage: from sage.rings.polynomial.real_roots import *
sage: wordsize_rational(1/5, 1/7, 32)
429496729/2147483648
sage: wordsize_rational(1/7, 1/5, 32)
306783379/2147483648
sage: wordsize_rational(1/5, 1/7, 64)
1844674407370955161/9223372036854775808
sage: wordsize_rational(1/7, 1/5, 64)
658812288346769701/4611686018427387904
sage: wordsize_rational(1/17, 1/19, 32)
252645135/4294967296
sage: wordsize_rational(1/17, 1/19, 64)
1085102592571150095/18446744073709551616
sage: wordsize_rational(1/1234567890, 1/1234567891, 32)
933866427/1152921504606064576
sage: wordsize_rational(1/1234567890, 1/1234567891, 64)
4010925763784056541/4951760157141521099596496896
```

Chapter 2. Univariate Polynomials
2.1.19 Isolate Complex Roots of Polynomials

AUTHOR:

• Carl Witty (2007-11-18): initial version

This is an implementation of complex root isolation. That is, given a polynomial with exact complex coefficients, we compute isolating intervals for the complex roots of the polynomial. (Polynomials with integer, rational, Gaussian rational, or algebraic coefficients are supported.)

We use a simple algorithm. First, we compute a squarefree decomposition of the input polynomial; the resulting polynomials have no multiple roots. Then, we find the roots numerically, using NumPy (at low precision) or Pari (at high precision). Then, we verify the roots using interval arithmetic.

EXAMPLES:

```python
sage: x = polygen(ZZ)
sage: (x^5 - x - 1).roots(ring=CIF)
[(1.167303978261419?, 1), (-0.764884433600585? - 0.3524715460317277?*I, 1), (-0.
˓→764884433600585? + 0.3524715460317277?*I, 1), (0.18123244469876? - 1.0839541013177117
˓→*I, 1), (0.18123244469876? + 1.0839541013177117?*I, 1)]
```

sage.rings.polynomial.complex_roots.complex_roots(p, skip_squarefree=False, retval='interval', min_prec=0)

Compute the complex roots of a given polynomial with exact coefficients (integer, rational, Gaussian rational, and algebraic coefficients are supported). Returns a list of pairs of a root and its multiplicity.

Roots are returned as a ComplexIntervalFieldElement; each interval includes exactly one root, and the intervals are disjoint.

By default, the algorithm will do a squarefree decomposition to get squarefree polynomials. The skip_squarefree parameter lets you skip this step. (If this step is skipped, and the polynomial has a repeated root, then the algorithm will loop forever!)

You can specify retval='interval' (the default) to get roots as complex intervals. The other options are retval='algebraic' to get elements of QQbar, or retval='algebraic_real' to get only the real roots, and to get them as elements of AA.

EXAMPLES:

```python
sage: from sage.rings.polynomial.complex_roots import complex_roots
sage: x = polygen(ZZ)
sage: complex_roots(x^5 - x - 1)
[(1.167303978261419?, 1), (-0.764884433600585? - 0.3524715460317277?*I, 1), (-0.
˓→764884433600585? + 0.3524715460317277?*I, 1), (0.181232444469876? - 1.0839541013177117
˓→*I, 1), (0.181232444469876? + 1.0839541013177117?*I, 1)]
```

Unfortunately due to numerical noise there can be a small imaginary part to each root depending on CPU, compiler, etc, and that affects the printing order. So we verify the real part of each root and check that the imaginary part is small in both cases:

```python
sage: v = complex_roots(x^2 + 27*x + 181)
```

(continues on next page)
True
sage: v[1][0].imag().upper() < 1e25
True

sage: K.<im> = QuadraticField(-1)
sage: eps = 1/2^100
sage: x = polygen(K)
sage: p = (x-1)*(x-1-eps)*(x-1+eps)*(x-1-eps*im)*(x-1+eps*im)

This polynomial actually has all-real coefficients, and is very, very close to \((x-1)^5\):

sage: [RR(QQ(a)) for a in list(p - (x-1)^5)]
[3.87259191484932e-121, -3.87259191484932e-121]

sage: rts = complex_roots(p)
sage: [ComplexIntervalField(10)(rt[0] - 1) for rt in rts]

We can get roots either as intervals, or as elements of QQbar or AA.

sage: p = (x^2 + x - 1)
sage: p = p * p(x*im)
sage: p
-x^4 + (im - 1)*x^3 + im*x^2 + (-im - 1)*x + 1

Two of the roots have a zero real component; two have a zero imaginary component. These zero components will be found slightly inaccurately, and the exact values returned are very sensitive to the (non-portable) results of NumPy. So we post-process the roots for printing, to get predictable doctest results.

sage: def tiny(x):
....:     return x.contains_zero() and x.absolute_diameter() < 1e-14
sage: def smash(x):
....:     x = CIF(x[0]) # discard multiplicity
....:     if tiny(x.imag()): return x.real()
....:     if tiny(x.real()): return CIF(0, x.imag())

sage: def tiny(x):
....:     return x.contains_zero() and x.absolute_diameter() < 1e-14
sage: def smash(x):
....:     x = CIF(x[0]) # discard multiplicity
....:     if tiny(x.imag()): return x.real()
....:     if tiny(x.real()): return CIF(0, x.imag())

sage: rts = complex_roots(p, retval='algebraic'); type(rts[0][0]), rts
(<class 'sage.rings.qqbar.AlgebraicNumber'>, [-1.618033988749895?, -0.618033988749895?*I, 1.618033988749895?*I, 0.618033988749895?])

sage: rts = complex_roots(p, retval='algebraic_real'); type(rts[0][0]), rts
(<class 'sage.rings.qqbar.AlgebraicReal'>, [-1.618033988749895?, 1, (0.618033988749895?)])

We are given a squarefree polynomial \(p\), a list of estimated roots, and a precision.

We attempt to verify that the estimated roots are in fact distinct roots of the polynomial, using interval arithmetic of precision \(prec\). If we succeed, we return a list of intervals bounding the roots; if we fail, we return None.

EXAMPLES:
```python
sage: x = polygen(ZZ)
sage: p = x^3 - 1
sage: rts = [CC.zeta(3)^i for i in range(0, 3)]
sage: from sage.rings.polynomial.complex_roots import interval_roots
sage: interval_roots(p, rts, 53)
[1, -0.500000000000000? + 0.866025403784439?*I, -0.500000000000000? - 0.
  → 866025403784439?*I]
sage: interval_roots(p, rts, 200)
[1, -0.500000000000000000000000000000000000000000000000000000000000?
  + 0.
  → 866025403784438646763723170752936183471402626905190314027904?
  *I, -0.
  → 500000000000000000000000000000000000000000000000000000000000?
  - 0.
  → 866025403784438646763723170752936183471402626905190314027904?*I]
sage.rings.polynomial.complex_roots.intervals_disjoint(intvs)
Given a list of complex intervals, check whether they are pairwise disjoint.
EXAMPLES:

```python
sage: from sage.rings.polynomial.complex_roots import intervals_disjoint
sage: a = CIF(RIF(0, 3), 0)
sage: b = CIF(0, RIF(1, 3))
sage: c = CIF(RIF(1, 2), RIF(1, 2))
sage: d = CIF(RIF(2, 3), RIF(2, 3))
sage: intervals_disjoint([a,b,c,d])
False
sage: d2 = CIF(RIF(2, 3), RIF(2.001, 3))
sage: intervals_disjoint([a,b,c,d2])
True
```
2.1.21 Ideals in Univariate Polynomial Rings

AUTHORS:

- David Roe (2009-12-14) – initial version.

class sage.rings.polynomial.ideal.Ideal_1poly_field(ring, gen)

Bases: Ideal_pid

An ideal in a univariate polynomial ring over a field.

groebner_basis(algorithm=None)

Return a Gröbner basis for this ideal.

The Gröbner basis has 1 element, namely the generator of the ideal. This trivial method exists for compatibility with multi-variate polynomial rings.

INPUT:

- algorithm – ignored

EXAMPLES:

sage: R.<x> = QQ[]
  sage: I = R.ideal([x^2 - 1, x^3 - 1])
  sage: G = I.groebner_basis(); G
  [x - 1]
  sage: type(G)
  <class 'sage.rings.polynomial.multi_polynomial_sequence.PolynomialSequence_generic'>
  sage: list(G)
  [x - 1]

residue_class_degree()

Returns the degree of the generator of this ideal.

This function is included for compatibility with ideals in rings of integers of number fields.

EXAMPLES:

sage: R.<t> = GF(5)[]
  sage: P = R.ideal(t^4 + t + 1)
  sage: P.residue_class_degree()
  4
residue_field(names=None, check=True)

If this ideal is \( P \subset F_p[t] \), returns the quotient \( F_p[t]/P \).

EXAMPLES:

```
sage: R.<t> = GF(17)[]; P = R.ideal(t^3 + 2*t + 9)
sage: k.<a> = P.residue_field(); k
```

Residue field in \( a \) of Principal ideal \((t^3 + 2*t + 9)\) of Univariate Polynomial \( \to \) Ring in \( t \) over Finite Field of size 17

### 2.1.22 Quotients of Univariate Polynomial Rings

**EXAMPLES:**

```
sage: R.<x> = QQ[]
sage: S = R.quotient(x**3-3*x+1, 'alpha')
sage: S.gen()**2 in S
True
sage: x in S
True
sage: S.gen() in R
False
sage: 1 in S
True
```

```python
class sage.rings.polynomial.polynomial_quotient_ring.PolynomialQuotientRingFactory

Bases: UniqueFactory

Create a quotient of a polynomial ring.

INPUT:

- ring - a univariate polynomial ring
- polynomial - an element of ring with a unit leading coefficient
- names - (optional) name for the variable

OUTPUT: Creates the quotient ring \( R/I \), where \( R \) is the ring and \( I \) is the principal ideal generated by polynomial.

EXAMPLES:

We create the quotient ring \( \mathbb{Z}[x]/(x^3 + 7) \), and demonstrate many basic functions with it:

```
sage: Z = IntegerRing()
sage: R = PolynomialRing(Z, 'x'); x = R.gen()
sage: S = R.quotient(x^3 + 7, 'a'); a = S.gen()
sage: S
Univariate Quotient Polynomial Ring in a over Integer Ring with modulus \( x^3 + 7 \)
sage: a^3
-7
sage: S.is_field()
False
sage: a in S
True
```
We create the “iterated” polynomial ring quotient

\[ R = \left( \mathbb{F}_2[y]/(y^2 + y + 1) \right)[x]/(x^3 - 5). \]

Next we create a number field, but viewed as a quotient of a polynomial ring over \( \mathbb{Q} \):

\[ S = \mathbb{Q}[x]/(x^3 + 2x - 5), \]

There are conversion functions for easily going back and forth between quotients of polynomial rings over \( \mathbb{Q} \) and number fields:

The leading coefficient must be a unit (but need not be 1).
```python
sage: R = PolynomialRing(Integers(9), 'x'); x = R.gen()
sage: S = R.quotient(2*x^4 + 2*x^3 + x + 2, 'a')
sage: S = R.quotient(3*x^4 + 2*x^3 + x + 2, 'a')
Traceback (most recent call last):
  ... 
TypeError: polynomial must have unit leading coefficient
```

Another example:

```python
sage: R.<x> = PolynomialRing(IntegerRing())
sage: f = x^2 + 1
sage: R.quotient(f)
Univariate Quotient Polynomial Ring in xbar over Integer Ring with modulus x^2 + 1
```

This shows that the issue at github issue #5482 is solved:

```python
sage: R.<x> = PolynomialRing(QQ)
sage: f = x^2-1
sage: R.quotient_by_principal_ideal(f)
Univariate Quotient Polynomial Ring in xbar over Rational Field with modulus x^2 - 1
```

---

**create_key**(ring, polynomial, names=None)

Return a unique description of the quotient ring specified by the arguments.

**create_object**(version, key)

Return the quotient ring specified by key.

```python
sage: R.<x> = QQ[]
sage: PolynomialQuotientRing.create_key(R, x + 1)
(Univariate Polynomial Ring in x over Rational Field, x + 1, ('xbar',))
```

```python
sage: R.<x> = QQ[]
sage: PolynomialQuotientRing.create_object((8, 0, 0), (R, x^2 - 1, ('xbar')))  
Univariate Quotient Polynomial Ring in xbar over Rational Field with modulus x^2 - 1
```

---

**class** `sage.rings.polynomial.polynomial_quotient_ring.PolynomialQuotientRing_coercion`

Bases: `DefaultConvertMap_unique`

A coercion map from a `PolynomialQuotientRing` to a `PolynomialQuotientRing` that restricts to the coercion map on the underlying ring of constants.

**EXAMPLES:**

```python
sage: R.<x> = ZZ[]
sage: S.<x> = QQ[]
sage: f = S.quo(x^2 + 1).coerce_map_from(R.quo(x^2 + 1)); f
Coercion map:
  From: Univariate Quotient Polynomial Ring in xbar over Integer Ring with modulus x^2 + 1
  To: Univariate Quotient Polynomial Ring in xbar over Rational Field with modulus x^2 + 1
```
**is_injective()**

Return whether this coercion is injective.

**EXAMPLES:**

If the modulus of the domain and the codomain is the same and the leading coefficient is a unit in the domain, then the map is injective if the underlying map on the constants is:

```
sage: R.<x> = ZZ[]
sage: S.<x> = QQ[]
sage: f = S.quo(x^2 + 1).coerce_map_from(R.quo(x^2 + 1))
sage: f.is_injective()
True
```

**is_surjective()**

Return whether this coercion is surjective.

**EXAMPLES:**

If the underlying map on constants is surjective, then this coercion is surjective since the modulus of the codomain divides the modulus of the domain:

```
sage: R.<x> = ZZ[]
sage: f = R.quo(x).coerce_map_from(R.quo(x^2))
sage: f.is_surjective()
True
```

If the modulus of the domain and the codomain is the same, then the map is surjective iff the underlying map on the constants is:

```
sage: A.<a> = ZqCA(9)
sage: R.<x> = A[]
sage: S.<x> = A.fraction_field()[]
sage: f = S.quo(x^2 + 2).coerce_map_from(R.quo(x^2 + 2))
sage: f.is_surjective()
False
```

class sage.rings.polynomial.polynomial_quotient_ring.PolynomialQuotientRing_domain(ring, polynomial, name=None, category=None)

**EXAMPLES:**

```
sage: R.<x> = PolynomialRing(ZZ)
sage: S.<xbar> = R.quotient(x^2 + 1)
sage: S
Univariate Quotient Polynomial Ring in xbar over Integer Ring with modulus x^2 + 1
sage: loads(S.dumps()) == S
True
sage: loads(xbar.dumps()) == xbar
True
```
field_extension(names)

Takes a polynomial quotient ring, and returns a tuple with three elements: the NumberField defined by the same polynomial quotient ring, a homomorphism from its parent to the NumberField sending the generators to one another, and the inverse isomorphism.

OUTPUT:

• field
• homomorphism from self to field
• homomorphism from field to self

EXAMPLES:

```
sage: R.<x> = PolynomialRing(Rationals())
sage: S.<alpha> = R.quotient(x^3-2)
sage: F.<b>, f, g = S.field_extension()
sage: F
Number Field in b with defining polynomial x^3 - 2
sage: a = F.gen()
sage: f(alpha)
b
sage: g(a)
alpha
```

Note that the parent ring must be an integral domain:

```
sage: R.<x> = GF(25,'f25')[x]
sage: S.<a> = R.quo(x^3 - 2)
sage: F, g, h = S.field_extension('b')
Traceback (most recent call last):
  ... AttributeError: 'PolynomialQuotientRing_generic_with_category' object has no attribute 'field_extension'
```

Over a finite field, the corresponding field extension is not a number field:

```
sage: R.<x> = GF(25, 'a')[x]
sage: S.<alpha> = R.quo(x^3 + 2*x + 1)
sage: F, g, h = S.field_extension('b')
```

We do an example involving a relative number field:

```
sage: R.<x> = QQ['x']
sage: K.<a> = NumberField(x^3 - 2)
sage: S.<X> = K['X']
sage: Q.<b> = S.quo(X^3 + 2*X + 1)
sage: Q.field_extension('b')
(Number Field in b with defining polynomial X^3 + 2*X + 1 over its base field, ... Defn: b |--> b, Relative number field morphism:
```

We slightly change the example above so it works.

```
sage: R.<x> = QQ['x']
sage: K.<a> = NumberField(x^3 - 2)
sage: S.<X> = K['X']
sage: f = (X+a)^3 + 2*(X+a) + 1
sage: f
X^3 + 3*a*X^2 + (3*a^2 + 2)*X + 2*a + 3
sage: Q.<z> = S.quo(f)
sage: F.<w>, g, h = Q.field_extension()
sage: c = g(z)
sage: f(c)
0
sage: h(g(z))
z
sage: g(h(w))
w
```

AUTHORS:
- Craig Citro (2006-08-07)
- William Stein (2006-08-06)
EXAMPLES:

```
sage: R.<x> = QQ[]
sage: f = x^5 + x + 17
sage: k = R.quotient(f)
sage: v = k.complex_embeddings(100)
sage: [phi(k.0^2) for phi in v]
[2.9757207403766761469671194565, -2.4088994371613850098316292196 + 1.9025105350528612407363802*I, -2.4088994371613850098316292196 - 1.9025105350528612407363802*I, 0.92103906697304634806949137 + 3.075331188457747326541886*I, 0.92103906697304634806949137 - 3.075331188457747326541886*I]
```

**class** `sage.rings.polynomial.polynomial_quotient_ring.PolynomialQuotientRing_generic(ring, polynomial, name=None, category=None)`

Bases: `QuotientRing_generic`

Quotient of a univariate polynomial ring by an ideal.

**EXAMPLES:**

```
sage: R.<x> = PolynomialRing(Integers(8)); R
Univariate Polynomial Ring in x over Ring of integers modulo 8
sage: S.<xbar> = R.quotient(x^2 + 1); S
Univariate Quotient Polynomial Ring in xbar over Ring of integers modulo 8 with modulus x^2 + 1

We demonstrate object persistence.

```
sage: loads(S.dumps()) == S
True
sage: loads(xbar.dumps()) == xbar
True
```

We create some sample homomorphisms;

```
sage: R.<x> = PolynomialRing(ZZ)
sage: S = R.quo(x^2-4)
sage: f = S.hom([2])
sage: f
Ring morphism:
  From: Univariate Quotient Polynomial Ring in xbar over Integer Ring with modulus x^2 - 4
  To:   Integer Ring
  Defn: xbar --> 2
sage: f(x)
2
sage: f(x^2 - 4)
0
```

(continues on next page)
Element
alias of PolynomialQuotientRingElement

S_class_group(S, proof=True)
If self is an étale algebra \( D \) over a number field \( K \) (i.e. a quotient of \( K[x] \) by a squarefree polynomial) and \( S \) is a finite set of places of \( K \), return a list of generators of the \( S \)-class group of \( D \).

NOTE:
Since the ideal function behaves differently over number fields than over polynomial quotient rings (the quotient does not even know its ring of integers), we return a set of pairs \((\text{gen}, \text{order})\), where \text{gen} is a tuple of generators of an ideal \( I \) and \text{order} is the order of \( I \) in the \( S \)-class group.

INPUT:
• \( S \) - a set of primes of the coefficient ring
• \text{proof} - if False, assume the GRH in computing the class group

OUTPUT:
A list of generators of the \( S \)-class group, in the form \((\text{gen}, \text{order})\), where \text{gen} is a tuple of elements generating a fractional ideal \( I \) and \text{order} is the order of \( I \) in the \( S \)-class group.

EXAMPLES:
A trivial algebra over \( \mathbb{Q}(\sqrt{-5}) \) has the same class group as its base:

\[
\begin{align*}
\text{sage: } & K.<a> = QuadraticField(-5) \\
\text{sage: } & R.<x> = K[] \\
\text{sage: } & S.<xbar> = R.quotient(x) \\
\text{sage: } & S.S_class_group([]) \\
& \left[ (\left(2, -a + 1\right), 2) \right]
\end{align*}
\]

When we include the prime \((2, -a + 1)\), the \( S \)-class group becomes trivial:

\[
\begin{align*}
\text{sage: } & S.S_class_group([K.ideal(2, -a+1)]) \\
& \left[ \right]
\end{align*}
\]

Here is an example where the base and the extension both contribute to the class group:

\[
\begin{align*}
\text{sage: } & K.<a> = QuadraticField(-5) \\
\text{sage: } & K.class_group() \\
& \text{Class group of order 2 with structure C2 of Number Field in a with defining polynomial } x^2 + 5 \text{ with } a = 2.23606797749979970?I \\
\text{sage: } & R.<x> = K[] \\
\text{sage: } & S.<xbar> = R.quotient(x^2 + 23) \\
\text{sage: } & S.S_class_group([]) \\
& \left[ (\left(2, -a + 1, 1/2*xbar + 1/2, -1/2*a*xbar + 1/2*a + 1\right), 6) \right] \\
\text{sage: } & S.S_class_group([K.ideal(3, a-1)]) \\
& \left[ \right] \\
\text{sage: } & S.S_class_group([K.ideal(2, a+1)]) \\
& \left[ \right] \\
\text{sage: } & S.S_class_group([K.ideal(a)]) \\
& \left[ (\left(2, -a + 1, 1/2*xbar + 1/2, -1/2*a*xbar + 1/2*a + 1\right), 6) \right]
\end{align*}
\]
Now we take an example over a nontrivial base with two factors, each contributing to the class group:

```
sage: K.<a> = QuadraticField(-5)
sage: R.<x> = K[]
sage: S.<xbar> = R.quotient((x^2 + 23)*(x^2 + 31))
sage: S.S_class_group([])  # representation varies, not tested
([(1/4*xbar^2 + 31/4, (-1/8*a + 1/8)*xbar^2 - 31/8*a + 31/8,
  1/16*a*xbar^2 + 16*a*xbar + 31/16*a + 31/8), 6),
 (1/8*a - 1/8)*xbar^2 + 23/8*a - 23/8,
  -1/16*a*xbar^2 + 16*a*xbar + 31/16*a + 31/8), 6),
 (1/16*a*xbar^2 + (-1/4*a - 1/8)*xbar^2 + 23/16*a*xbar - 23/16*a - 23/8), 2])
```

By using the ideal \((a)\), we cut the part of the class group coming from \(x^2 + 31\) from 12 to 2, i.e. we lose a generator of order 6 (this was fixed in github issue #14489):

```
sage: S.S_class_group([K.ideal(a)])  # representation varies, not tested
([(1/4*xbar^2 + 31/4, (-1/8*a + 1/8)*xbar^2 - 31/8*a + 31/8,
  1/16*a*xbar^2 + 16*a*xbar + 31/16*a + 31/8), 6),
 (1/8*a - 1/8)*xbar^2 + 23/8*a - 23/8,
  -1/16*a*xbar^2 + 16*a*xbar + 31/16*a + 31/8), 6),
 (1/16*a*xbar^2 + (-1/4*a - 1/8)*xbar^2 + 23/16*a*xbar - 23/16*a - 23/8), 2])
```

Note that all the returned values live where we expect them to:

```
sage: CG = S.S_class_group([])
sage: type(CG[0][0][1])
<class 'sage.rings.polynomial.polynomial_quotient_ring.PolynomialQuotientRing_generic_with_category.element_class'>
sage: type(CG[0][1])
<class 'sage.rings.integer.Integer'>
```

**S_units**\(\)\(S, \text{proof}=\text{True}\)

If self is an étale algebra \(D\) over a number field \(K\) (i.e. a quotient of \(K[x]\) by a squarefree polynomial) and \(S\) is a finite set of places of \(K\), return a list of generators of the group of \(S\)-units of \(D\).

**INPUT:**

- \(S\) - a set of primes of the base field
- \(\text{proof}\) - if False, assume the GRH in computing the class group

**OUTPUT:**

A list of generators of the \(S\)-unit group, in the form \((\text{gen}, \text{order})\), where \text{gen} is a unit of order \text{order}.

**EXAMPLES:**
sage: K.<a> = QuadraticField(-3)
sage: K.unit_group()
Unit group with structure C6 of Number Field in a with defining polynomial \( x^2 + 3 \) with a = 1.732050807568878\*I
sage: K.<a> = QQ['x'].quotient(x^2 + 3)
sage: u,o = K.S_units([])[0]; o
6
sage: 2*u - 1 in {a, -a}
True
sage: u^6
1
sage: u^3
-1
sage: 2*u^2 + 1 in {a, -a}
True

sage: K.<a> = QuadraticField(-3)
sage: y = polygen(K)
sage: L.<b> = K[y].quotient(y^3 + 5); L
Univariate Quotient Polynomial Ring in b over Number Field in a with defining polynomial \( x^2 + 3 \) with a = 1.732050807568878\*I with modulus \( y^3 + 5 \)
sage: [u for u, o in L.S_units([]) if o is Infinity]
[(-1/3*a - 1)*b^2 - 4/3*a*b - 5/6*a + 7/2,
  2/3*a*b^2 + (2/3*a - 2)*b - 5/6*a - 7/2]

Note that all the returned values live where we expect them to:

sage: U = L.S_units([])
sage: type(U[0][0])
<class 'sage.rings.polynomial.polynomial_quotient_ring.PolynomialQuotientRing_field_with_category.element_class'>
sage: type(U[0][1])
<class 'sage.rings.integer.Integer'>
sage: type(U[1][1])
<class 'sage.rings.infinity.PlusInfinity'>

ambient()

base_ring()

Return the base ring of the polynomial ring, of which this ring is a quotient.

EXAMPLES:
The base ring of \( \mathbb{Z}[z]/(z^3 + z^2 + z + 1) \) is \( \mathbb{Z} \).
Polynomials, Release 10.0

```python
sage: R.<z> = PolynomialRing(ZZ)
sage: S.<beta> = R.quo(z^3 + z^2 + z + 1)
sage: S.base_ring()
Integer Ring
```

Next we make a polynomial quotient ring over $S$ and ask for its base ring.

```python
sage: T.<t> = PolynomialRing(S)
sage: W = T.quotient(t^99 + 99)
sage: W.base_ring()
Univariate Quotient Polynomial Ring in beta over Integer Ring with modulus z^3 \rightarrow z^2 + z + 1
```

cardinality()

Return the number of elements of this quotient ring. order is an alias of cardinality.

EXAMPLES:

```python
sage: R.<x> = ZZ[]
sage: R.quo(1).cardinality()
1
sage: R.quo(x^3-2).cardinality()
+Infinity
```

```python
sage: R.<x> = GF(9, 'a')[]
sage: R.quo(2*x^3+x+1).cardinality()
729
sage: GF(9, 'a').extension(2*x^3+x+1).cardinality()
729
sage: R.quo(2).cardinality()
1
```

characteristic()

Return the characteristic of this quotient ring. This is always the same as the characteristic of the base ring.

EXAMPLES:

```python
sage: R.<z> = PolynomialRing(ZZ)
sage: S.<a> = R.quo(z - 19)
sage: S.characteristic()
0
```

```python
sage: R.<x> = PolynomialRing(GF(9, 'a'))
sage: S = R.quotient(x^3 + 1)
sage: S.characteristic()
3
```

2.1. Univariate Polynomials and Polynomial Rings 243
class_group(proof=True)

If self is a quotient ring of a polynomial ring over a number field $K$, by a polynomial of nonzero discriminant, return a list of generators of the class group.

NOTE:

Since the ideal function behaves differently over number fields than over polynomial quotient rings (the quotient does not even know its ring of integers), we return a set of pairs $(\text{gen, order})$, where \text{gen} is a tuple of generators of an ideal $I$ and \text{order} is the order of $I$ in the class group.

INPUT:

• proof - if False, assume the GRH in computing the class group

OUTPUT:

A list of pairs (\text{gen, order}), where \text{gen} is a tuple of elements generating a fractional ideal and \text{order} is the order of $I$ in the class group.

EXAMPLES:

```sage
sage: K.<a> = QuadraticField(-3)
sage: K.class_group()
Class group of order 1 of Number Field in a with defining polynomial x^2 + 3
˓→with a = 1.732050807568878?*I
sage: K.<a> = QQ['x'].quotient(x^2 + 3)
sage: K.class_group()[]
```

A trivial algebra over $\mathbb{Q}(\sqrt{-5})$ has the same class group as its base:

```sage
sage: K.<a> = QuadraticField(-5)
sage: R.<x> = K[]
sage: S.<xbar> = R.quotient(x)
sage: S.class_group()
[((2, -a + 1), 2)]
```

The same algebra constructed in a different way:

```sage
sage: K.<a> = QQ['x'].quotient(x^2 + 5)
sage: K.class_group()()
[((2, a + 1), 2)]
```

Here is an example where the base and the extension both contribute to the class group:

```sage
sage: K.<a> = QuadraticField(-5)
sage: K.class_group()
Class group of order 2 with structure C2 of Number Field in a with defining␣ ˓→polynomial x^2 + 5 with a = 2.236067977499790?*I
sage: R.<x> = K[]
sage: S.<xbar> = R.quotient(x^2 + 23)
sage: S.class_group()
[((2, -a + 1, 1/2*xbar + 1/2, -1/2*a*xbar + 1/2*a + 1), 6)]
```

Here is an example of a product of number fields, both of which contribute to the class group:
Now we take an example over a nontrivial base with two factors, each contributing to the class group:

```
sage: K.<a> = QuadraticField(-5)
sage: R.<x> = K[]
sage: S.<xbar> = R.quotient((x^2 + 23)*(x^2 + 31))
sage: S.class_group()
# representation varies, not tested
[((1/4*xbar^2 + 31/4, (-1/8*a + 1/8)*xbar^2 - 31/8*a + 31/8, 1/16*a*xbar^3 + 1/16*xbar^2 + 31/16*xbar + 31/16, -1/16*a*xbar^3 + (1/16*a + 1/8)*xbar^2 - 31/16*a*xbar + 31/16*a + 31/8), 6),
((-1/4*xbar^2 - 23/4, (1/8*a - 1/8)*xbar^2 + 23/8*a - 23/8, -1/16*xbar^3 - 1/16*xbar^2 - 23/16*xbar - 23/16, 1/16*a*xbar^3 + (-1/16*a - 1/8)*xbar^2 + 23/16*a*xbar - 23/16*a - 23/8), 6),
((-5/4*xbar^2 - 115/4, 1/4*a*xbar^2 + 23/4*a, -1/16*xbar^3 - 7/16*xbar^2 - 23/16*xbar - 161/16, 1/16*a*xbar^3 - 1/16*a*xbar^2 + 23/16*a*xbar - 23/16*a), 2)]
```

Note that all the returned values live where we expect them to:

```
sage: CG = S.class_group()
sage: type(CG[0][0][1])
<class 'sage.rings.polynomial.polynomial_quotient_ring.PolynomialQuotientRing_generic_with_category.element_class'>
sage: type(CG[0][1])
<class 'sage.rings.integer.Integer'>
```

**construction()**

Functorial construction of self

**EXAMPLES:**

```
sage: P.<t>=ZZ[]
sage: Q = P.quo(5+t^2)
sage: F, R = Q.construction()
sage: F(R) == Q
True
sage: P.<t> = GF(3)[]
sage: Q = P.quo([2+t^2])
sage: F, R = Q.construction()
sage: F(R) == Q
True
```

**AUTHOR:**
cover_ring()

Return the polynomial ring of which this ring is the quotient.

EXAMPLES:

```sage
sage: R.<x> = PolynomialRing(QQ)
sage: S = R.quotient(x^2-2)
sage: S.polynomial_ring()
Univariate Polynomial Ring in x over Rational Field
```

degree()

Return the degree of this quotient ring. The degree is the degree of the polynomial that we quotiented out by.

EXAMPLES:

```sage
sage: R.<x> = PolynomialRing(GF(3))
sage: S = R.quotient(x^2005 + 1)
sage: S.degree()
2005
```

discriminant(v=None)

Return the discriminant of this ring over the base ring. This is by definition the discriminant of the polynomial that we quotiented out by.

EXAMPLES:

```sage
sage: R.<x> = PolynomialRing(QQ)
sage: S = R.quotient(x^3 + x^2 + x + 1)
sage: S.discriminant()
-16
sage: S = R.quotient((x + 1) * (x + 1))
sage: S.discriminant()
0
```

The discriminant of the quotient polynomial ring need not equal the discriminant of the corresponding number field, since the discriminant of a number field is by definition the discriminant of the ring of integers of the number field:

```sage
sage: S = R.quotient(x^2 - 8)
sage: S.number_field().discriminant()
8
sage: S.discriminant()
32
```

gen(n=0)

Return the generator of this quotient ring. This is the equivalence class of the image of the generator of the polynomial ring.

EXAMPLES:

```sage
sage: R.<x> = PolynomialRing(QQ)
sage: S = R.quotient(x^2 - 8, 'gamma')
```
is_field(proof=True)

Return whether or not this quotient ring is a field.

EXAMPLES:

```
sage: R.<z> = PolynomialRing(ZZ)
sage: S = R.quo(z^2-2)
sage: S.is_field()  
False
sage: R.<x> = PolynomialRing(QQ)
sage: S = R.quotient(x^2 - 2)
sage: S.is_field()  
True
```

If proof is True, requires the is_irreducible method of the modulus to be implemented:

```
sage: R1.<x> = Qp(2)[]
sage: F1 = R1.quotient_ring(x^2+x+1)
sage: R2.<x> = F1[]
sage: F2 = R2.quotient_ring(x^2+x+1)
sage: F2.is_field()  
Traceback (most recent call last):
...
NotImplementedError: cannot rewrite Univariate Quotient Polynomial Ring in xbar...over 2-adic Field with capped relative precision 20 with modulus (1 + O(2^20))*x^2 + (1 + O(2^20))*x + 1 + O(2^20) as an isomorphic ring
sage: F2.is_field(proof = False)  
False
```

is_finite()

Return whether or not this quotient ring is finite.

EXAMPLES:

```
sage: R.<x> = ZZ[]
sage: R.quo(1).is_finite()  
True
sage: R.quo(x^3-2).is_finite()  
False
sage: R.<x> = GF(9,'a')[]
sage: R.quo(2*x^3+x+1).is_finite()  
True
sage: R.quo(2).is_finite()  
True
sage: P.<v> = GF(2)[]
sage: P.quotient(v^2-v).is_finite()  
True
```
is_integral_domain(proof=True)
Return whether or not this quotient ring is an integral domain.

EXAMPLES:

```python
sage: R.<z> = PolynomialRing(ZZ)
sage: S = R.quotient(z^2 - z)
sage: S.is_integral_domain()
False
sage: T = R.quotient(z^2 + 1)
sage: T.is_integral_domain()
True
sage: U = R.quotient(-1)
sage: U.is_integral_domain()
False
sage: R2.<y> = PolynomialRing(R)
sage: S2 = R2.quotient(z^2 - y^3)
sage: S2.is_integral_domain()
True
sage: S3 = R2.quotient(z^2 - 2*y*z + y^2)
sage: S3.is_integral_domain()
False
sage: R.<z> = PolynomialRing(ZZ.quotient(4))
sage: S = R.quotient(z-1)
sage: S.is_integral_domain()
False
```

krull_dimension()
Return the Krull dimension.

This is the Krull dimension of the base ring, unless the quotient is zero.

EXAMPLES:

```python
sage: R = PolynomialRing(ZZ, 'x').quotient(x^6-1)
sage: R.krull_dimension()
1
sage: R = PolynomialRing(ZZ, 'x').quotient(1)
sage: R.krull_dimension()
-1
```

lift(x)
Return an element of the ambient ring mapping to the given argument.

EXAMPLES:

```python
sage: P.<x> = QQ[]
sage: Q = P.quotient(x^2+2)
sage: Q.lift(Q.0^3)
-2*x
sage: Q(-2*x)
-2*xbar
sage: Q.0^3
-2*xbar
```
modulus()

Return the polynomial modulus of this quotient ring.

EXAMPLES:

```sage
sage: R.<x> = PolynomialRing(GF(3))
sage: S = R.quotient(x^2 - 2)
sage: S.modulus()
x^2 + 1
```

ngens()

Return the number of generators of this quotient ring over the base ring. This function always returns 1.

EXAMPLES:

```sage
sage: R.<x> = PolynomialRing(QQ)
sage: S.<y> = PolynomialRing(R)
sage: T.<z> = S.quotient(y + x)
sage: T
Univariate Quotient Polynomial Ring in z over Univariate Polynomial Ring in x over Rational Field with modulus y + x
sage: T.ngens()
1
```

number_field()

Return the number field isomorphic to this quotient polynomial ring, if possible.

EXAMPLES:

```sage
sage: R.<x> = PolynomialRing(QQ)
sage: S.<alpha> = R.quotient(x^29 - 17*x - 1)
sage: K = S.number_field()
sage: K
Number Field in alpha with defining polynomial x^29 - 17*x - 1
sage: alpha = K.gen()
sage: alpha^29
17*alpha + 1
```

order()

Return the number of elements of this quotient ring.

order is an alias of cardinality.

EXAMPLES:

```sage
sage: R.<x> = ZZ[]
sage: R.quo(1).cardinality()
1
sage: R.quo(x^3-2).cardinality()
+Infinity
sage: R.quo(1).order()
1
sage: R.quo(x^3-2).order()
+Infinity
```
polynomial_ring()

Return the polynomial ring of which this ring is the quotient.

EXAMPLES:

```
sage: R.<x> = GF(9,'a')[]
sage: R.quo(2*x^3+x+1).cardinality()
729
sage: GF(9,'a').extension(2*x^3+x+1).cardinality()
729
sage: R.quo(2).cardinality()
1
```

random_element(*args, **kwds)

Return a random element of this quotient ring.

INPUT:

- *args, **kwds - Arguments for randomization that are passed on to the random_element method of the polynomial ring, and from there to the base ring

OUTPUT:

Element of this quotient ring

EXAMPLES:

```
sage: F1.<a> = GF(2^7)
sage: P1.<x> = F1[]
sage: F2 = F1.extension(x^2+x+1, 'u')
sage: F2.random_element().parent() is F2
True
```

retract(x)

Return the coercion of x into this polynomial quotient ring.

The rings that coerce into the quotient ring canonically are:

- this ring
- any canonically isomorphic ring
- anything that coerces into the ring of which this is the quotient

selmer_generators(S, m, proof=True)

If self is an étale algebra $D$ over a number field $K$ (i.e. a quotient of $K[x]$ by a squarefree polynomial) and $S$ is a finite set of places of $K$, compute the Selmer group $D(S, m)$. This is the subgroup of $D^*/(D^*)^m$ consisting of elements $a$ such that $D(\sqrt[m]{a})/D$ is unramified at all primes of $D$ lying above a place outside of $S$.

INPUT:

- $S$ - A set of primes of the coefficient ring (which is a number field).
- $m$ - a positive integer
- **proof** - if False, assume the GRH in computing the class group

**OUTPUT:**
A list of generators of $D(S, m)$.

**EXAMPLES:**

```python
sage: K.<a> = QuadraticField(-5)
sage: R.<x> = K[]
sage: D.<T> = R.quotient(x)
sage: D.selmer_generators((), 2)
[-1, 2]
sage: D.selmer_generators([K.ideal(2, -a+1)], 2)
[2, -1]
sage: D.selmer_generators([K.ideal(2, -a+1), K.ideal(3, a+1)], 2)
[2, a + 1, -1]
sage: D.selmer_generators((K.ideal(2, -a+1), K.ideal(3, a+1)), 4)
[2, a + 1, -1]
sage: D.selmer_generators([K.ideal(2, -a+1)], 3)
[2]
sage: D.selmer_generators([K.ideal(2, -a+1), K.ideal(3, a+1)], 3)
[2, a + 1]
sage: D.selmer_generators([K.ideal(2, -a+1), K.ideal(3, a+1), K.ideal(a)], 3)
[2, a + 1, -a]
```

**selmer_group** $(S, m, proof=True)$

If self is an étale algebra $D$ over a number field $K$ (i.e. a quotient of $K[x]$ by a squarefree polynomial) and $S$ is a finite set of places of $K$, compute the Selmer group $D(S, m)$. This is the subgroup of $D^*/(D^*)^m$ consisting of elements $a$ such that $D(\sqrt{a})/D$ is unramified at all primes of $D$ lying above a place outside of $S$.

**INPUT:**

- **S** - A set of primes of the coefficient ring (which is a number field).
- **m** - a positive integer
- **proof** - if False, assume the GRH in computing the class group

**OUTPUT:**
A list of generators of $D(S, m)$.

**EXAMPLES:**

```python
sage: K.<a> = QuadraticField(-5)
sage: R.<x> = K[]
sage: D.<T> = R.quotient(x)
sage: D.selmer_generators((), 2)
[-1, 2]
sage: D.selmer_generators([K.ideal(2, -a+1)], 2)
[2, -1]
sage: D.selmer_generators([K.ideal(2, -a+1), K.ideal(3, a+1)], 2)
[2, a + 1, -1]
sage: D.selmer_generators((K.ideal(2, -a+1), K.ideal(3, a+1)), 4)
[2, a + 1, -1]
sage: D.selmer_generators([K.ideal(2, -a+1)], 3)
[2]
sage: D.selmer_generators([K.ideal(2, -a+1), K.ideal(3, a+1)], 3)
[2, a + 1]
sage: D.selmer_generators([K.ideal(2, -a+1), K.ideal(3, a+1), K.ideal(a)], 3)
[2, a + 1, -a]
```

(continues on next page)
**units** *(proof=True)*

If this quotient ring is over a number field \( K \), by a polynomial of nonzero discriminant, returns a list of generators of the units.

**INPUT:**

- proof - if False, assume the GRH in computing the class group

**OUTPUT:**

A list of generators of the unit group, in the form \((\text{gen}, \text{order})\), where \(\text{gen} \) is a unit of order \(\text{order}\).

**EXAMPLES:**

```python
sage: K.<a> = QuadraticField(-3)
sage: K.unit_group()
Unit group with structure C6 of Number Field in a with defining polynomial \( x^2 + 3 \) with a = 1.732050807568878\*I
sage: K.<a> = QQ['x'].quotient(x^2 + 3)
sage: u = K.units()[0][0]
sage: 2*u - 1 in {a, -a}
True
sage: 2*u^2 + 1 in {a, -a}
True
```

```python
sage: K.<a> = QQ['x'].quotient(x^2 + 5)
sage: K.units()(()
[(-1, 2)]
```

```python
sage: K.<a> = QuadraticField(-3)
sage: y = polygen(K)
sage: L.<b> = K['y'].quotient(y^3 + 5); L
Univariate Quotient Polynomial Ring in b over Number Field in a with defining polynomial \( x^2 + 3 \) with a = 1.732050807568878\*I with modulus \( y^3 + 5 \)
sage: [u for u, o in L.units() if o is Infinity]
```

```python
[(-1/3*a - 1)*b^2 - 4/3*a*b - 5/6*a + 7/2, 2/3*a*b^2 + (2/3*a - 2)*b - 5/6*a - 7/2]
```

```python
sage: L.<b> = K.extension(y^3 + 5)
sage: L.unit_group()
Unit group with structure C6 x Z x Z of Number Field in b with defining polynomial \( x^3 + 5 \) over its base field
sage: L.unit_group().gens()  # abstract generators
(u0, u1, u2)
sage: L.unit_group().gens_values()[1:]
```

```python
[(-1/3*a - 1)*b^2 - 4/3*a*b - 5/6*a + 7/2, 2/3*a*b^2 + (2/3*a - 2)*b - 5/6*a]
```

(continues on next page)
Note that all the returned values live where we expect them to:

```
sage: L.<b> = K['y'].quotient(y^3 + 5)
sage: U = L.units()
sage: type(U[0][0])
<class 'sage.rings.polynomial.polynomial_quotient_ring.PolynomialQuotientRing_field_with_category.element_class'>
sage: type(U[0][1])
<class 'sage.rings.integer.Integer'>
sage: type(U[1][1])
<class 'sage.rings.infinity.PlusInfinity'>
```

```
sage: L.<b> = K['y'].quotient(y^3 + 5)
sage: U = L.units()
sage: type(U[0][0])
<class 'sage.rings.polynomial.polynomial_quotient_ring.PolynomialQuotientRing_field_with_category.element_class'>
sage: type(U[0][1])
<class 'sage.rings.integer.Integer'>
sage: type(U[1][1])
<class 'sage.rings.infinity.PlusInfinity'>
```

`sage.rings.polynomial.polynomial_quotient_ring.is_PolynomialQuotientRing(x)`

### 2.1.23 Elements of Quotients of Univariate Polynomial Rings

**EXAMPLES:** We create a quotient of a univariate polynomial ring over \( \mathbb{Z} \).

```
sage: R.<x> = ZZ[]
sage: S.<a> = R.quotient(x^3 + 3*x - 1)
sage: 2 * a^3
-6*a + 2
```

Next we make a univariate polynomial ring over \( \mathbb{Z}[x]/(x^3 + 3x - 1) \).

```
sage: S1.<y> = S[]
```

And, we quotient out that by \( y^2 + a \).

```
sage: T.<z> = S1.quotient(y^2+a)
```

In the quotient \( z^2 \) is \( -a \).

```
sage: z^2
-a
```

And since \( a^3 = -3x + 1 \), we have:

```
sage: z^6
3*a - 1
```

```
sage: R.<x> = PolynomialRing(Integers(9))
sage: S.<a> = R.quotient(x^4 + 2*x^3 + x + 2)
sage: a^100
7*a^3 + 8*a + 7
```

```
sage: R.<x> = PolynomialRing(Integers(9))
sage: S.<a> = R.quotient(x^4 + 2*x^3 + x + 2)
sage: a^100
7*a^3 + 8*a + 7
```

```
sage: R.<x> = PolynomialRing(QQ)
sage: S.<a> = R.quotient(x^3-2)
sage: a
```

(continues on next page)
For the purposes of comparison in Sage the quotient element $a^3$ is equal to $x^3$. This is because when the comparison is performed, the right element is coerced into the parent of the left element, and $x^3$ coerces to $a^3$.

```sage
sage: a == x
True
sage: a^3 == x^3
True
sage: x^3
x^3
sage: S(x^3)
2
```

AUTHORS:

• William Stein

class sage.rings.polynomial.polynomial_quotient_ring_element.PolynomialQuotientRingElement

Bases: Polynomial_singular_repr, CommutativeRingElement

Element of a quotient of a polynomial ring.

EXAMPLES:

```sage
sage: P.<x> = QQ[]
sage: Q.<xi> = P.quo([(x^2+1)])
sage: xi^2
-1
sage: singular(xi)
xi
sage: (singular(xi)*singular(xi)).NF('std(0)')
-1
```

`charpoly(var)`

The characteristic polynomial of this element, which is by definition the characteristic polynomial of right multiplication by this element.

INPUT:

• `var` - string - the variable name

EXAMPLES:

```sage
sage: R.<x> = PolynomialRing(QQ)
sage: S.<a> = R.quo(x^3 -389*x^2 + 2*x - 5)
sage: a.charpoly('X')
X^3 - 389*X^2 + 2*X - 5
```
fcp(var='x')

Return the factorization of the characteristic polynomial of this element.

EXAMPLES:

```
sage: R.<x> = PolynomialRing(QQ)
sage: S.<a> = R.quotient(x^3 -389*x^2 + 2*x - 5)
sage: a.fcp('x')
x^3 - 389*x^2 + 2*x - 5
sage: S(1).fcp('y')
(y - 1)^3
```

field_extension(names)

Given a polynomial with base ring a quotient ring, return a 3-tuple: a number field defined by the same polynomial, a homomorphism from its parent to the number field sending the generators to one another, and the inverse isomorphism.

INPUT:

• names - name of generator of output field

OUTPUT:

• field
  • homomorphism from self to field
  • homomorphism from field to self

EXAMPLES:

```
sage: R.<x> = PolynomialRing(QQ)
sage: S.<alpha> = R.quotient(x^3-2)
sage: F.<a>, f, g = alpha.field_extension()
sage: F
Number Field in a with defining polynomial x^3 - 2
code: sage: a = F.gen()
code: f(alpha)
code: g(a)
```

Over a finite field, the corresponding field extension is not a number field:

```
sage: R.<x> = GF(25,'b')[x]
sage: S.<a> = R.quo(x^3 + 2*x + 1)
sage: F.<b>, g, h = a.field_extension()
sage: h(b^2 + 3)
```

We do an example involving a relative number field:

```
sage: R.<x> = QQ['x']
sage: K.<a> = NumberField(x^3-2)
sage: S.<X> = K['X']
```
Another more awkward example:

```python
sage: R.<x> = QQ['x']
sage: K.<a> = NumberField(x^3-2)
sage: S.<X> = K['X']
sage: f = (X+a)^3 + 2*(X+a) + 1
sage: f
X^3 + 3*a*X^2 + (3*a^2 + 2)*X + 2*a + 3
sage: Q.<z> = S.quo(f)
sage: F.<w>, g, h = z.field_extension()
sage: c = g(z)
sage: f(c)
0
sage: h(g(z))
z
sage: g(h(w))
w
```

AUTHORS:

- Craig Citro (2006-08-06)
- William Stein (2006-08-06)

**is_unit()**

Return True if self is invertible.

**Warning:** Only implemented when the base ring is a field.

**EXAMPLES:**

```python
sage: R.<x> = QQ[]
sage: S.<y> = R.quotient(x^2 + 2*x + 1)
sage: (2*y).is_unit()
True
sage: (y+1).is_unit()
False
```

**lift()**

Return lift of this polynomial quotient ring element to the unique equivalent polynomial of degree less than the modulus.

**EXAMPLES:**

```python
sage: R.<x> = PolynomialRing(QQ)
sage: S.<a> = R.quotient(x^3-2)
sage: b = a^2 - 3
sage: b
a^2 - 3
```

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(continued from previous page)

```
sage: b.lift()
x^2 - 3
```

**list** *(copy=True)*

Return list of the elements of self, of length the same as the degree of the quotient polynomial ring.

**EXAMPLES:**

```
sage: R.<x> = PolynomialRing(QQ)
sage: S.<a> = R.quotient(x^3 + 2*x - 5)
sage: a^10
-134*a^2 - 35*a + 300
sage: (a^10).list()
[300, -35, -134]
```

**matrix()**

The matrix of right multiplication by this element on the power basis for the quotient ring.

**EXAMPLES:**

```
sage: R.<x> = PolynomialRing(QQ)
sage: S.<a> = R.quotient(x^3 + 2*x - 5)
sage: a.matrix()
[ 0 1 0]
[ 0 0 1]
[ 5 -2 0]
```

**minpoly()**

The minimal polynomial of this element, which is by definition the minimal polynomial of the matrix() of this element.

**ALGORITHM:** Use `minpoly_mod()` if possible, otherwise compute the minimal polynomial of the matrix().

**EXAMPLES:**

```
sage: R.<x> = PolynomialRing(QQ)
sage: S.<a> = R.quotient(x^3 + 2*x - 5)
sage: (a+123).minpoly()
x^3 - 369*x^2 + 45389*x - 1861118
sage: (a+123).matrix().minpoly()
x^3 - 369*x^2 + 45389*x - 1861118
```

One useful application of this function is to compute a minimal polynomial of a finite-field element over an intermediate extension, rather than the absolute minimal polynomial over the prime field:

```
sage: F2.<i> = GF((431,2), modulus=[1,0,1])
sage: F6.<u> = F2.extension(3)
sage: (u+1).minpoly()
x^3 + (396*i + 428)*x^2 + (80*i + 39)*x + 9*i + 178
```

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norm()

The norm of this element, which is the determinant of the matrix of right multiplication by this element.

EXAMPLES:

```
sage: R.<x> = PolynomialRing(QQ)
sage: S.<a> = R.quotient(x^3 - 389*x^2 + 2*x - 5)
sage: a.norm()
5
```

rational_reconstruction(*args, **kwargs)

Compute a rational reconstruction of this polynomial quotient ring element to its cover ring.

This method is a thin convenience wrapper around \texttt{Polynomial.rational\_reconstruction()}.

EXAMPLES:

```
sage: R.<x> = GF(65537)[]
sage: m = x^11 + 25345*x^10 + 10956*x^9 + 13873*x^8 + 23962*x^7 + 17496*x^6 +
     30348*x^5 + 7440*x^4 + 65438*x^3 + 7676*x^2 + 54266*x + 47805
sage: f = 20437*x^10 + 62630*x^9 + 63241*x^8 + 12820*x^7 + 42171*x^6 + 63091*x^5 +
     15288*x^4 + 32516*x^3 + 2181*x^2 + 45236*x + 2447
sage: f_mod_m = R.quotient(m)(f)
sage: f_mod_m.rational_reconstruction()
(51388*x^5 + 29141*x^4 + 59341*x^3 + 7034*x^2 + 14152*x + 23746,
 x^5 + 15208*x^4 + 19504*x^3 + 20457*x^2 + 11180*x + 28352)
```

trace()

The trace of this element, which is the trace of the matrix of right multiplication by this element.

EXAMPLES:

```
sage: R.<x> = PolynomialRing(QQ)
sage: S.<a> = R.quotient(x^3 - 389*x^2 + 2*x - 5)
sage: a.trace()
389
```

## 2.1.24 Polynomial Compilers

AUTHORS:

- Tom Boothby, initial design & implementation
- Robert Bradshaw, bug fixes / suggested & assisted with significant design improvements

```python
class sage.rings.polynomial.polynomial_compiled.CompiledPolynomialFunction
    Bases: object

    Builds a reasonably optimized directed acyclic graph representation for a given polynomial. A CompiledPoly-
    nomialFunction is callable from python, though it is a little faster to call the eval function from pyrex.

    This class is not intended to be called by a user, rather, it is intended to improve the performance of immutable
    polynomial objects.
```

Todo:

- Recursive calling
• Faster casting of coefficients / argument
• Multivariate polynomials
• Cython implementation of Pippenger’s Algorithm that doesn’t depend heavily upon dicts.
• Computation of parameter sequence suggested by Pippenger
• Univariate exponentiation can use Brauer’s method to improve extremely sparse polynomials of very high degree

```python
class sage.rings.polynomial.polynomial_compiled.abc_pd
    Bases: binary_pd
class sage.rings.polynomial.polynomial_compiled.add_pd
    Bases: binary_pd
class sage.rings.polynomial.polynomial_compiled.binary_pd
    Bases: generic_pd
class sage.rings.polynomial.polynomial_compiled.coeff_pd
    Bases: generic_pd
class sage.rings.polynomial.polynomial_compiled.dummy_pd
    Bases: generic_pd
class sage.rings.polynomial.polynomial_compiled.generic_pd
    Bases: object
class sage.rings.polynomial.polynomial_compiled.mul_pd
    Bases: binary_pd
class sage.rings.polynomial.polynomial_compiled.pow_pd
    Bases: unary_pd
class sage.rings.polynomial.polynomial_compiled.sqr_pd
    Bases: unary_pd
class sage.rings.polynomial.polynomial_compiled.unary_pd
    Bases: generic_pd
class sage.rings.polynomial.polynomial_compiled.univar_pd
    Bases: generic_pd
class sage.rings.polynomial.polynomial_compiled.var_pd
    Bases: generic_pd
```

### 2.1.25 Polynomial multiplication by Kronecker substitution

### 2.1.26 Integer-valued polynomial rings

**AUTHORS:**

• Frédéric Chapoton (2023-03): Initial version
class sage.rings.polynomial.integer_valued_polynomials.IntegerValuedPolynomialRing(R)
Bases: UniqueRepresentation, Parent

The integer-valued polynomial ring over a base ring \( R \).

Integer-valued polynomial rings are commutative and associative algebras, with a basis indexed by non-negative integers.

There are two natural bases, made of the sequence \( \binom{x^n}{n} \) for \( n \geq 0 \) (the binomial basis) and of the other sequence \( \binom{x+n}{n} \) for \( n \geq 0 \) (the shifted basis).

These two bases are available as follows:

```python
sage: B = IntegerValuedPolynomialRing(QQ).Binomial()
sage: S = IntegerValuedPolynomialRing(QQ).Shifted()
```

or by using the shortcuts:

```python
sage: B = IntegerValuedPolynomialRing(QQ).B()
sage: S = IntegerValuedPolynomialRing(QQ).S()
```

There is a conversion formula between the two bases:

\[
\binom{x^i}{i} = \sum_{k=0}^{i} (-1)^{i-k} \binom{i}{k} \binom{x+k}{k}
\]

with inverse:

\[
\binom{x+i}{i} = \sum_{k=0}^{i} \binom{i}{k} \binom{x+k}{k}
\]

REFERENCES:

- Wikipedia article Integer-valued polynomial

B

alias of Binomial

class Bases(parent_with_realization)
Bases: Category_realization_of_parent
class ElementMethods
Bases: object

content()

Return the content of \( \text{self} \).

This is the gcd of the coefficients.

EXAMPLES:

```python
sage: F = IntegerValuedPolynomialRing(ZZ).S()
sage: B = F.basis()
sage: (3*B[4]+6*B[7]).content()
3
```

polynomial()

Convert to a polynomial in \( x \).

EXAMPLES:
```python
sage: F = IntegerValuedPolynomialRing(ZZ).S()
sage: B = F.gen()
sage: (B+1).polynomial()
x + 2

sage: F = IntegerValuedPolynomialRing(ZZ).B()
sage: B = F.gen()
sage: (B+1).polynomial()
x + 1
```

**shift**(\(j=1\))

Shift all indices by \(j\).

**INPUT:**
- \(j\) – integer (default: 1)

In the binomial basis, the shift by 1 corresponds to a summation operator from 0 to \(x\).

**EXAMPLES:**

```python
sage: F = IntegerValuedPolynomialRing(ZZ).B()
sage: B = F.gen()
sage: (B+1).shift()
sage: (B+1).shift(3)
```

**sum_of_coefficients()**

Return the sum of coefficients.

In the shifted basis, this is the evaluation at \(x = 0\).

**EXAMPLES:**

```python
sage: F = IntegerValuedPolynomialRing(ZZ).S()
sage: B = F.basis()
sage: (B[2]*B[4]).sum_of_coefficients()
1
```

**class** `ParentMethods`

**Bases:** object

**algebra_generators()**

Return the generators of this algebra.

**EXAMPLES:**

```python
sage: A = IntegerValuedPolynomialRing(ZZ).S(); A
Integer-Valued Polynomial Ring over Integer Ring in the shifted basis
sage: A.algebra_generators()
Family (S[1],)
```

**degree_on_basis**(\(m\))

Return the degree of the basis element indexed by \(m\).

**EXAMPLES:**

```python
```
```python
sage: A = IntegerValuedPolynomialRing(QQ).S()
sage: A.degree_on_basis(4)
4
```

**from_polynomial** ($p$)

Convert a polynomial into the ring of integer-valued polynomials.

This raises a `ValueError` if this is not possible.

**INPUT:**
- $p$ – a polynomial in one variable

**EXAMPLES:**

```python
sage: A = IntegerValuedPolynomialRing(ZZ).S()
sage: S = A.basis()
sage: S[5].polynomial()
1/120*x^5 + 1/8*x^4 + 17/24*x^3 + 15/8*x^2 + 137/60*x + 1
sage: A.from_polynomial(_)
S[5]
sage: x = polygen(QQ, 'x')
sage: A.from_polynomial(x)
-S[0] + S[1]
sage: A = IntegerValuedPolynomialRing(ZZ).B()
sage: B = A.basis()
sage: B[5].polynomial()
1/120*x^5 - 1/12*x^4 + 7/24*x^3 - 5/12*x^2 + 1/5*x
sage: A.from_polynomial(_)
B[5]
sage: x = polygen(QQ, 'x')
sage: A.from_polynomial(x)
B[1]
```

**gen** ($i=0$)

Return the generator of this algebra.

The optional argument is ignored.

**EXAMPLES:**

```python
sage: F = IntegerValuedPolynomialRing(ZZ).B()
sage: F.gen()
B[1]
```

**gens**()

Return the generators of this algebra.

**EXAMPLES:**

```python
sage: A = IntegerValuedPolynomialRing(ZZ).S(); A
Integer-Valued Polynomial Ring over Integer Ring
in the shifted basis
sage: A.algebra_generators()
Family (S[1],)
```
one_basis()

Return the number 0, which index the unit of this algebra.

EXAMPLES:

```
sage: A = IntegerValuedPolynomialRing(QQ).S()
sage: A.one_basis()
0
sage: A.one()
S[0]
```

super_categories()

Return the super-categories of `self`.

EXAMPLES:

```
sage: A = IntegerValuedPolynomialRing(QQ); A
Integer-Valued Polynomial Ring over Rational Field
sage: C = A.Bases(); C
Category of bases of Integer-Valued Polynomial Ring over Rational Field
sage: C.super_categories()
[Category of realizations of Integer-Valued Polynomial Ring over Rational Field,
 Join of Category of algebras with basis over Rational Field and
 Category of filtered algebras over Rational Field and
 Category of commutative algebras over Rational Field and
 Category of realizations of unital magmas]
```

class Binomial(A)

Bases: `CombinatorialFreeModule`, `BindableClass`

The integer-valued polynomial ring in the binomial basis.

The basis used here is given by $B[i] = \binom{i}{i}$ for $i \in \mathbb{N}$.

Assuming $n_1 \leq n_2$, the product of two monomials $B[n_1] \cdot B[n_2]$ is given by the sum

$$\sum_{k=0}^{n_1} \binom{n_1}{k} \binom{n_1 + n_2 - k}{n_1} B[n_1 + n_2 - k].$$

The product of two monomials is therefore a positive linear combination of monomials.

EXAMPLES:

```
sage: F = IntegerValuedPolynomialRing(QQ).B(); F
Integer-Valued Polynomial Ring over Rational Field
in the binomial basis
sage: F.gen()
B[1]
sage: S = IntegerValuedPolynomialRing(ZZ).B(); S
Integer-Valued Polynomial Ring over Integer Ring
in the binomial basis
sage: S.base_ring()
```
Integer Ring

\begin{Verbatim}
\texttt{sage: G = IntegerValuedPolynomialRing(S).B(); G}
\end{Verbatim}
Integer-Valued Polynomial Ring over Integer-Valued Polynomial Ring
over Integer Ring in the binomial basis in the binomial basis

\begin{Verbatim}
\texttt{sage: G.base_ring()}
\end{Verbatim}
Integer-Valued Polynomial Ring over Integer Ring
in the binomial basis

Integer-valued polynomial rings commute with their base ring:

\begin{Verbatim}
\texttt{sage: K = IntegerValuedPolynomialRing(QQ).B()}
\texttt{sage: a = K.gen()}
\texttt{sage: K.is_commutative()}
True
\texttt{sage: L = IntegerValuedPolynomialRing(K).B()}
\texttt{sage: c = L.gen()}
\texttt{sage: L.is_commutative()}
True
\texttt{sage: s = a * c^3; s}
\texttt{sage: parent(s)}
Integer-Valued Polynomial Ring over Integer-Valued Polynomial
Ring over Rational Field in the binomial basis in the binomial basis
\end{Verbatim}

Integer-valued polynomial rings are commutative:

\begin{Verbatim}
\texttt{sage: c^3 * a == c * a * c * c}
True
\end{Verbatim}

We can also manipulate elements in the basis:

\begin{Verbatim}
\texttt{sage: F = IntegerValuedPolynomialRing(QQ).B()}
\texttt{sage: B = F.basis()}
\end{Verbatim}

and coerce elements from our base field:

\begin{Verbatim}
\texttt{sage: F(4/3)}
4/3*B[0]
\end{Verbatim}

\begin{class}
\textbf{Element}
\end{class}
Bases: \texttt{IndexedFreeModuleElement}

\begin{method}
\textbf{product_on_basis}(n1, n2)
\end{method}
Return the product of basis elements n1 and n2.

INPUT:
\begin{itemize}
\item n1, n2 – integers
\end{itemize}

EXAMPLES:
The integer-valued polynomial ring in the shifted basis.

The basis used here is given by $S[i] = \binom{x_i + x}{i}$ for $i \in \mathbb{N}$.

Assuming $n_1 \leq n_2$, the product of two monomials $S[n_1] \cdot S[n_2]$ is given by the sum

$$
\sum_{k=0}^{n_1} (-1)^k \binom{n_1}{k} \binom{n_1 + n_2 - k}{n_1} S[n_1 + n_2 - k].
$$

**EXAMPLES:**

```python
sage: F = IntegerValuedPolynomialRing(QQ).S(); F
Integer-Valued Polynomial Ring over Rational Field in the shifted basis
sage: F.gen()
S[1]

sage: S = IntegerValuedPolynomialRing(ZZ).S(); S
Integer-Valued Polynomial Ring over Integer Ring in the shifted basis
sage: S.base_ring()
Integer Ring

sage: G = IntegerValuedPolynomialRing(S).S(); G
Integer-Valued Polynomial Ring over Integer-Valued Polynomial Ring over Integer Ring in the shifted basis in the shifted basis
sage: G.base_ring()
Integer-Valued Polynomial Ring over Integer Ring in the shifted basis
```

Integer-valued polynomial rings commute with their base ring:

```python
sage: K = IntegerValuedPolynomialRing(QQ).S()
sage: a = K.gen()
sage: K.is_commutative()
True
sage: L = IntegerValuedPolynomialRing(K).S()
sage: c = L.gen()
sage: L.is_commutative()
True
sage: s = a * c^3; s
```

(continues on next page)
Integer-valued polynomial rings are commutative:

```
sage: c^3 * a == c * a * c * c
True
```

We can also manipulate elements in the basis and coerce elements from our base field:

```
sage: F = IntegerValuedPolynomialRing(QQ).S()
sage: S = F.basis()
```

**class Element**

Bases: `IndexedFreeModuleElement`

**delta()**

Return the image by the difference operator $\Delta$.

The operator $\Delta$ is defined on polynomials by

$$f \mapsto f(x + 1) - f(x).$$

**EXAMPLES:**

```
sage: F = IntegerValuedPolynomialRing(ZZ).S()
sage: S = F.basis()
sage: S[5].delta()
```

**derivative_at_minus_one()**

Return the derivative at $-1$.

This is sometimes useful when $-1$ is a root.

**See also:**

`umbra()`

**EXAMPLES:**

```
sage: F = IntegerValuedPolynomialRing(ZZ).S()
sage: B = F.gen()
sage: (B+1).derivative_at_minus_one()
1
```

**h_polynomial()**

Return the $h$-vector as a polynomial.

**See also:**

`h_vector()`
EXAMPLES:

```
sage: x = polygen(QQ, 'x')  
sage: A = IntegerValuedPolynomialRing(ZZ).S()  
sage: ex = A.from_polynomial((1+x)**3)  
sage: ex.h_polynomial()  
z^3 + 4*z^2 + z
```

**h_vector()**

Return the numerator of the generating series of values.

If `self` is an Ehrhart polynomial, this is the \( h \)-vector.

See also:

`h_polynomial()`

EXAMPLES:

```
sage: x = polygen(QQ, 'x')  
sage: A = IntegerValuedPolynomialRing(ZZ).S()  
sage: ex = A.from_polynomial((1+x)**3)  
sage: ex.h_vector()  
(0, 1, 4, 1)
```

**umbra()**

Return the Bernoulli umbra.

This is the derivative at \(-1\) of the shift by one.

See also:

`derivative_at_minus_one()`

EXAMPLES:

```
sage: F = IntegerValuedPolynomialRing(ZZ).S()  
sage: B = F.gen()  
sage: (B+1).umbra()  
3/2
```

**variable_shift**(\(k=1\))

Return the image by the shift of variables.

On polynomials, the action is the shift on variables \( x \mapsto x + k \).

INPUT:

• \( k \) – integer (default: 1)

EXAMPLES:

```
sage: A = IntegerValuedPolynomialRing(ZZ).S()  
sage: S = A.basis()  
sage: S[5].variable_shift()  
sage: S[5].variable_shift(-1)  
```
from_h_vector(h)

Convert from some $h$-vector.

INPUT:

• $h$ – a tuple or vector

See also:

Element.h_vector()  

EXAMPLES:

```
sage: A = IntegerValuedPolynomialRing(ZZ).S()
sage: S = A.basis()
sage: A.from_h_vector(ex.h_vector())
```

product_on_basis(n1, n2)

Return the product of basis elements $n1$ and $n2$.

INPUT:

• $n1, n2$ – integers

EXAMPLES:

```
sage: A = IntegerValuedPolynomialRing(QQ).S()
sage: A.product_on_basis(0, 1)
S[1]
sage: A.product_on_basis(1, 2)
```

a_realization()

Return a default realization.

The Binomial realization is chosen.

EXAMPLES:

```
sage: IntegerValuedPolynomialRing(QQ).a_realization()
Integer-Valued Polynomial Ring over Rational Field
in the binomial basis
```

2.2 Generic Convolution

Asymptotically fast convolution of lists over any commutative ring in which the multiply-by-two map is injective. (More precisely, if $x \in R$, and $x = 2^k \cdot y$ for some $k \geq 0$, we require that $R(x/2^k)$ returns $y$.)

The main function to be exported is convolution().

EXAMPLES:

```
sage: convolution([1, 2, 3, 4, 5], [6, 7])
[6, 19, 32, 45, 58, 35]
```

The convolution function is reasonably fast, even though it is written in pure Python. For example, the following takes less than a second:
**sage:** `v = convolution(list(range(1000)), list(range(1000)))`

**ALGORITHM:**
Converts the problem to multiplication in the ring $S[x]/(x^M - 1)$, where $S = R[y]/(y^K + 1)$ (where $R$ is the original base ring). Performs FFT with respect to the roots of unity $1, y, y^2, \ldots, y^{2K-1}$ in $S$. The FFT/IFFT are accomplished with just additions and subtractions and rotating python lists. (I think this algorithm is essentially due to Schonhage, not completely sure.) The pointwise multiplications are handled recursively, switching to a classical algorithm at some point.

Complexity is $O(n \log(n) \log(\log(n)))$ additions/subtractions in $R$ and $O(n \log(n))$ multiplications in $R$.

**AUTHORS:**
- David Harvey (2007-07): first implementation
- William Stein: editing the docstrings for inclusion in Sage.

**2.3 Fast calculation of cyclotomic polynomials**

This module provides a function `cyclotomic_coeffs()`, which calculates the coefficients of cyclotomic polynomials. This is not intended to be invoked directly by the user, but it is called by the method `cyclotomic_polynomial()` method of univariate polynomial ring objects and the top-level `cyclotomic_polynomial()` function.

**sage.rings.polynomial.convolution.convolution(L1, L2)**
Return convolution of non-empty lists L1 and L2.
L1 and L2 may have arbitrary lengths.

**EXAMPLES:**
```
sage: convolution([1, 2, 3], [4, 5, 6, 7])
[4, 13, 28, 34, 32, 21]
```

**sage.rings.polynomial.cyclotomic.bateman_bound(nn)**
Return the coefficients of the n-th cyclotomic polynomial by using the formula
\[
\Phi_n(x) = \prod_{d | n} (1 - x^{n/d})^\mu(d)
\]
where $\mu(d)$ is the Möbius function that is 1 if $d$ has an even number of distinct prime divisors, -1 if it has an odd number of distinct prime divisors, and 0 if $d$ is not squarefree.

Multiplications and divisions by polynomials of the form $1 - x^n$ can be done very quickly in a single pass.
If `sparse` is `True`, the result is returned as a dictionary of the non-zero entries, otherwise the result is returned as a list of python ints.
EXAMPLES:

```python
sage: from sage.rings.polynomial.cyclotomic import cyclotomic_coeffs
sage: cyclotomic_coeffs(30)
[1, 1, 0, -1, -1, -1, 0, 1, 1]
sage: cyclotomic_coeffs(10^5)
{0: 1, 10000: -1, 20000: 1, 30000: -1, 40000: 1}
sage: R = QQ['x']
sage: R(cyclotomic_coeffs(30))
x^8 + x^7 - x^5 - x^4 - x^3 + x + 1
```

Check that it has the right degree:

```python
sage: euler_phi(30)
8
sage: R(cyclotomic_coeffs(14)).factor()
x^6 - x^5 + x^4 - x^3 + x^2 - x + 1
```

The coefficients are not always +/-1:

```python
sage: cyclotomic_coeffs(105)
[1, 1, 1, 0, 0, -1, -1, -2, -1, -1, 0, 1, 1, 1, 1, 0, 0, -1, 0, -1, 0, -1, 0,
 -0, -1, 0, -1, 0, 1, 1, 1, 1, 1, 0, 0, -1, -1, -2, -1, -1, 0, 0, 0, 1, 1, 1]
```

In fact the height is not bounded by any polynomial in n (Erdos), although takes a while just to exceed linear:

```python
sage: v = cyclotomic_coeffs(1181895)
sage: max(v)
14102773
```

The polynomial is a palindrome for any n:

```python
sage: n = ZZ.random_element(50000)
sage: v = cyclotomic_coeffs(n, sparse=False)
sage: v == list(reversed(v))
True
```

AUTHORS:

• Robert Bradshaw (2007-10-27): initial version (inspired by work of Andrew Arnold and Michael Monagan)

REFERENCE:

• http://www.cccm.sfu.ca/~ada26/cyclotomic/

sage.rings.polynomial.cyclotomic.cyclotomic_value(n, x)

Return the value of the \( \Phi_n \) at \( x \).

INPUT:

• \( n \) – an Integer, specifying which cyclotomic polynomial is to be evaluated
• \( x \) – an element of a ring

OUTPUT:

• the value of the cyclotomic polynomial \( \Phi_n \) at \( x \)
• Reduce to the case that \( n \) is squarefree: use the identity
\[
\Phi_n(x) = \Phi_{q}(x^{n/q})
\]
where \( q \) is the radical of \( n \).

• Use the identity
\[
\Phi_n(x) = \prod_{d|n} (x^d - 1)^{\mu(n/d)},
\]
where \( \mu \) is the Möbius function.

• Handles the case that \( x^d = 1 \) for some \( d \), but not the case that \( x^d - 1 \) is non-invertible: in this case polynomial evaluation is used instead.

EXAMPLES:

```sage
sage: cyclotomic_value(51, 3)
1282860140677441
sage: cyclotomic_polynomial(51)(3)
1282860140677441
```
It works for non-integral values as well:

```sage
sage: cyclotomic_value(144, 4/3)
79148745433504023621920372161/79766443076872509863361
sage: cyclotomic_polynomial(144)(4/3)
79148745433504023621920372161/79766443076872509863361
```
3.1 Multivariate Polynomials and Polynomial Rings

Sage implements multivariate polynomial rings through several backends. The most generic implementation uses the classes `sage.rings.polynomial.polydict.PolyDict` and `sage.rings.polynomial.polydict.ETuple` to construct a dictionary with exponent tuples as keys and coefficients as values.

Additionally, specialized and optimized implementations over many specific coefficient rings are implemented via a shared library interface to SINGULAR; and polynomials in the boolean polynomial ring

\[ F_2[x_1, \ldots, x_n]/(x_1^2 + x_1, \ldots, x_n^2 + x_n). \]

are implemented using the PolyBoRi library (cf. `sage.rings.polynomial.pbori`).

### 3.1.1 Term orders

Sage supports the following term orders:

**Lexicographic (lex)**

\[ x^a < x^b \] if and only if there exists \( 1 \leq i \leq n \) such that \( a_1 = b_1, \ldots, a_{i-1} = b_{i-1}, a_i < b_i \). This term order is called ‘lp’ in Singular.

**EXAMPLES:**

```python
sage: P.<x,y,z> = PolynomialRing(QQ, 3, order='lex')
sage: x > y
True
sage: x > y^2
True
sage: x > 1
True
sage: x^1*y^2 > y^3*z^4
True
sage: x^3*y^2*z^4 < x^3*y^2*z^1
False
```

**Degree reverse lexicographic (degrevlex)**

Let \( \deg(x^a) = a_1 + a_2 + \cdots + a_n \), then \( x^a < x^b \) if and only if \( \deg(x^a) < \deg(x^b) \) or \( \deg(x^a) = \deg(x^b) \) and there exists \( 1 \leq i \leq n \) such that \( a_n = b_n, \ldots, a_{i+1} = b_{i+1}, a_i > b_i \). This term order is called ‘dp’ in Singular.

**EXAMPLES:**


```python
sage: P.<x,y,z> = PolynomialRing(QQ, 3, order='degrevlex')
sage: x > y
True
sage: x > y^2*z
False
sage: x > 1
True
sage: x^1*y^5*z^2 > x^4*y^1*z^3
True
sage: x^2*y*z^2 > x*y^3*z
False
```

**Degree lexicographic (deglex)**

Let \( \deg(x^a) = a_1 + a_2 + \cdots + a_n \), then \( x^a < x^b \) if and only if \( \deg(x^a) < \deg(x^b) \) or \( \deg(x^a) = \deg(x^b) \) and there exists \( 1 \leq i \leq n \) such that \( a_1 = b_1, \ldots, a_{i-1} = b_{i-1}, a_i < b_i \). This term order is called ‘Dp’ in Singular.

**EXAMPLES:**

```python
sage: P.<x,y,z> = PolynomialRing(QQ, 3, order='deglex')
sage: x > y
True
sage: x > y^2*z
False
sage: x > 1
True
sage: x*y > z
False
```

**Inverse lexicographic (invlex)**

\( x^a < x^b \) if and only if there exists \( 1 \leq i \leq n \) such that \( a_n = b_n, \ldots, a_{i+1} = b_{i+1}, a_i < b_i \). This order is called ‘rp’ in Singular.

**EXAMPLES:**

```python
sage: P.<x,y,z> = PolynomialRing(QQ, 3, order='invlex')
sage: x > y
False
sage: y > x^2
True
sage: x > 1
True
sage: x*y > z
False
```

This term order only makes sense in a non-commutative setting because if \( P \) is the ring \( k[x_1, \ldots, x_n] \) and term order ‘invlex’ then it is equivalent to the ring \( k[x_n, \ldots, x_1] \) with term order ‘lex’.

**Negative lexicographic (neglex)**

\( x^a < x^b \) if and only if there exists \( 1 \leq i \leq n \) such that \( a_1 = b_1, \ldots, a_{i-1} = b_{i-1}, a_i > b_i \). This term order is called ‘ls’ in Singular.

**EXAMPLES:**

```python
sage: P.<x,y,z> = PolynomialRing(QQ, 3, order='neglex')
sage: x > y
False
sage: y > x^2
True
sage: x > 1
True
sage: x*y > z
False
```

This term order only makes sense in a non-commutative setting because if \( P \) is the ring \( k[x_1, \ldots, x_n] \) and term order ‘neglex’ then it is equivalent to the ring \( k[x_n, \ldots, x_1] \) with term order ‘neglex’.

Chapter 3. Multivariate Polynomials
<table>
<thead>
<tr>
<th>sage:</th>
<th>\texttt{P.&lt;x,y,z&gt; = PolynomialRing(QQ, 3, order='neglex')}</th>
</tr>
</thead>
<tbody>
<tr>
<td>sage:</td>
<td>\texttt{x &gt; y}</td>
</tr>
<tr>
<td>False</td>
<td></td>
</tr>
<tr>
<td>sage:</td>
<td>\texttt{x &gt; 1}</td>
</tr>
<tr>
<td>False</td>
<td></td>
</tr>
<tr>
<td>sage:</td>
<td>\texttt{x^1<em>y^2 &gt; y^3</em>z^4}</td>
</tr>
<tr>
<td>False</td>
<td></td>
</tr>
<tr>
<td>sage:</td>
<td>\texttt{x^3<em>y^2</em>z^4 &lt; x^3<em>y^2</em>z^1}</td>
</tr>
<tr>
<td>True</td>
<td></td>
</tr>
<tr>
<td>sage:</td>
<td>\texttt{x*y &gt; z}</td>
</tr>
<tr>
<td>False</td>
<td></td>
</tr>
<tr>
<td>sage:</td>
<td>\texttt{x^y &gt; z}</td>
</tr>
<tr>
<td>False</td>
<td></td>
</tr>
</tbody>
</table>

**Negative degree reverse lexicographic (negdegrelex)**

Let \( \text{deg}(x^a) = a_1 + a_2 + \cdots + a_n \), then \( x^a < x^b \) if and only if \( \text{deg}(x^a) > \text{deg}(x^b) \) or \( \text{deg}(x^a) = \text{deg}(x^b) \) and there exists \( 1 \leq i \leq n \) such that \( a_n = b_n, \ldots, a_{i+1} = b_{i+1}, a_i > b_i \). This term order is called ‘ds’ in Singular.

**EXAMPLES:**

<table>
<thead>
<tr>
<th>sage:</th>
<th>\texttt{P.&lt;x,y,z&gt; = PolynomialRing(QQ, 3, order='negdegrelex')}</th>
</tr>
</thead>
<tbody>
<tr>
<td>sage:</td>
<td>\texttt{x &gt; y}</td>
</tr>
<tr>
<td>True</td>
<td></td>
</tr>
<tr>
<td>sage:</td>
<td>\texttt{x &gt; x^2}</td>
</tr>
<tr>
<td>True</td>
<td></td>
</tr>
<tr>
<td>sage:</td>
<td>\texttt{x &gt; 1}</td>
</tr>
<tr>
<td>False</td>
<td></td>
</tr>
<tr>
<td>sage:</td>
<td>\texttt{x^1<em>y^2 &gt; y^3</em>z^4}</td>
</tr>
<tr>
<td>True</td>
<td></td>
</tr>
<tr>
<td>sage:</td>
<td>\texttt{x^2<em>y^2</em>z^2 &gt; x^y^3*z}</td>
</tr>
<tr>
<td>False</td>
<td></td>
</tr>
</tbody>
</table>

**Negative degree lexicographic (negdeglex)**

Let \( \text{deg}(x^a) = a_1 + a_2 + \cdots + a_n \), then \( x^a < x^b \) if and only if \( \text{deg}(x^a) > \text{deg}(x^b) \) or \( \text{deg}(x^a) = \text{deg}(x^b) \) and there exists \( 1 \leq i \leq n \) such that \( a_1 = b_1, \ldots, a_{i-1} = b_{i-1}, a_i < b_i \). This term order is called ‘Ds’ in Singular.

**EXAMPLES:**

<table>
<thead>
<tr>
<th>sage:</th>
<th>\texttt{P.&lt;x,y,z&gt; = PolynomialRing(QQ, 3, order='negdeglex')}</th>
</tr>
</thead>
<tbody>
<tr>
<td>sage:</td>
<td>\texttt{x &gt; y}</td>
</tr>
<tr>
<td>True</td>
<td></td>
</tr>
<tr>
<td>sage:</td>
<td>\texttt{x &gt; x^2}</td>
</tr>
<tr>
<td>True</td>
<td></td>
</tr>
<tr>
<td>sage:</td>
<td>\texttt{x &gt; 1}</td>
</tr>
<tr>
<td>False</td>
<td></td>
</tr>
<tr>
<td>sage:</td>
<td>\texttt{x^1<em>y^2 &gt; y^3</em>z^4}</td>
</tr>
<tr>
<td>True</td>
<td></td>
</tr>
<tr>
<td>sage:</td>
<td>\texttt{x^2<em>y^2</em>z^2 &gt; x^y^3*z}</td>
</tr>
<tr>
<td>True</td>
<td></td>
</tr>
</tbody>
</table>

**Weighted degree reverse lexicographic (wdegrelex), positive integral weights**

Let \( \text{deg}_w(x^a) = a_1w_1 + a_2w_2 + \cdots + a_nw_n \) with weights \( w \), then \( x^a < x^b \) if and only if \( \text{deg}_w(x^a) < \text{deg}_w(x^b) \) or \( \text{deg}_w(x^a) = \text{deg}_w(x^b) \) and there exists \( 1 \leq i \leq n \) such that \( a_n = b_n, \ldots, a_{i+1} = b_{i+1}, a_i > b_i \). This term order is called ‘wp’ in Singular.

**EXAMPLES:**

<table>
<thead>
<tr>
<th>sage:</th>
<th>\texttt{P.&lt;x,y,z&gt; = PolynomialRing(QQ, 3, order='wdegrelex')}</th>
</tr>
</thead>
<tbody>
<tr>
<td>sage:</td>
<td>\texttt{x &gt; y}</td>
</tr>
<tr>
<td>True</td>
<td></td>
</tr>
<tr>
<td>sage:</td>
<td>\texttt{x &gt; x^2}</td>
</tr>
<tr>
<td>True</td>
<td></td>
</tr>
<tr>
<td>sage:</td>
<td>\texttt{x &gt; 1}</td>
</tr>
<tr>
<td>False</td>
<td></td>
</tr>
<tr>
<td>sage:</td>
<td>\texttt{x^1<em>y^2 &gt; y^3</em>z^4}</td>
</tr>
<tr>
<td>True</td>
<td></td>
</tr>
<tr>
<td>sage:</td>
<td>\texttt{x^2<em>y^2</em>z^2 &gt; x^y^3*z}</td>
</tr>
<tr>
<td>True</td>
<td></td>
</tr>
</tbody>
</table>
Weighted degree lexicographic (wdeglex), positive integral weights

Let \( \deg_w(x^a) = a_1 w_1 + a_2 w_2 + \cdots + a_n w_n \) with weights \( w \), then \( x^a < x^b \) if and only if \( \deg_w(x^a) < \deg_w(x^b) \) or \( \deg_w(x^a) = \deg_w(x^b) \) and there exists \( 1 \leq i \leq n \) such that \( a_1 = b_1, \ldots, a_{i-1} = b_{i-1}, a_i < b_i \). This term order is called ‘Wp’ in Singular.

EXAMPLES:

```python
sage: P.<x,y,z> = PolynomialRing(QQ, 3, order=TermOrder('wdeglex',(1,2,3)))
sage: x > y
False
sage: x > x^2
False
sage: x > 1
True
sage: x^1*y^2 > x^2*z
True
sage: y*z > x^3*y
False
```

Negative weighted degree reverse lexicographic (negwdegrevlex), positive integral weights

Let \( \deg_w(x^a) = a_1 w_1 + a_2 w_2 + \cdots + a_n w_n \) with weights \( w \), then \( x^a < x^b \) if and only if \( \deg_w(x^a) > \deg_w(x^b) \) or \( \deg_w(x^a) = \deg_w(x^b) \) and there exists \( 1 \leq i \leq n \) such that \( a_n = b_n, \ldots, a_{i+1} = b_{i+1}, a_i > b_i \). This term order is called ‘ws’ in Singular.

EXAMPLES:

```python
sage: P.<x,y,z> = PolynomialRing(QQ, 3, order=TermOrder('negwdegrevlex',(1,2,3)))
sage: x > y
True
sage: x > x^2
True
sage: x > 1
False
sage: x^1*y^2 > x^2*z
True
sage: y*z > x^3*y
False
```

Degree negative lexicographic (degneglex)

Let \( \deg(x^a) = a_1 + a_2 + \cdots + a_n \), then \( x^a < x^b \) if and only if \( \deg(x^a) < \deg(x^b) \) or \( \deg(x^a) = \deg(x^b) \) and there exists \( 1 \leq i \leq n \) such that \( a_1 = b_1, \ldots, a_{i-1} = b_{i-1}, a_i > b_i \). This term order is called ‘dp_asc’ in PolyBoRi. Singular has the extra weight vector ordering \((a(1:n),ls)\) for this purpose.
EXAMPLES:

```python
sage: t = TermOrder('degneglex')
sage: P.<x,y,z> = PolynomialRing(QQ, order=t)
sage: x*y > y*z # indirect doctest
False
sage: x*y > x
True
```

Negative weighted degree lexicographic (negwdeglex), positive integral weights

Let \( \deg_w(x^a) = a_1w_1 + a_2w_2 + \cdots + a_nw_n \) with weights \( w \), then \( x^a < x^b \) if and only if \( \deg_w(x^a) > \deg_w(x^b) \) or \( \deg_w(x^a) = \deg_w(x^b) \) and there exists \( 1 \leq i \leq n \) such that \( a_1 = b_1, \ldots, a_{i-1} = b_{i-1}, a_i < b_i \). This term order is called ‘Ws’ in Singular.

EXAMPLES:

```python
sage: P.<x,y,z> = PolynomialRing(QQ, 3, order=TermOrder('negwdeglex',(1,2,3)))
sage: x > y
True
sage: x > x^2
True
sage: x > 1
False
sage: x^1*y^2 > x^2*z
False
sage: y*z > x^3*y
False
```

Of these, only ‘degrevlex’, ‘deglex’, ‘degneglex’, ‘wdegrevlex’, ‘wdeglex’, ‘invlex’ and ‘lex’ are global orders.

Sage also supports matrix term order. Given a square matrix \( A \),

\[
  x^a <_A x^b \text{ if and only if } Aa < Ab
\]

where \( < \) is the lexicographic term order.

EXAMPLES:

```python
sage: m = matrix(2,[[2,3,0,1]]); m
[2 3]
[0 1]
sage: T = TermOrder(m); T
Matrix term order with matrix
[2 3]
[0 1]
sage: P.<a,b> = PolynomialRing(QQ,2,order=T)
sage: P
Multivariate Polynomial Ring in a, b over Rational Field
sage: a > b
False
sage: a^3 < b^2
True
sage: S = TermOrder('M(2,3,0,1)')
sage: T == S
True
```

Additionally all these monomial orders may be combined to product or block orders, defined as:

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Let $x = (x_1, x_2, \ldots, x_n)$ and $y = (y_1, y_2, \ldots, y_m)$ be two ordered sets of variables, $<_1$ a monomial order on $k[x]$ and $<_2$ a monomial order on $k[y]$.

The product order (or block order) $<_b := (<_1, <_2)$ on $k[x,y]$ is defined as: $x^a y^b < x^A y^B$ if and only if $x^a <_1 x^A$ or ($x^a = x^A$ and $y^b <_2 y^B$).

These block orders are constructed in Sage by giving a comma separated list of monomial orders with the length of each block attached to them.

**EXAMPLES:**

As an example, consider constructing a block order where the first four variables are compared using the degree reverse lexicographical order while the last two variables in the second block are compared using negative lexicographical order.

```sage
sage: P.<a,b,c,d,e,f> = PolynomialRing(QQ, 6, order='degrevlex(4),neglex(2)')
sage: a > c^4
False
sage: a > e^4
True
sage: e > f^2
False
```

The same result can be achieved by:

```sage
sage: T1 = TermOrder('degrevlex',4)
sage: T2 = TermOrder('neglex',2)
sage: T = T1 + T2
sage: P.<a,b,c,d,e,f> = PolynomialRing(QQ, 6, order=T)
sage: a > c^4
False
sage: a > e^4
True
```

If any other unsupported term order is given the provided string can be forced to be passed through as is to Singular, Macaulay2, and Magma. This ensures that it is for example possible to calculate a Groebner basis with respect to some term order Singular supports but Sage doesn’t:

```sage
sage: T = TermOrder("royalorder")
Traceback (most recent call last):
... ValueError: unknown term order 'royalorder'
sage: T = TermOrder("royalorder",force=True)
sage: T
royalorder term order
sage: T.singular_str()
'royalorder'
```

**AUTHORS:**

- David Joyner and William Stein: initial version of multi_polynomial_ring
- Kiran S. Kedlaya: added macaulay2 interface
- Martin Albrecht: implemented native term orders, refactoring
- Kwankyu Lee: implemented matrix and weighted degree term orders
- Simon King (2011-06-06): added termorder_from_singular
class sage.rings.polynomial.term_order.TermOrder(name='lex', n=0, force=False)
Bases: SageObject

A term order.

See sage.rings.polynomial.term_order for details on supported term orders.

blocks()
Return the term order blocks of self.

NOTE:
This method has been added in github issue #11316. There used to be an attribute of the same name and the same content. So, it is a backward incompatible syntax change.

EXAMPLES:

```python
sage: t=TermOrder('deglex',2)+TermOrder('lex',2)
sage: t.blocks()
(Degree lexicographic term order, Lexicographic term order)
```

property greater_tuple
The default greater_tuple method for this term order.

EXAMPLES:

```python
sage: O = TermOrder()
sage: O.greater_tuple.__func__ is O.greater_tuple_lex.__func__
True
sage: O = TermOrder('deglex')
sage: O.greater_tuple.__func__ is O.greater_tuple_deglex.__func__
True
```

greater_tuple_block(f, g)
Return the greater exponent tuple with respect to the block order as specified when constructing this element.

This method is called by the lm/lc lt methods of MPolynomial_polydict.

INPUT:

• f - exponent tuple
• g - exponent tuple

EXAMPLES:

```python
sage: P.<a,b,c,d,e,f>=PolynomialRing(QQbar, 6, order='degrevlex(3),degrevlex(3) \rightarrow')
sage: f = a + c^4; f.lm() # indirect doctest
c^4
sage: g = a + e^4; g.lm()
a
```

greater_tuple_deglex(f, g)
Return the greater exponent tuple with respect to the total degree lexicographical term order.

INPUT:

• f - exponent tuple
• g - exponent tuple

EXAMPLES:

```python
sage: P.<x,y,z> = PolynomialRing(QQbar, 3, order='deglex')
sage: f = x + y; f.lm() # indirect doctest
x
sage: f = x + y^2*z; f.lm()
y^2*z
```

This method is called by the lm/lc/lt methods of MPolynomial_polydict.

### greater_tuple_degneglex(f, g)

Return the greater exponent tuple with respect to the degree negative lexicographical term order.

INPUT:

• f - exponent tuple
• g - exponent tuple

EXAMPLES:

```python
sage: P.<x,y,z> = PolynomialRing(QQbar, 3, order='degneglex')
sage: f = x + y; f.lm() # indirect doctest
y
sage: f = x + y^2*z; f.lm()
y^2*z
```

This method is called by the lm/lc/lt methods of MPolynomial_polydict.

### greater_tuple_degrevlex(f, g)

Return the greater exponent tuple with respect to the total degree reversed lexicographical term order.

INPUT:

• f - exponent tuple
• g - exponent tuple

EXAMPLES:

```python
sage: P.<x,y,z> = PolynomialRing(QQbar, 3, order='degrevlex')
sage: f = x + y; f.lm() # indirect doctest
x
sage: f = x + y^2*z; f.lm()
y^2*z
```

This method is called by the lm/lc/lt methods of MPolynomial_polydict.

### greater_tuple_invlex(f, g)

Return the greater exponent tuple with respect to the inversed lexicographical term order.

INPUT:

• f - exponent tuple
• g - exponent tuple

EXAMPLES:
sage: P.<x,y,z> = PolynomialRing(QQbar, 3, order='invlex')
sage: f = x + y; f.lm() # indirect doctest
    y
sage: f = y + x^2; f.lm()  
    y

This method is called by the lm/lc/lt methods of MPolynomial_polydict.

greater_tuple_lex(f, g)
Return the greater exponent tuple with respect to the lexicographical term order.

INPUT:
  • f - exponent tuple
  • g - exponent tuple

EXAMPLES:

sage: P.<x,y,z> = PolynomialRing(QQbar, 3, order='lex')
sage: f = x + y^2; f.lm() # indirect doctest
    x

This method is called by the lm/lc/lt methods of MPolynomial_polydict.

greater_tuple_matrix(f, g)
Return the greater exponent tuple with respect to the matrix term order.

INPUT:
  • f - exponent tuple
  • g - exponent tuple

EXAMPLES:

sage: P.<x,y> = PolynomialRing(QQbar, 2, order='m(1,3,1,0)')
sage: y > x^2 # indirect doctest
    True
sage: y > x^3
    False

greater_tuple_negdeglex(f, g)
Return the greater exponent tuple with respect to the negative degree lexicographical term order.

INPUT:
  • f - exponent tuple
  • g - exponent tuple

EXAMPLES:

sage: P.<x,y,z> = PolynomialRing(QQbar, 3, order='negdeglex')
sage: f = x + y; f.lm() # indirect doctest
    x
sage: f = x + x^2; f.lm()  
    x
sage: f = x^2*y^z^2 + x^y^3*z; f.lm()  
x^2*y^z^2

3.1. Multivariate Polynomials and Polynomial Rings
This method is called by the lm/lc/lt methods of MPolynomial_polydict.

**greater_tuple_negdegrevlex**(*f, g*)

Return the greater exponent tuple with respect to the negative degree reverse lexicographical term order.

**INPUT:**
- *f* - exponent tuple
- *g* - exponent tuple

**EXAMPLES:**

```sage
sage: P.<x,y,z> = PolynomialRing(QQbar, 3, order='negdegrevlex')
sage: f = x + y; f.lm() # indirect doctest
x
sage: f = x + x^2; f.lm()
x
sage: f = x^2*y^2*z^2 + x*y^3*z; f.lm()
x*y^3*z
```

This method is called by the lm/lc/lt methods of MPolynomial_polydict.

**greater_tuple_neglex**(*f, g*)

Return the greater exponent tuple with respect to the negative lexicographical term order.

This method is called by the lm/lc/lt methods of MPolynomial_polydict.

**INPUT:**
- *f* - exponent tuple
- *g* - exponent tuple

**EXAMPLES:**

```sage
sage: P.<a,b,c,d,e,f>=PolynomialRing(QQbar, 6, order='degrevlex(3),degrevlex(3) \to')
sage: f = a + c^4; f.lm() # indirect doctest
c^4
sage: g = a + e^4; g.lm()
a
```

**greater_tuple_negwdeglex**(*f, g*)

Return the greater exponent tuple with respect to the negative weighted degree lexicographical term order.

**INPUT:**
- *f* - exponent tuple
- *g* - exponent tuple

**EXAMPLES:**

```sage
sage: t = TermOrder('negwdeglex',(1,2,3))
sage: P.<x,y,z> = PolynomialRing(QQbar, 3, order=t)
sage: f = x + y; f.lm() # indirect doctest
x
sage: f = x + x^2; f.lm()
x
```

(continues on next page)
This method is called by the \texttt{lm/lc/lt} methods of \texttt{MPolynomial_polydict}.

\begin{verbatim}
sage: t = TermOrder('negwdegrevlex', (1,2,3))
sage: P.<x,y,z> = PolynomialRing(QQbar, 3, order=t)
sage: f = x + y; f.lm() # indirect doctest
x
sage: f = x + x^2; f.lm()
x
sage: f = x^3 + z; f.lm()
x^3
\end{verbatim}

This method is called by the \texttt{lm/lc/lt} methods of \texttt{MPolynomial_polydict}.

\begin{verbatim}
sage: t = TermOrder('wdeglex', (1,2,3))
sage: P.<x,y,z> = PolynomialRing(QQbar, 3, order=t)
sage: f = x + y; f.lm() # indirect doctest
y
sage: f = x*y + z; f.lm()
x*y
\end{verbatim}

This method is called by the \texttt{lm/lc/lt} methods of \texttt{MPolynomial_polydict}.

\begin{verbatim}
sage: t = TermOrder('wdegrevlex', (1,2,3))
n sage: P.<x,y,z> = PolynomialRing(QQbar, 3, order=t)
\end{verbatim}
```python
sage: t = TermOrder('wdegrevlex',(1,2,3))
sage: P.<x,y,z> = PolynomialRing(QQbar, 3, order=t)
sage: f = x + y; f.lm()  # indirect doctest
y
sage: f = x + y^2*z; f.lm()
y^2*z
```

This method is called by the lm/lc/lt methods of `MPolynomial_polydict`.

**is_block_order()**

Return true if self is a block term order.

**EXAMPLES:**

```python
sage: t=TermOrder('deglex',2)+TermOrder('lex',2)
sage: t.is_block_order()  
True
```

**is_global()**

Return true if this term order is definitely global. Return false otherwise, which includes unknown term orders.

**EXAMPLES:**

```python
sage: T = TermOrder('lex')
sage: T.is_global()  
True
sage: T = TermOrder('degrevlex', 3) + TermOrder('degrevlex', 3)
sage: T.is_global()  
True
sage: T = TermOrder('degrevlex', 3) + TermOrder('negdegrevlex', 3)
sage: T.is_global()  
False
sage: T = TermOrder('degneglex', 3)
sage: T.is_global()  
True
sage: T = TermOrder('invlex', 3)
sage: T.is_global()  
True
```

**is_local()**

Return true if this term order is definitely local. Return false otherwise, which includes unknown term orders.

**EXAMPLES:**

```python
sage: T = TermOrder('lex')
sage: T.is_local()  
False
sage: T = TermOrder('negdeglex', 3) + TermOrder('negdegrevlex', 3)
sage: T.is_local()  
True
sage: T = TermOrder('degrevlex', 3) + TermOrder('negdegrevlex', 3)
sage: T.is_local()  
False
```
**is_weighted_degree_order()**

Return true if self is a weighted degree term order.

**EXAMPLES:**

```python
sage: t=TermOrder('wdeglex',(2,3))
sage: t.is_weighted_degree_order()
True
```

**macaulay2_str()**

Return a Macaulay2 representation of self.

Used to convert polynomial rings to their Macaulay2 representation.

**EXAMPLES:**

```python
sage: P = PolynomialRing(GF(127), 8,names='x',order='degrevlex(3),lex(5)')
sage: T = P.term_order()
sage: T.macaulay2_str()
'\{GRevLex => 3,Lex => 5\}'
sage: P._macaulay2_().options()['MonomialOrder'] # optional - macaulay2
{MonomialSize => 16 }
{GRevLex => {1, 1, 1}}
{Lex => 5 }
{Position => Up }
```

**magma_str()**

Return a MAGMA representation of self.

Used to convert polynomial rings to their MAGMA representation.

**EXAMPLES:**

```python
sage: P = PolynomialRing(GF(127), 10,names='x',order='degrevlex')
sage: magma(P) # optional - magma
Polynomial ring of rank 10 over GF(127)
Order: Graded Reverse Lexicographical
Variables: x0, x1, x2, x3, x4, x5, x6, x7, x8, x9
sage: T = P.term_order()
sage: T.magma_str()
"grevlex"
```

**matrix()**

Return the matrix defining matrix term order.

**EXAMPLES:**

```python
sage: t = TermOrder("M(1,2,0,1)")
sage: t.matrix()
[[1 2]
 [0 1]

**name()**

**EXAMPLES:**
sage: TermOrder('lex').name()
'lex'

**singular_moreblocks()**

Return a the number of additional blocks SINGULAR needs to allocate for handling non-native orderings like `degneglex`.

**EXAMPLES:**

```
sage: P = PolynomialRing(GF(127),10, names='x', order='lex(3),deglex(5),lex(2)')
sage: T = P.term_order()
sage: T.singular_moreblocks()
0
sage: P = PolynomialRing(GF(127),10, names='x', order='lex(3),degneglex(5),lex(2)')
sage: T = P.term_order()
sage: T.singular_moreblocks()
1
sage: P = PolynomialRing(GF(127),10, names='x', order='degneglex(5),degneglex(5)')
sage: T = P.term_order()
sage: T.singular_moreblocks()
2
```

**singular_str()**

Return a SINGULAR representation of self.

Used to convert polynomial rings to their SINGULAR representation.

**EXAMPLES:**

```
sage: P = PolynomialRing(GF(127),10, names='x', order='lex(3),deglex(5),lex(2)')
sage: T = P.term_order()
sage: T.singular_str()
'(lp(3),Dp(5),lp(2))'
```

The `degneglex` ordering is somehow special, it looks like a block ordering in SINGULAR:

```
sage: T = TermOrder("degneglex", 2)
sage: P = PolynomialRing(QQ,2, names='x', order=T)
sage: T = P.term_order()
sage: T.singular_str()
'(a(1:2),ls(2))'
```
sage: T = TermOrder("degneglex", 2) + TermOrder("degneglex", 2)
sage: P = PolynomialRing(QQ, 4, names='x', order=T)
sage: T = P.term_order()
sage: T.singular_str()
'(a(1:2),ls(2),a(1:2),ls(2))'
sage: P._singular_()
polynomial ring, over a field, global ordering
  // coefficients: QQ
  // number of vars : 4
  // block 1 : ordering a
  //     : names x0 x1
  //     : weights 1 1
  // block 2 : ordering ls
  //     : names x0 x1
  // block 3 : ordering a
  //     : names x2 x3
  //     : weights 1 1
  // block 4 : ordering ls
  //     : names x2 x3
  // block 5 : ordering C

The position of the ordering C block can be controlled by setting `_singular_ringorder_column` attribute to an integer:

sage: T = TermOrder("degneglex", 2) + TermOrder("degneglex", 2)
sage: T._singular_ringorder_column = 0
sage: P = PolynomialRing(QQ, 4, names='x', order=T)
sage: P._singular_()
polynomial ring, over a field, global ordering
  // coefficients: QQ
  // number of vars : 4
  // block 1 : ordering c
  // block 2 : ordering a
  //     : names y0 y1
  // block 3 : ordering ls
  //     : names x0 x1
  // block 4 : ordering a
  //     : names x2 x3
  //     : weights 1 1
  // block 5 : ordering ls
  //     : names x2 x3

sage: T._singular_ringorder_column = 1
sage: P = PolynomialRing(QQ, 4, names='y', order=T)
sage: P._singular_()
polynomial ring, over a field, global ordering
  // coefficients: QQ
  // number of vars : 4
  // block 1 : ordering c
  // block 2 : ordering a
  //     : names y0 y1
  // block 3 : ordering ls
  //     : names x0 x1
  // block 4 : ordering a
  //     : names x2 x3
  //     : weights 1 1
  // block 5 : ordering ls
  //     : names x2 x3

(continues on next page)
property sortkey

The default sortkey method for this term order.

EXAMPLES:

```plaintext
sage: O = TermOrder()
sage: O.sortkey.__func__ is O.sortkey_lex.__func__
True
sage: O = TermOrder('deglex')
sage: O.sortkey.__func__ is O.sortkey_deglex.__func__
True
```

sortkey_block(f)

Return the sortkey of an exponent tuple with respect to the block order as specified when constructing this element.

INPUT:

- `f` – exponent tuple

EXAMPLES:

```plaintext
sage: P.<a,b,c,d,e,f>=PolynomialRing(QQbar, 6, order='degrevlex(3),degrevlex(3) →')
sage: a > c⁴ # indirect doctest
False
```
sage: a > e^4
True

sortkey_deglex(f)
Return the sortkey of an exponent tuple with respect to the degree lexicographical term order.

INPUT:
• f – exponent tuple

EXAMPLES:

sage: P.<x,y> = PolynomialRing(QQbar, 2, order='deglex')
sage: x > y^2  # indirect doctest
False
sage: x > 1
True

sortkey_degneglex(f)
Return the sortkey of an exponent tuple with respect to the degree negative lexicographical term order.

INPUT:
• f – exponent tuple

EXAMPLES:

sage: P.<x,y,z> = PolynomialRing(QQbar, 3, order='degneglex')
sage: x*y > y*z  # indirect doctest
False
sage: x*y > x
True

sortkey_degrevlex(f)
Return the sortkey of an exponent tuple with respect to the degree reversed lexicographical term order.

INPUT:
• f – exponent tuple

EXAMPLES:

sage: P.<x,y> = PolynomialRing(QQbar, 2, order='degrevlex')
sage: x > y^2  # indirect doctest
False
sage: x > 1
True

sortkey_invlex(f)
Return the sortkey of an exponent tuple with respect to the inversed lexicographical term order.

INPUT:
• f – exponent tuple

EXAMPLES:
Polynomials, Release 10.0

```
sage: P.<x,y> = PolynomialRing(QQbar, 2, order='invlex')
sage: x > y^2 # indirect doctest
False
sage: x > 1
True
```

**sortkey_lex(f)**

Return the sortkey of an exponent tuple with respect to the lexicographical term order.

INPUT:

- f – exponent tuple

EXAMPLES:

```
sage: P.<x,y> = PolynomialRing(QQbar, 2, order='lex')
sage: x > y^2 # indirect doctest
True
sage: x > 1
True
```

**sortkey_matrix(f)**

Return the sortkey of an exponent tuple with respect to the matrix term order.

INPUT:

- f - exponent tuple

EXAMPLES:

```
sage: P.<x,y> = PolynomialRing(QQbar, 2, order='m(1,3,1,0)')
sage: y > x^2 # indirect doctest
True
sage: y > x^3
False
```

**sortkey_negdeglex(f)**

Return the sortkey of an exponent tuple with respect to the negative degree lexicographical term order.

INPUT:

- f – exponent tuple

EXAMPLES:

```
sage: P.<x,y> = PolynomialRing(QQbar, 2, order='negdeglex')
sage: x > y^2 # indirect doctest
True
sage: x > 1
False
```

**sortkey_negdegrevlex(f)**

Return the sortkey of an exponent tuple with respect to the negative degree reverse lexicographical term order.

INPUT:

- f – exponent tuple
EXAMPLES:

```python
sage: P.<x,y> = PolynomialRing(QQbar, 2, order='negdegrevlex')
sage: x > y^2 # indirect doctest
True
sage: x > 1
False
```

**sortkey_neglex(f)**

Return the sortkey of an exponent tuple with respect to the negative lexicographical term order.

INPUT:

- `f` – exponent tuple

EXAMPLES:

```python
sage: P.<x,y> = PolynomialRing(QQbar, 2, order='neglex')
sage: x > y^2 # indirect doctest
False
sage: x > 1
False
```

**sortkey_negwdeglex(f)**

Return the sortkey of an exponent tuple with respect to the negative weighted degree lexicographical term order.

INPUT:

- `f` – exponent tuple

EXAMPLES:

```python
sage: t = TermOrder('negwdeglex',(3,2))
sage: P.<x,y> = PolynomialRing(QQbar, 2, order=t)
sage: x > y^2 # indirect doctest
True
sage: x^2 > y^3
True
```

**sortkey_negwdegrevlex(f)**

Return the sortkey of an exponent tuple with respect to the negative weighted degree reverse lexicographical term order.

INPUT:

- `f` – exponent tuple

EXAMPLES:

```python
sage: t = TermOrder('negwdegrevlex',(3,2))
sage: P.<x,y> = PolynomialRing(QQbar, 2, order=t)
sage: x > y^2 # indirect doctest
True
sage: x^2 > y^3
True
```
sortkey_wdeglex($f$)
Return the sortkey of an exponent tuple with respect to the weighted degree lexicographical term order.

INPUT:
• $f$ – exponent tuple

EXAMPLES:

```
sage: t = TermOrder('wdeglex', (3,2))
sage: P.<x,y> = PolynomialRing(QQbar, 2, order=t)
sage: x > y^2 # indirect doctest
False
sage: x > y
True
```

sortkey_wdegrevlex($f$)
Return the sortkey of an exponent tuple with respect to the weighted degree reverse lexicographical term order.

INPUT:
• $f$ – exponent tuple

EXAMPLES:

```
sage: t = TermOrder('wdegrevlex', (3,2))
sage: P.<x,y> = PolynomialRing(QQbar, 2, order=t)
sage: x > y^2 # indirect doctest
False
sage: x^2 > y^3
True
```

tuple_weight($f$)
Return the weight of tuple $f$.

INPUT:
• $f$ - exponent tuple

EXAMPLES:

```
sage: t=TermOrder('wdeglex', (1,2,3))
sage: P.<a,b,c>=PolynomialRing(QQbar, order=t)
sage: P.term_order().tuple_weight([3,2,1])
10
```

weights()
Return the weights for weighted term orders.

EXAMPLES:

```
sage: t=TermOrder('wdeglex', (2,3))
sage: t.weights()
(2, 3)
```

sage.rings.polynomial.term_order.termorder_from_singular($S$)
Return the Sage term order of the basering in the given Singular interface
INPUT:
An instance of the Singular interface.

EXAMPLES:

```python
sage: from sage.rings.polynomial.term_order import termorder_from_singular
sage: singular.eval('ring r1 = (9,x),(a,b,c,d,e,f),(M((1,2,3,0)),wp(2,3),lp)')
''
sage: termorder_from_singular(singular)
Block term order with blocks:
(Matrix term order with matrix
[1 2]
[3 0],
Weighted degree reverse lexicographic term order with weights (2, 3),
Lexicographic term order of length 2)
```

A term order in Singular also involves information on orders for modules. This information is reflected in
_\texttt{\_singular\_ringorder\_column} attribute of the term order.

```python
sage: singular.ring(0, '(x,y,z,w)', '(C,dp(2),lp(2))')
polynomial ring, over a field, global ordering
// coefficients: QQ
// number of vars : 4
// block 1 : ordering C
// block 2 : ordering dp
// : names x y
// block 3 : ordering lp
// : names z w
sage: T = termorder_from_singular(singular)
sage: T
Block term order with blocks:
(Degree reverse lexicographic term order of length 2,
Lexicographic term order of length 2)
sage: T._\texttt{\_singular\_ringorder\_column}
0
```

```python
sage: singular.ring(0, '(x,y,z,w)', '(c,dp(2),lp(2))')
polynomial ring, over a field, global ordering
// coefficients: QQ
// number of vars : 4
// block 1 : ordering c
// block 2 : ordering dp
// : names x y
// block 3 : ordering lp
// : names z w
sage: T = termorder_from_singular(singular)
sage: T
Block term order with blocks:
(Degree reverse lexicographic term order of length 2,
Lexicographic term order of length 2)
sage: T._\texttt{\_singular\_ringorder\_column}
1
```
3.1.2 Base class for multivariate polynomial rings

class sage.rings.polynomial.multi_polynomial_ring_base.BooleanPolynomialRing_base

Bases: MPolynomialRing_base

Abstract base class for BooleanPolynomialRing.
This class is defined for the purpose of isinstance tests. It should not be instantiated.

EXAMPLES:

```
sage: from sage.rings.polynomial.multi_polynomial_ring_base import *
˓→BooleanPolynomialRing_base
sage: R.<x, y, z> = BooleanPolynomialRing()
sage: isinstance(R, BooleanPolynomialRing_base)
True
```

By design, there is only one direct implementation subclass:

```
sage: len(BooleanPolynomialRing_base.__subclasses__()) <= 1
True
```

class sage.rings.polynomial.multi_polynomial_ring_base.MPolynomialRing_base

Bases: CommutativeRing

Create a polynomial ring in several variables over a commutative ring.

EXAMPLES:

```
sage: R.<x,y> = ZZ['x,y']; R
Multivariate Polynomial Ring in x, y over Integer Ring
sage: class CR(CommutativeRing):
  ....: def __init__(self):
  ....:     CommutativeRing.__init__(self,self)
  ....: def __call__(self,x):
  ....:     return None
sage: cr = CR()
sage: cr.is_commutative()
True
sage: cr['x,y']
Multivariate Polynomial Ring in x, y over <__main__.CR_with_category object at ...>
```

change_ring(base_ring=None, names=None, order=None)

Return a new multivariate polynomial ring which isomorphic to self, but has a different ordering given by the parameter ‘order’ or names given by the parameter ‘names’.

INPUT:

- base_ring – a base ring
- names – variable names
- order – a term order

EXAMPLES:
```
sage: P.<x,y,z> = PolynomialRing(GF(127),3,order='lex')
sage: x > y^2
True
sage: Q.<x,y,z> = P.change_ring(order='degrevlex')
sage: x > y^2
False
```

**characteristic()**

Return the characteristic of this polynomial ring.

**EXAMPLES:**

```
sage: R = PolynomialRing(QQ, 'x', 3)
sage: R.characteristic()
0
sage: R = PolynomialRing(GF(7), 'x', 20)
sage: R.characteristic()
7
```

**completion(names=None, prec=20, extras={}, **kwds)**

Return the completion of self with respect to the ideal generated by the variable(s) names.

**INPUT:**

- names – (optional) variable or list/tuple of variables (given either as elements of the polynomial ring or as strings); the default is all variables of self
- prec – default precision of resulting power series ring, possibly infinite
- extras – passed as keywords to PowerSeriesRing or LazyPowerSeriesRing; can also be keyword arguments

**EXAMPLES:**

```
sage: P.<x,y,z,w> = PolynomialRing(ZZ)
sage: P.completion(w)
Power Series Ring in w over Multivariate Polynomial Ring in x, y, z over Integer Ring
sage: P.completion((w,x,y))
Multivariate Power Series Ring in w, x, y over Univariate Polynomial Ring in z over Integer Ring
sage: Q.<w,x,y,z> = P.completion(); Q
Multivariate Power Series Ring in w, x, y, z over Integer Ring
sage: H = PolynomialRing(PolynomialRing(ZZ,3,z),4,f); H
Multivariate Polynomial Ring in f0, f1, f2, f3 over Multivariate Polynomial Ring in z0, z1, z2 over Integer Ring
sage: H.completion(H.gens())
Multivariate Power Series Ring in f0, f1, f2, f3 over Multivariate Polynomial Ring in z0, z1, z2 over Integer Ring
sage: H.completion(H.gens())[2]
Power Series Ring in f2 over Multivariate Polynomial Ring in f0, f1, f3 over Multivariate Polynomial Ring in z0, z1, z2 over Integer Ring
```
sage: P.<x,y,z,w> = PolynomialRing(ZZ)
sage: P.completion(prec=oo)
Multivariate Lazy Taylor Series Ring in x, y, z, w over Integer Ring
sage: P.completion((w,x,y), prec=oo)
Multivariate Lazy Taylor Series Ring in w, x, y over Univariate Polynomial Ring in z over Integer Ring

construction()

Returns a functor F and base ring R such that F(R) == self.

EXAMPLES:

    sage: S = ZZ['x,y']
sage: F, R = S.construction(); R
Integer Ring
sage: F
MPoly[x,y]
sage: F(R) == S
True
sage: F(R) == ZZ['x']['y']
False

flattening_morphism()

Return the flattening morphism of this polynomial ring

EXAMPLES:

    sage: QQ['a','b']['x','y'].flattening_morphism()
    Flattening morphism:
    From: Multivariate Polynomial Ring in x, y over Multivariate Polynomial Ring in a, b over Rational Field
    To:    Multivariate Polynomial Ring in a, b, x, y over Rational Field
    sage: QQ['x,y'].flattening_morphism()
    Identity endomorphism of Multivariate Polynomial Ring in x, y over Rational Field

gen(n=0)

interpolation(*bound, *args)

Create a polynomial with specified evaluations.

CALL FORMATS:

This function can be called in two ways:

1. interpolation(bound, points, values)
2. interpolation(bound, function)

INPUT:

* bound – either an integer bounding the total degree or a list/tuple of integers bounding the degree of the variables
• points – list/tuple containing the evaluation points
• values – list/tuple containing the desired values at points
• function – evaluable function in \( n \) variables, where \( n \) is the number of variables of the polynomial ring

OUTPUT:
1. A polynomial respecting the bounds and having values as values when evaluated at points.
2. A polynomial respecting the bounds and having the same values as function at exactly so many points so that the polynomial is unique.

EXAMPLES:

```
sage: def F(a,b,c):
....:     return a^3*b + b + c^2 + 25
....:
sage: R.<x,y,z> = PolynomialRing(QQ)
sage: R.interpolation([4, F])
x^3*y + z^2 + y + 25
```

```
sage: def F(a,b,c):
....:     return a^3*b + b + c^2 + 25
....:
sage: R.<x,y,z> = PolynomialRing(QQ)
sage: R.interpolation([3,1,2], F)
x^3*y + z^2 + y + 25
```

```
sage: def F(a,b,c):
....:     return a^3*b + b + c^2 + 25
....:
sage: R.<x,y,z> = PolynomialRing(QQ)
sage: points = [(5,1,1),(7,2,2),(8,5,-1),(2,5,3),(1,4,0),(5,9,0),
....:            (2,7,0),(1,10,13),(0,0,1),(-1,1,0),(2,5,3),(1,1,1),(7,4,11),
....:            (12,1,9),(1,1,3),(4,-1,2),(0,1,5),(5,1,3),(3,1,-2),(2,11,3),
....:            (4,12,19),(3,1,1),(5,2,-3),(12,1,1),(2,3,4)]
sage: R.interpolation([3,1,2], points, [F(*x) for x in points])
x^3*y + z^2 + y + 25
```

ALGORITHM:
Solves a linear system of equations with the linear algebra module. If the points are not specified, it samples exactly as many points as needed for a unique solution.

**Note:** It will only run if the base ring is a field, even though it might work otherwise as well. If your base ring is an integral domain, let it run over the fraction field.

Also, if the solution is not unique, it spits out one solution, without any notice that there are more.

Lastly, the interpolation function for univariate polynomial rings is called `lagrange_polynomial()`.
**Warning:** If you don’t provide point/value pairs but just a function, it will only use as many points as needed for a unique solution with the given bounds. In particular it will *not* notice or check whether the result yields the correct evaluation for other points as well. So if you give wrong bounds, you will get a wrong answer without any warning.

```python
def F(a,b,c): ....: return a^3*b + b + c^2 + 25 ....: sage: R.<x,y,z> = PolynomialRing(QQ) sage: R.interpolation(3,F) 1/2*x^3 + x*y + z^2 - 1/2*x + y + 25```

See also:

`lagrange_polynomial`

**irrelevant_ideal()**

Return the irrelevant ideal of this multivariate polynomial ring.

This is the ideal generated by all of the indeterminate generators of this ring.

**EXAMPLES:**

```python
sage: R.<x,y,z> = QQ[] sage: R.irrelevant_ideal() Ideal (x, y, z) of Multivariate Polynomial Ring in x, y, z over Rational Field```

**is_exact()**

Test whether this multivariate polynomial ring is defined over an exact base ring.

**EXAMPLES:**

```python
sage: PolynomialRing(QQ, 2, 'x').is_exact() True sage: PolynomialRing(RDF, 2, 'x').is_exact() False```

**is_field(proof=True)**

Test whether this multivariate polynomial ring is a field.

A polynomial ring is a field when there are no variable and the base ring is a field.

**EXAMPLES:**

```python
sage: PolynomialRing(QQ, 'x', 2).is_field() False sage: PolynomialRing(QQ, 'x', 0).is_field() True sage: PolynomialRing(ZZ, 'x', 0).is_field() False sage: PolynomialRing(Zmod(1), names=['x','y']).is_finite() True```

**is_integral_domain(proof=True)**

**EXAMPLES:**

```python
sage: ZZ['x','y'].is_integral_domain() True```

(continues on next page)
is_integral_domain()

EXAMPLES:

```python
sage: Integers(8)['x,y'].is_integral_domain()
False
```

is_noetherian()

EXAMPLES:

```python
sage: ZZ['x,y'].is_noetherian()
True
sage: Integers(8)['x,y'].is_noetherian()
True
```

krull_dimension()

macaulay_resultant(*args, **kwds)

This is an implementation of the Macaulay Resultant. It computes the resultant of universal polynomials as well as polynomials with constant coefficients. This is a project done in sage days 55. It’s based on the implementation in Maple by Manfred Minimair, which in turn is based on the references listed below: It calculates the Macaulay resultant for a list of polynomials, up to sign!

REFERENCES:

• [CLO2005]
• [Can1990]
• [Mac1916]

AUTHORS:

• Hao Chen, Solomon Vishkautsan (7-2014)

INPUT:

• `args` – a list of \( n \) homogeneous polynomials in \( n \) variables.
  works when \( \text{args}[0] \) is the list of polynomials, or \( \text{args} \) is itself the list of polynomials

kwds:

• `sparse` – boolean (optional - default: False)
  if True function creates sparse matrices.

OUTPUT:

• the macaulay resultant, an element of the base ring of `self`

Todo: Working with sparse matrices should usually give faster results, but with the current implementation it actually works slower. There should be a way to improve performance with regards to this.

EXAMPLES:

The number of polynomials has to match the number of variables:

```python
sage: R.<x,y,z> = PolynomialRing(QQ,3)
sage: R.macaulay_resultant([y,x+z])
Traceback (most recent call last):
...
TypeError: number of polynomials(= 2) must equal number of variables (= 3)
```
The polynomials need to be all homogeneous:

```python
sage: R.<x,y,z> = PolynomialRing(QQ,3)
sage: R.macaulay_resultant([y, x+z, z+x^3])
Traceback (most recent call last):
  ...TypeError: resultant for non-homogeneous polynomials is not supported
```

All polynomials must be in the same ring:

```python
sage: S.<x,y> = PolynomialRing(QQ, 2)
sage: R.<x,y,z> = PolynomialRing(QQ,3)
sage: S.macaulay_resultant([y, z+x])
Traceback (most recent call last):
  ...TypeError: not all inputs are polynomials in the calling ring
```

The following example recreates Proposition 2.10 in Ch.3 in [CLO2005]:

```python
sage: K.<x,y> = PolynomialRing(ZZ, 2)
sage: flist,R = K._macaulay_resultant_universal_polynomials([1,1,2])
sage: R.macaulay_resultant(flist)
u2^2*u4^2*u6 - 2*u1*u2*u4*u5*u6 + u1^2*u5^2*u6 - u2^2*u3*u4*u7 + u1*u2*u5*u7 + u0*u2*u4*u5*u7 - u0*u1*u5^2*u7 + u1*u2*u3*u4*u8 - u0*u2*u4^2*u8 - u1^2*u3*u5*u8 + u0*u1*u4*u5*u8 + u2^2*u3^2*u9 - 2*u0*u2*u3*u5*u9 + u0^2*u5^2*u9 - u1*u2*u3*u4*u10 + u0*u1*u3*u5*u10 - u0^2*u4*u5*u10 + u1^2*u3^2*u11 - 2*u0*u1*u3*u4*u11 + u0^2*u4^2*u11
```

The following example degenerates into the determinant of a $3 \times 3$ matrix:

```python
sage: K.<x,y> = PolynomialRing(ZZ, 2)
sage: flist,R = K._macaulay_resultant_universal_polynomials([1,1,1])
sage: R.macaulay_resultant(flist)
-u2*u4*u6 + u1*u5*u6 + u2*u3*u7 - u0*u5*u7 - u1*u3*u8 + u0*u4*u8
```

The following example is by Patrick Ingram (arXiv 1310.4114):

```python
sage: U = PolynomialRing(ZZ,'y',2); y0,y1 = U.gens()
sage: R = PolynomialRing(U,'x',3); x0,x1,x2 = R.gens()
sage: f0 = y0*x2^2 - x0*x2 + 2*x1^x2
sage: f1 = y1*x2^2 - x1^x2 + 2*x0*x2
sage: f2 = x0*x1 - x2^2
sage: flist = [f0,f1,f2]
sage: R.macaulay_resultant([f0,f1,f2])
y0^2*y1^2 - 4*y0^3 - 4*y1^3 + 18*y0*y1 - 27
```

A simple example with constant rational coefficients:

```python
sage: R.<x,y,z,w> = PolynomialRing(QQ,4)
sage: R.macaulay_resultant([w,z,y,x])
1
```

An example where the resultant vanishes:
Polynomials, Release 10.0

```
sage: R.<x,y,z> = PolynomialRing(QQ,3)
sage: R.macaulay_resultant([x+y,y^2,x])
0
```

An example of bad reduction at a prime $p = 5$:

```
sage: R.<x,y,z> = PolynomialRing(QQ,3)
sage: R.macaulay_resultant([y,x^3+25*y^2*x,5*z])
125
```

The input can given as an unpacked list of polynomials:

```
sage: R.<x,y,z> = PolynomialRing(QQ,3)
sage: R.macaulay_resultant(y,x^3+25*y^2*x,5*z)
125
```

An example when the coefficients live in a finite field:

```
sage: F = FiniteField(11)
sage: R.<x,y,z,w> = PolynomialRing(F,4)
sage: R.macaulay_resultant([z,x^3,5*y,w])
4
```

Example when the denominator in the algorithm vanishes(in this case the resultant is the constant term of the quotient of char polynomials of numerator/denominator):

```
sage: R.<x,y,z> = PolynomialRing(QQ,3)
sage: R.macaulay_resultant([y, x+z, z^2])
-1
```

When there are only 2 polynomials, macaulay resultant degenerates to the traditional resultant:

```
sage: R.<x> = PolynomialRing(QQ,1)
sage: f = x^2+1; g = x^5+1
sage: fh = f.homogenize()
sage: gh = g.homogenize()
sage: RH = fh.parent()
sage: f.resultant(g) == RH.macaulay_resultant([fh,gh])
True
```

```
monomial(*exponents)

Return the monomial with given exponents.

EXAMPLES:

```
sage: R.<x,y,z> = PolynomialRing(ZZ, 3)
sage: R.monomial(1,1,1)
x*y*z
sage: e=(1,2,3)
sage: R.monomial(*e)
x*y^2*z^3
sage: m = R.monomial(1,2,3)
sage: R.monomial(*m.degrees()) == m
True
```
**monomials_of_degree**(degree)

Return a list of all monomials of the given total degree in this multivariate polynomial ring.

**EXAMPLES:**

```python
sage: R.<x,y,z> = ZZ[]
sage: mons = R.monomials_of_degree(2)
sage: mons
[z^2, y*z, x*z, y^2, x*y, x^2]
```

```python
sage: P = PolynomialRing(QQ, 3, 'x, y, z', order=TermOrder('wdeglex', [1, 2, -1]))
sage: P.monomials_of_degree(2)
[z^2, y, x*z, x^2]
```

```python
sage: P = PolynomialRing(QQ, 3, 'x, y, z', order='lex')
sage: P.monomials_of_degree(3)
[z^3, y*z^2, y^2*z, y^3, x*z^2, x*y*z, x*y^2, x^2*z, x^2*y, x^3]
```

```python
sage: P = PolynomialRing(QQ, 3, 'x, y, z', order='invlex')
sage: P.monomials_of_degree(3)
[x^3, x^2*y, x*y^2, y^3, x^2*z, x*y*z, y^2*z, x*z^2, y*z^2, z^3]
```

The number of such monomials equals \( \binom{n+k-1}{k} \) where \( n \) is the number of variables and \( k \) the degree:

```python
sage: len(mons) == binomial(3+2-1,2)
True
```

**ngens()**

**random_element**(degree=2, terms=None, choose_degree=False, **kwargs)

Return a random polynomial of at most degree \( d \) and at most \( t \) terms.

First monomials are chosen uniformly random from the set of all possible monomials of degree up to \( d \) (inclusive). This means that it is more likely that a monomial of degree \( d \) appears than a monomial of degree \( d-1 \) because the former class is bigger.

Exactly \( t \) distinct monomials are chosen this way and each one gets a random coefficient (possibly zero) from the base ring assigned.

The returned polynomial is the sum of this list of terms.

**INPUT:**

- **degree** – maximal degree (likely to be reached) (default: 2)
- **terms** – number of terms requested (default: 5). If more terms are requested than exist, then this parameter is silently reduced to the maximum number of available terms.
- **choose_degree** – choose degrees of monomials randomly first rather than monomials uniformly random.
- ****kwargs – passed to the random element generator of the base ring

**EXAMPLES:**

```python
sage: P.<x,y,z> = PolynomialRing(QQ)
sage: f = P.random_element(2, 5)
sage: f.degree() <= 2
True
sage: f.parent() is P
True
```
Polynomials, Release 10.0

(continued from previous page)

sage: len(list(f)) <= 5
True

sage: f = P.random_element(2, 5, choose_degree=True)

sage: f.degree() <= 2
True

sage: f.parent() is P
True

sage: len(list(f)) <= 5
True

Stacked rings:

sage: R = QQ['x,y']
sage: S = R['t,u']
sage: f = S._random_nonzero_element(degree=2, terms=1)
sage: len(list(f))
1

sage: f.degree() <= 2
True

sage: f.parent() is S
True

Default values apply if no degree and/or number of terms is provided:

sage: M = random_matrix(QQ['x,y,z'], 2, 2)

sage: all(a.degree() <= 2 for a in M.list())
True

sage: all(len(list(a)) <= 5 for a in M.list())
True

sage: M = random_matrix(QQ['x,y,z'], 2, 2, terms=1, degree=2)

sage: all(a.degree() <= 2 for a in M.list())
True

sage: all(len(list(a)) <= 1 for a in M.list())
True

sage: P.random_element(0, 1) in QQ
True

sage: P.random_element(2, 0)

sage: R.<x> = PolynomialRing(Integers(3), 1)
sage: f = R.random_element()

sage: f.degree() <= 2
True

sage: len(list(f)) <= 3
True

To produce a dense polynomial, pick terms=Infinity:
The number of terms is silently reduced to the maximum available if more terms are requested:

```python
sage: P.<x,y,z> = GF(127)[]
sage: f = P.random_element(degree=2, terms=1000)
sage: len(list(f)) <= 10
True
```

remove_var(order=None, *var)

Remove a variable or sequence of variables from self.

If order is not specified, then the subring inherits the term order of the original ring, if possible.

EXAMPLES:

```python
sage: P.<x,y,z,w> = PolynomialRing(ZZ)
sage: P.remove_var(z)
Multivariate Polynomial Ring in x, y, w over Integer Ring
sage: P.remove_var(z,x)
Multivariate Polynomial Ring in y, w over Integer Ring
sage: P.remove_var(y,z,x)
Univariate Polynomial Ring in w over Integer Ring
```

Removing all variables results in the base ring:

```python
sage: P.remove_var(y,z,x,w)
Integer Ring
```

If possible, the term order is kept:

```python
sage: R.<x,y,z,w> = PolynomialRing(ZZ, order='deglex')
sage: R.remove_var(y).term_order()
Degree lexicographic term order
sage: R.<x,y,z,w> = PolynomialRing(ZZ, order='lex')
sage: R.remove_var(y).term_order()
Lexicographic term order
```

Be careful with block orders when removing variables:

```python
sage: R.<x,y,z,u,v> = PolynomialRing(ZZ, order='deglex(2),lex(3)')
sage: R.remove_var(x,y,z)
Traceback (most recent call last):
...
ValueError: impossible to use the original term order (most likely because it was a block order). Please specify the term order for the subring

```
sage: R.remove_var(x,y,z, order='degrevlex')
```

Multivariate Polynomial Ring in u, v over Integer Ring

**repr_long()**

Return structured string representation of self.

EXAMPLES:

```
sage: P.<x,y,z> = PolynomialRing(QQ,order=TermOrder('degrevlex',1)+TermOrder('lex',2))
sage: print(P.repr_long())
Polynomial Ring
Base Ring : Rational Field
Size : 3 Variables
Block 0 : Ordering : degrevlex
  Names : x
Block 1 : Ordering : lex
  Names : y, z
```

**some_elements()**

Return a list of polynomials.

This is typically used for running generic tests.

EXAMPLES:

```
sage: R.<x,y> = QQ[

sage: R.some_elements()
[x, y, x + y, x^2 + x*y, 0, 1]
```

**term_order()**

**univariate_ring(x)**

Return a univariate polynomial ring whose base ring comprises all but one variables of self.

INPUT:

- x – a variable of self.

EXAMPLES:

```
sage: P.<x,y,z> = QQ[

sage: P.univariate_ring(y)
Univariate Polynomial Ring in y over Multivariate Polynomial Ring in x, z over Rational Field
```

**variable_names_recursive(depth=None)**

Returns the list of variable names of this and its base rings, as if it were a single multi-variate polynomial.

EXAMPLES:
Polynomials, Release 10.0

```python
sage: R = QQ['x,y'][z,w]
sage: R.variable_names_recursive()
('x', 'y', 'z', 'w')
sage: R.variable_names_recursive(3)
('y', 'z', 'w')
```

**weyl_algebra()**

Return the Weyl algebra generated from `self`.

**EXAMPLES:**

```python
sage: R = QQ['x,y,z']
sage: W = R.weyl_algebra(); W
Differential Weyl algebra of polynomials in x, y, z over Rational Field
sage: W.polynomial_ring() == R
True
```

3.1.3 Base class for elements of multivariate polynomial rings

**class** `sage.rings.polynomial.multi_polynomial.MPolynomial`

Bases: CommutativePolynomial

**args()**

Returns the named of the arguments of self, in the order they are accepted from call.

**EXAMPLES:**

```python
sage: R.<x,y> = ZZ[

sage: x.args()
(x, y)
```

**change_ring(R)**

Return a copy of this polynomial but with coefficients in `R`, if at all possible.

**INPUT:**

- `R` – a ring or morphism.

**EXAMPLES:**

```python
sage: R.<x,y> = QQ[

sage: f = x^3 + 3/5*y + 1
```
sage: f.change_ring(GF(7))
x^3 + 2*y + 1

sage: R.<x,y> = GF(9,'a')[]
sage: (x+2*y).change_ring(GF(3))
x - y

sage: K.<z> = CyclotomicField(3)
sage: R.<x,y> = K[]
sage: f = x^2 + z*y
sage: f.change_ring(K.embeddings(CC)[1])
x^2 + (-0.500000000000000 - 0.866025403784438*I)*y

coefficients()

Return the nonzero coefficients of this polynomial in a list.

The returned list is decreasingly ordered by the term ordering of self.parent(), i.e. the
list of coefficients matches the list of monomials returned by sage.rings.polynomial.
multi_polynomial_libsingular.MPolynomial_libsingular.monomials().

EXAMPLES:

sage: R.<x,y,z> = PolynomialRing(QQ,3,order='degrevlex')
sage: f=23*x^6*y^7 + x^3*y+6*x^7*z
sage: f.coefficients()
[23, 6, 1]
sage: R.<x,y,z> = PolynomialRing(QQ,3,order='lex')
sage: f=23*x^6*y^7 + x^3*y+6*x^7*z
sage: f.coefficients()
[6, 23, 1]

Test the same stuff with base ring $\mathbb{Z}$ – different implementation:

sage: R.<x,y,z> = PolynomialRing(ZZ,3,order='degrevlex')
sage: f=23*x^6*y^7 + x^3*y+6*x^7*z
sage: f.coefficients()
[23, 6, 1]
sage: R.<x,y,z> = PolynomialRing(ZZ,3,order='lex')
sage: f=23*x^6*y^7 + x^3*y+6*x^7*z
sage: f.coefficients()
[6, 23, 1]

AUTHOR:
  • Didier Deshommes

content()

Returns the content of this polynomial. Here, we define content as the gcd of the coefficients in the base ring.

See also:
  content_ideal()
sage: R.<x,y> = ZZ[]
sage: f = 4*x+6*y
sage: f.content()
2
sage: f.content().parent()
Integer Ring

**content_ideal()**

Return the content ideal of this polynomial, defined as the ideal generated by its coefficients.

**See also:**

*content()*

**EXAMPLES:**

```sage
sage: R.<x,y> = ZZ[]
sage: f = 2*x*y + 6*x - 4*y + 2
sage: f.content_ideal()
Principal ideal (2) of Integer Ring
sage: S.<z,t> = R[]
sage: g = x*z + y*t
sage: g.content_ideal()
Ideal (x, y) of Multivariate Polynomial Ring in x, y over Integer Ring
```

**denominator()**

Return a denominator of self.

First, the lcm of the denominators of the entries of self is computed and returned. If this computation fails, the unit of the parent of self is returned.

Note that some subclasses may implement its own denominator function.

**Warning:** This is not the denominator of the rational function defined by self, which would always be 1 since self is a polynomial.

**EXAMPLES:**

First we compute the denominator of a polynomial with integer coefficients, which is of course 1.

```sage
sage: R.<x,y> = ZZ[]
sage: f = x^3 + 17*y + x + y
sage: f.denominator()
1
```

Next we compute the denominator of a polynomial over a number field.

```sage
sage: R.<x,y> = NumberField(symbolic_expression(x^2+3) , 'a')['x,y']
sage: f = (1/17)*x^19 + (1/6)*y - (2/3)*x + 1/3; f
1/17*x^19 - 2/3*x + 1/6*y + 1/3
sage: f.denominator()
102
```

Finally, we try to compute the denominator of a polynomial with coefficients in the real numbers, which is a ring whose elements do not have a denominator method.
Check that the denominator is an element over the base whenever the base has no denominator function. This closes github issue #9063:

```python
sage: R.<a,b,c> = GF(5)[]
sage: x = R(0)
sage: x.denominator()
1
sage: type(x.denominator())
<class 'sage.rings.finite_rings.integer_mod.IntegerMod_int'>
sage: type(a.denominator())
<class 'sage.rings.finite_rings.integer_mod.IntegerMod_int'>
sage: from sage.rings.polynomial.multi_polynomial_element import MPolynomial
sage: isinstance(a / b, MPolynomial)
False
sage: isinstance(a.numerator() / a.denominator(), MPolynomial)
True
```

**derivative(*args)**

The formal derivative of this polynomial, with respect to variables supplied in args.

Multiple variables and iteration counts may be supplied; see documentation for the global derivative() function for more details.

**See also:**

 `_derivative()`

**EXAMPLES:**

Polynomials implemented via Singular:

```python
sage: R.<x, y> = PolynomialRing(FiniteField(5))
sage: f = x^3*y^5 + x^7*y
sage: type(f)
<class 'sage.rings.polynomial.multi_polynomial_libsingular.MPolynomial_libsingular'>
sage: f.derivative(x)
2*x^6*y + x^7
sage: f.derivative(y)
x^7
```

Generic multivariate polynomials:

```python
sage: R.<t> = PowerSeriesRing(QQ)
sage: S.<x, y> = PolynomialRing(R)
sage: f = (t^2 + O(t^3)) * x^2 * y^3 + (37*t^4 + O(t^5)) * x^3
sage: type(f)
<class 'sage.rings.polynomial.multi_polynomial_element.MPolynomial_polydict'>
sage: f.derivative(x)  # with respect to x
```

(continues on next page)
Polynomials over the symbolic ring (just for fun…):

```
sage: x = var("x")
sage: S.<u, v> = PolynomialRing(SR)
sage: f = u*v*x
sage: f.derivative(x) == u*v
True
sage: f.derivative(u) == v*x
True
```

discriminant  \(\text{variable}\)

Returns the discriminant of self with respect to the given variable.

**INPUT:**

- \textbf{variable} - The variable with respect to which we compute the discriminant

**OUTPUT:**

- An element of the base ring of the polynomial ring.

**EXAMPLES:**

```
sage: R.<x,y,z>=QQ[]
sage: f=4*x*y^2 + 1/4*x*y*z + 3/2*x*z^2 - 1/2*z^2
sage: f.discriminant(x)
1
sage: f.discriminant(y)
-383/16*x^2*z^2 + 8*x*z^2
sage: f.discriminant(z)
-383/16*x^2*y^2 + 8*x*y^2
```

Note that, unlike the univariate case, the result lives in the same ring as the polynomial:

```
sage: R.<x,y>=QQ[]
sage: f=x^5*y+3*x^2*y^2-2*x*y-1
sage: f.discriminant(y)
x^10 + 2*x^5 + 24*x^3 + 12*x^2 + 1
sage: f.polynomial(y).discriminant()
x^10 + 2*x^5 + 24*x^3 + 12*x^2 + 1
```

(continues on next page)
AUTHOR:
Miguel Marco

gcd(other)

Return a greatest common divisor of this polynomial and other.

INPUT:
• other – a polynomial with the same parent as this polynomial

EXAMPLES:

```python
sage: Q.<z> = Frac(QQ['z'])
sage: R.<x,y> = Q[]
sage: r = x*y - (2*z-1)/(z^2+z+1) * x + y/z
sage: p = r * (x + z*y - 1/z^2)
sage: q = r * (x*y*z + 1)
sage: gcd(p,q)
(z^3 + z^2 + z)*x*y + (-2*z^2 + z)*x + (z^2 + z + 1)*y
```

Polynomials over polynomial rings are converted to a simpler polynomial ring with all variables to compute the gcd:

```python
sage: A.<z,t> = ZZ[]
sage: B.<x,y> = A[]
sage: r = x*y*z*t+1
sage: p = r * (x - y + z - t + 1)
sage: q = r * (x*z - y*t)
sage: gcd(p,q)
z*t*x*y + 1
sage: _.parent()
Multivariate Polynomial Ring in x, y over Multivariate Polynomial Ring in z, t over Integer Ring
```

Some multivariate polynomial rings have no gcd implementation:

```python
sage: R.<x,y> = GaussianIntegers()[]
sage: x.gcd(x)
Traceback (most recent call last):
... NotImplementedError: GCD is not implemented for multivariate polynomials over Gaussian Integers in Number Field in I with defining polynomial x^2 + 1 with I = 1*I
```

gradient()

Return a list of partial derivatives of this polynomial, ordered by the variables of self.parent().

EXAMPLES:

```python
sage: P.<x,y,z> = PolynomialRing(ZZ,3)
sage: f = x*y + 1
```
(continues on next page)
sage: f.gradient()
[y, x, 0]

**homogeneous_components()**

Return the homogeneous components of this polynomial.

**OUTPUT:**

A dictionary mapping degrees to homogeneous polynomials.

**EXAMPLES:**

```python
sage: R.<x,y> = QQ[]
sage: (x^3 + 2*x*y^3 + 4*y^3 + y).homogeneous_components()
{1: y, 3: x^3 + 4*y^3, 4: 2*x*y^3}
sage: R.zero().homogeneous_components()
{}
```

In case of weighted term orders, the polynomials are homogeneous with respect to the weights:

```python
sage: S.<a,b,c> = PolynomialRing(ZZ, order=TermOrder('wdegrelex', (1,2,3)))
sage: (a^6 + b^3 + b*c + a^2*c + c + a + 1).homogeneous_components()
{0: 1, 1: a, 3: c, 5: a^2*c + b*c, 6: a^6 + b^3}
```

**homogenize(var=’h’)**

Return the homogenization of this polynomial.

The polynomial itself is returned if it is homogeneous already. Otherwise, the monomials are multiplied with the smallest powers of var such that they all have the same total degree.

**INPUT:**

- var – a variable in the polynomial ring (as a string, an element of the ring, or a zero-based index in the list of variables) or a name for a new variable (default: ’h’)

**OUTPUT:**

If var specifies a variable in the polynomial ring, then a homogeneous element in that ring is returned. Otherwise, a homogeneous element is returned in a polynomial ring with an extra last variable var.

**EXAMPLES:**

```python
sage: R.<x,y> = QQ[]
sage: f = x^2 + y + 1 + 5*x*y^10
sage: f.homogenize()
5*x*y^10 + x^2*h^9 + y*h^10 + h^11
```

The parameter var can be used to specify the name of the variable:

```python
sage: g = f.homogenize('z'); g
5*x*y^10 + x^2*z^9 + y*z^10 + z^11
sage: g.parent()
Multivariate Polynomial Ring in x, y, z over Rational Field
```

However, if the polynomial is homogeneous already, then that parameter is ignored and no extra variable is added to the polynomial ring:
sage: f = x^2 + y^2
sage: g = f.homogenize('z'); g
x^2 + y^2
sage: g.parent()
Multivariate Polynomial Ring in x, y over Rational Field

If you want the ring of the result to be independent of whether the polynomial is homogenized, you can use var to use an existing variable to homogenize:

sage: R.<x,y,z> = QQ[]
sage: f = x^2 + y^2
sage: g = f.homogenize(z); g
x^2 + y^2
sage: g.parent()
Multivariate Polynomial Ring in x, y, z over Rational Field
sage: f = x^2 - y
sage: g = f.homogenize(z); g
x^2 - y*z
sage: g.parent()
Multivariate Polynomial Ring in x, y, z over Rational Field

The parameter var can also be given as a zero-based index in the list of variables:

sage: g = f.homogenize(2); g
x^2 - y*z

If the variable specified by var is not present in the polynomial, then setting it to 1 yields the original polynomial:

sage: g(x,y,1)
x^2 - y

If it is present already, this might not be the case:

sage: g = f.homogenize(x); g
x^2 - x*y
sage: g(1,y,z)
-y + 1

In particular, this can be surprising in positive characteristic:

sage: R.<x,y> = GF(2)[]
sage: f = x + 1
sage: f.homogenize(x)
0

inverse_mod(I)

Returns an inverse of self modulo the polynomial ideal I, namely a multivariate polynomial f such that self * f - 1 belongs to I.

INPUT:

* I – an ideal of the polynomial ring in which self lives

OUTPUT:
• a multivariate polynomial representing the inverse of \( f \) modulo \( I \)

EXAMPLES:

```
sage: R.<x1,x2> = QQ[]
sage: I = R.ideal(x2**2 + x1 - 2, x1**2 - 1)
sage: f = x1 + 3*x2^2; g = f.inverse_mod(I); g
1/16*x1 + 3/16
sage: (f*g).reduce(I)
1
```

Test a non-invertible element:

```
sage: R.<x1,x2> = QQ[]
sage: I = R.ideal(x2**2 + x1 - 2, x1**2 - 1)
sage: f = x1 + x2
sage: f.inverse_mod(I)
Traceback (most recent call last):
  ... ArithmeticError: element is non-invertible
```

**is_generator()**

Returns True if this polynomial is a generator of its parent.

EXAMPLES:

```
sage: R.<x,y>=ZZ[]
sage: x.is_generator()
True
sage: (x+y-y).is_generator()
True
sage: (x*y).is_generator()
False
sage: R.<x,y>=QQ[]
sage: x.is_generator()
True
sage: (x+y-y).is_generator()
True
sage: (x*y).is_generator()
False
```

**is_homogeneous()**

Return True if self is a homogeneous polynomial.

**Note:** This is a generic implementation which is likely overridden by subclasses.

**is_lorentzian**(explain=False)

Return whether this is a Lorentzian polynomial.

INPUT:

• explain – boolean (default: False); if True return a tuple whose first element is the boolean result of the test, and the second element is a string describing the reason the test failed, or None if the test succeeded.
Lorentzian polynomials are a class of polynomials connected with the area of discrete convex analysis. A polynomial $f$ with positive real coefficients is Lorentzian if:

- $f$ is homogeneous;
- the support of $f$ is $M$-convex
- $f$ has degree less than 2, or if its degree is at least two, the collection of sequential partial derivatives of $f$ which are quadratic forms have Gram matrices with at most one positive eigenvalue.

Note in particular that the zero polynomial is Lorentzian. Examples of Lorentzian polynomials include homogeneous stable polynomials, volume polynomials of convex bodies and projective varieties, and Schur polynomials after renormalizing the coefficient of each monomial $x^\alpha$ by $1/\alpha!$.

**EXAMPLES:**

Renormalized Schur polynomials are Lorentzian, but not in general if the renormalization is skipped:

```python
sage: P.<x,y> = QQ[]
sage: p = (x^2 / 2) + x*y + (y^2 / 2)
sage: p.is_lorentzian()
True
sage: p = x^2 + x*y + y^2
sage: p.is_lorentzian()
False
```

Homogeneous linear forms and constant polynomials with positive coefficients are Lorentzian, as well as the zero polynomial:

```python
sage: p = x + 2*y
sage: p.is_lorentzian()
True
sage: p = P(5)
```

Inhomogeneous polynomials and polynomials with negative coefficients are not Lorentzian:

```python
sage: p = x^2 + 2*x + y^2
sage: p.is_lorentzian()
False
sage: p = 2*x^2 - y^2
sage: p.is_lorentzian()
False
```

It is an error to check if a polynomial is Lorentzian if its base ring is not a subring of the real numbers, as the notion is not defined in this case:

```python
sage: Q.<z,w> = CC[]
sage: q = z^2 + w^2
sage: q.is_lorentzian()
Traceback (most recent call last):
  ... Not Implemented Error: is_lorentzian only implemented for real polynomials
```

The method can give a reason for a polynomial failing to be Lorentzian:
sage: p = x^2 + 2*x + y^2
sage: p.is_lorentzian(explain=True)
(False, 'inhomogeneous')

REFERENCES:
For full definitions and related discussion, see [BrHu2019] and [HMMS2019]. The second reference gives
the characterization of Lorentzian polynomials applied in this implementation explicitly.

is_nilpotent()
Return True if self is nilpotent, i.e., some power of self is 0.

EXAMPLES:

sage: R.<x,y> = QQbar[]
sage: (x+y).is_nilpotent()
False
sage: R(0).is_nilpotent()
True
sage: _.<x,y> = Zmod(4)[]
sage: (2*x).is_nilpotent()
True
sage: (2+y*x).is_nilpotent()
False
sage: _.<x,y> = Zmod(36)[]
sage: (4+6*x).is_nilpotent()
False
sage: (6*x + 12*y + 18*x*y + 24*(x^2+y^2)).is_nilpotent()
True

is_square(root=False)
Test whether this polynomial is a square root.

INPUT:
• root - if set to True return a pair (True, root) where root is a square root or (False, None) if
  it is not a square.

EXAMPLES:

sage: R.<a,b> = QQ[]
sage: a.is_square()
False
sage: ((1+a*b^2)^2).is_square()
True
sage: ((1+a*b^2)^2).is_square(root=True)
(True, a*b^2 + 1)

is_symmetric(group=None)
Return whether this polynomial is symmetric.

INPUT:
• group (default: symmetric group) – if set, test whether the polynomial is invariant with respect to the
given permutation group

EXAMPLES:
sage: R.<x,y,z> = QQ[]
sage: p = (x+y+z)**2 - 3*(x+y)*(x+z)*(y+z)
sage: p.is_symmetric()
True
sage: (x + y - z).is_symmetric()
False
sage: R.one().is_symmetric()
True
sage: p = (x-y)*(y-z)*(z-x)
sage: p.is_symmetric()
False
sage: p.is_symmetric(AlternatingGroup(3))
True
sage: R.<x,y> = QQ[]
sage: ((x + y)**2).is_symmetric()
True
sage: R.one().is_symmetric()
True
sage: (x + 2*y).is_symmetric()
False

An example with a GAP permutation group (here the quaternions):

sage: R = PolynomialRing(QQ, 'x', 8)
sage: x = R.gens()
sage: p = sum(prod(x[i] for i in e) for e in [(0,1,2), (0,1,7), (0,2,7), (1,2, ˓→7), (3,4,5), (3,4,6), (3,5,6), (4,5,6)])
sage: p.is_symmetric(libgap.TransitiveGroup(8, 5))
True
sage: p = sum(prod(x[i] for i in e) for e in [(0,1,2), (0,1,7), (0,2,7), (1,2, ˓→7), (3,4,5), (3,4,6), (3,5,6)])
sage: p.is_symmetric(libgap.TransitiveGroup(8, 5))
False

is_unit()

Return True if self is a unit, that is, has a multiplicative inverse.

EXAMPLES:

sage: R.<x,y> = QQbar[]
sage: (x+y).is_unit()
False
sage: R(0).is_unit()
False
sage: R(-1).is_unit()
True
sage: R(-1 + x).is_unit()
False
sage: R(2).is_unit()
True

Check that github issue #22454 is fixed:
Polynomials, Release 10.0

sage: _.<x,y> = Zmod(4)[]
sage: (1 + 2*x).is_unit()
True
sage: (x*y).is_unit()
False
sage: _.<x,y> = Zmod(36)[]
sage: (7+ 6*x + 12*y - 18*x*y).is_unit()
True

iterator_exp_coeff(as_ETuples=True)
Iterate over self as pairs of (ETuple, coefficient).

INPUT:

• as_ETuples – (default: False) if True iterate over pairs whose first element is an ETuple, otherwise as a tuples

EXAMPLES:

sage: R.<a,b,c> = QQ[]
sage: f = a*c^3 + a^2*b + 2*b^4
sage: list(f.iterator_exp_coeff())
[((0, 4, 0), 2), ((1, 0, 3), 1), ((2, 1, 0), 1)]
sage: list(f.iterator_exp_coeff(as_ETuples=False))
[((0, 4, 0), 2), ((1, 0, 3), 1), ((2, 1, 0), 1)]
sage: R.<a,b,c> = PolynomialRing(QQ, 3, order='lex')
sage: f = a*c^3 + a^2*b + 2*b^4
sage: list(f.iterator_exp_coeff())
[((2, 1, 0), 1), ((1, 0, 3), 1), ((0, 4, 0), 2)]

jacobian_ideal()
Return the Jacobian ideal of the polynomial self.

EXAMPLES:

sage: R.<x,y,z> = QQ[]
sage: f = x^3 + y^3 + z^3
sage: f.jacobian_ideal()
Ideal (3*x^2, 3*y^2, 3*z^2) of Multivariate Polynomial Ring in x, y, z over Rational Field

lift(I)
given an ideal I = (f_1,...,f_r) and some g (= self) in I, find s_1,...,s_r such that g = s_1 f_1 + ... + s_r f_r.

EXAMPLES:

sage: A.<x,y> = PolynomialRing(CC,2,order='degrevlex')
sage: I = A.ideal([x^10 + x^9*y^2, y^8 - x^2*y^7 ])
sage: f = x^y^13 + y^12
sage: M = f.lift(I)
sage: M
[y^7, x^7*y^2 + x^8 + x^5*y^3 + x^6*y + x^3*y^4 + x^4*y^2 + x*y^5 + x^2*y^3 + y^4]

(continues on next page)
This is an implementation of the Macaulay Resultant. It computes the resultant of universal polynomials as well as polynomials with constant coefficients. This is a project done in sage days 55. It’s based on the implementation in Maple by Manfred Minimair, which in turn is based on the references [CLO], [Can], [Mac]. It calculates the Macaulay resultant for a list of Polynomials, up to sign!

AUTHORS:

• Hao Chen, Solomon Vishkautsan (7-2014)

INPUT:

• args – a list of $n - 1$ homogeneous polynomials in $n$ variables.

works when args[0] is the list of polynomials, or args is itself the list of polynomials

OUTPUT:

• the macaulay resultant

EXAMPLES:

The number of polynomials has to match the number of variables:

```
sage: R.<x,y,z> = PolynomialRing(QQ,3)
sage: y.macaulay_resultant(x+z)
Traceback (most recent call last):
...  
TypeError: number of polynomials(= 2) must equal number of variables (= 3)
```

The polynomials need to be all homogeneous:

```
sage: R.<x,y,z> = PolynomialRing(QQ,3)
sage: y.macaulay_resultant([x+z, z-x^3])
Traceback (most recent call last):
...  
TypeError: resultant for non-homogeneous polynomials is not supported
```

All polynomials must be in the same ring:

```
sage: R.<x,y,z> = PolynomialRing(QQ,3)
sage: S.<x,y> = PolynomialRing(QQ, 2)
sage: y.macaulay_resultant(z+x,z)
Traceback (most recent call last):
...  
TypeError: not all inputs are polynomials in the calling ring
```

The following example recreates Proposition 2.10 in Ch.3 of Using Algebraic Geometry:

```
sage: K.<x,y> = PolynomialRing(ZZ, 2)
sage: flist,R = K._macaulay_resultant_universal_polynomials([1,1,2])
sage: flist[0].macaulay_resultant(flist[1:])
u2^2*u4^2*u6 - 2*u1^2*u2*u4*u5*u6 + u1^2*u5^2*u6 + u2^2*u3*u4*u7 + u1*u2*u3*u5*u7 =>
... + u0*u2*u4*u5*u7 - u0*u1*u5^2*u7 + u1*u2*u3*u4*u8 - u0*u2*u4^2*u8 - u1^3.1. Multivariate Polynomials and Polynomial Rings 319
```
The following example degenerates into the determinant of a 3 × 3 matrix:

```python
sage: K.<x,y> = PolynomialRing(ZZ, 2)
sage: flist, R = K._macaulay_resultant_universal_polynomials([1,1,1])
sage: flist[0].macaulay_resultant(flist[1:])
```

\[ -u_2 u_4 u_6 + u_1 u_5 u_6 + u_2 u_3 u_7 - u_0 u_5 u_7 - u_1 u_3 u_8 + u_0 u_4 u_8 \]

The following example is by Patrick Ingram (arXiv 1310.4114):

```python
sage: U = PolynomialRing(ZZ, 'y', 2); y0, y1 = U.gens()
sage: R = PolynomialRing(U, 'x', 3); x0, x1, x2 = R.gens()
sage: f0 = y0*x2^2 - x0^2 + 2*x1*x2
sage: f1 = y1*x2^2 - x1^2 + 2*x0*x2
sage: f2 = x0*x1 - x2^2
sage: f0.macaulay_resultant(f1,f2)
```

\[ y_0^2 y_1^2 - 4 y_0^3 - 4 y_1^3 + 18 y_0 y_1 - 27 \]

A simple example with constant rational coefficients:

```python
sage: R.<x,y,z,w> = PolynomialRing(QQ,4)
sage: w.macaulay_resultant([z,y,x])
```

1

An example where the resultant vanishes:

```python
sage: R.<x,y,z> = PolynomialRing(QQ,3)
sage: (x+y).macaulay_resultant([y^2,x])
```

0

An example of bad reduction at a prime \( p = 5 \):

```python
sage: R.<x,y,z> = PolynomialRing(QQ,3)
sage: y.macaulay_resultant([x^3+25*y^2*x,5*z])
```

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The input can given as an unpacked list of polynomials:

```python
sage: R.<x,y,z> = PolynomialRing(QQ,3)
sage: y.macaulay_resultant(x^3+25*y^2*x,5*z)
```

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An example when the coefficients live in a finite field:

```python
sage: F = FiniteField(11)
sage: R.<x,y,z,w> = PolynomialRing(F,4)
sage: z.macaulay_resultant([x^3,5*y,w])
```

4

Example when the denominator in the algorithm vanishes (in this case the resultant is the constant term of the quotient of char polynomials of numerator/denominator):
when there are only 2 polynomials, macaulay resultant degenerates to the traditional resultant:

```python
sage: R.<x> = PolynomialRing(QQ,1)
sage: f = x^2+1; g = x^5+1
sage: fh = f.homogenize()
sage: gh = g.homogenize()
sage: RH = fh.parent()
sage: f.resultant(g) == fh.macaulay_resultant(gh)
True
```

`map_coefficients(f, new_base_ring=None)`

Returns the polynomial obtained by applying `f` to the non-zero coefficients of self.

If `f` is a `sage.categories.map.Map`, then the resulting polynomial will be defined over the codomain of `f`. Otherwise, the resulting polynomial will be over the same ring as self. Set `new_base_ring` to override this behaviour.

**INPUT:**

- `f` – a callable that will be applied to the coefficients of self.
- `new_base_ring` (optional) – if given, the resulting polynomial will be defined over this ring.

**EXAMPLES:**

```python
sage: k.<a> = GF(9); R.<x,y> = k[]; f = x*a + 2*x^3*y*a + a
sage: f.map_coefficients(lambda a : a + 1)
(-a + 1)*x^3*y + (a + 1)*x + (a + 1)
```

Examples with different base ring:

```python
sage: R.<r> = GF(9); S.<s> = GF(81)
sage: h = Hom(R,S)[0]; h
Ring morphism:
    From: Finite Field in r of size 3^2
    To:Finite Field in s of size 3^4
    Defn:r |--> 2*s^3 + 2*s^2 + 1
sage: T.<X,Y> = R[]
sage: f = r*X+Y
sage: g = f.map_coefficients(h); g
(-a + 1)*x^3*y + (a + 1)*x + (a + 1)
sage: g.parent()
Multivariate Polynomial Ring in X, Y over Finite Field in s of size 3^4
```

```python
sage: h = lambda x: x.trace()
sage: g = f.map_coefficients(h); g
X - Y
sage: g.parent()
Multivariate Polynomial Ring in X, Y over Finite Field of size 3
```
newton_polytope()

Return the Newton polytope of this polynomial.

EXAMPLES:

```
sage: R.<x,y> = QQ[]
sage: f = 1 + x*y + x^3 + y^3
sage: P = f.newton_polytope()
sage: P
A 2-dimensional polyhedron in ZZ^2 defined as the convex hull of 3 vertices
sage: P.is_simple()
True
```

nth_root(n)

Return a $n$-th root of this element.

If there is no such root, a ValueError is raised.

EXAMPLES:

```
sage: R.<x,y,z> = QQ[]
sage: a = 32 * (x*y + 1)^5 * (x+y+z)^5
sage: a.nth_root(5)
2*x^2*y + 2*x*y^2 + 2*x*y*z + 2*x + 2*y + 2*z
sage: b = x + 2*y + 3*z
sage: b.nth_root(42)
Traceback (most recent call last):
  ... ValueError: not a 42nd power
```

numerator()

Return a numerator of self computed as self * self.denominator()

Note that some subclasses may implement its own numerator function.

**Warning:** This is not the numerator of the rational function defined by self, which would always be self since self is a polynomial.

EXAMPLES:

First we compute the numerator of a polynomial with integer coefficients, which is of course self.

Next we compute the numerator of a polynomial over a number field.

```python
sage: R.<x, y> = NumberField(symbolic_expression(x^2+3), 'a')['x, y']
sage: f = (1/17)*y^19 - (2/3)*x + 1/3; f
1/17*y^19 - 2/3*x + 1/3
sage: f.numerator()
3*y^19 - 34*x + 17
sage: f == f.numerator()
False
```

We try to compute the numerator of a polynomial with coefficients in the finite field of 3 elements.

```python
sage: K.<x,y,z> = GF(3)[x, y, z]
sage: f = 2*x*z + 2*z^2 + 2*y + 1; f
-x*z - z^2 - y + 1
sage: f.numerator()
-x*z - z^2 - y + 1
```

We check that the computation the numerator and denominator are valid.

```python
sage: K.<x,y,z> = NumberField(symbolic_expression(x^3+2), 'a')['x','s,t']
sage: f=K.random_element()
sage: f.numerator() / f.denominator() == f
True
```

```
polynomial(var)

Let var be one of the variables of the parent of self. This returns self viewed as a univariate polynomial in var over the polynomial ring generated by all the other variables of the parent.

EXAMPLES:

```python
sage: R.<x,w,z> = QQ[]
sage: f = x^3 + 3*w*x + w^5 + (17*w^3)*x + z^5
sage: f.polynomial(x)
x^3 + (17*w^3 + 3*w)*x + w^5 + z^5
sage: parent(f.polynomial(x))
Univariate Polynomial Ring in x over Multivariate Polynomial Ring in w, z over Rational Field
```
sage: R.<x,w,z,k> = ZZ[]
sage: f = x^3 + 3*w*x + w^5 + (17*w^3)*x + z^5 + x*w*z*k + 5
sage: f.polynomial(x)
x^3 + (17*w^3 + w*z*k + 3*w)*x + w^5 + z^5 + 5
sage: f.polynomial(w)
w^5 + 17*x*w^3 + (x*z^k + 3*x)*w + z^5 + x^3 + 5
sage: f.polynomial(z)
z^5 + x*w*z*k + w^5 + 17*x*w^3 + x^3 + 3*x*w + 5
sage: f.polynomial(k)
x*w*z*k + w^5 + z^5 + 17*x*w^3 + x^3 + 3*x*w + 5
sage: R.<x,y>=GF(5)[]
sage: f=x^2+x+y
sage: f.polynomial(x)
x^2 + x + y

reduced_form(**kwds)

Return a reduced form of this polynomial.

The algorithm is from Stoll and Cremona’s “On the Reduction Theory of Binary Forms” [CS2003]. This takes a two variable homogeneous polynomial and finds a reduced form. This is a $SL(2,\mathbb{Z})$-equivalent binary form whose covariant in the upper half plane is in the fundamental domain. If the polynomial has multiple roots, they are removed and the algorithm is applied to the portion without multiple roots.

This reduction should also minimize the sum of the squares of the coefficients, but this is not always the case. By default the coefficient minimizing algorithm in [HS2018] is applied. The coefficients can be minimized either with respect to the sum of their squares or the maximum of their global heights.

A portion of the algorithm uses Newton’s method to find a solution to a system of equations. If Newton’s method fails to converge to a point in the upper half plane, the function will use the less precise $z_0$ covariant from the $Q_0$ form as defined on page 7 of [CS2003]. Additionally, if this polynomial has a root with multiplicity at least half the total degree of the polynomial, then we must also use the $z_0$ covariant. See [CS2003] for details.

Note that, if the covariant is within error_limit of the boundary but outside the fundamental domain, our function will erroneously move it to within the fundamental domain, hence our conjugation will be off by 1. If you don’t want this to happen, decrease your error_limit and increase your precision.

Implemented by Rebecca Lauren Miller as part of GSOC 2016. Smallest coefficients added by Ben Hutz July 2018.

INPUT:

keywords:

• prec – integer, sets the precision (default:300)
• return_conjugation – boolean. Returns element of $SL(2,\mathbb{Z})$ (default:True)
• error_limit – sets the error tolerance (default:0.000001)
• smallest_coeffs – (default: True), boolean, whether to find the model with smallest coefficients
• norm_type – either 'norm' or 'height'. What type of norm to use for smallest coefficients
• emb – (optional) embedding of based field into CC

OUTPUT:
• a polynomial (reduced binary form)
• a matrix (element of $SL(2,\mathbb{Z})$)

**TODO:** When Newton’s Method doesn’t converge to a root in the upper half plane.

Now we just return $z_0$. It would be better to modify and find the unique root in the upper half plane.

**EXAMPLES:**

```sage
R.<x,h> = PolynomialRing(QQ)
sage: f = 19*x^8 - 262*x^7*h + 1507*x^6*h^2 - 4784*x^5*h^3 + 9202*x^4*h^4 - 10962*x^3*h^5 + 7844*x^2*h^6 - 3040*x*h^7 + 475*h^8
sage: f.reduced_form(prec=200, smallest_coeffs=False)
(-x^8 - 2*x^7*h + 7*x^6*h^2 + 16*x^5*h^3 + 2*x^4*h^4 - 2*x^3*h^5 + 4*x^2*h^6 - 5*h^8,
 [1 -2]
 [1 -1])
```

An example where the multiplicity is too high:

```sage
R.<x,y> = PolynomialRing(QQ)
sage: f = x^3 + 378666*x^2*y - 12444444*x*y^2 + 1234567890*y^3
sage: j = f * (x-545*y)^9
sage: j.reduced_form(prec=200, smallest_coeffs=False)
Traceback (most recent call last):
... ValueError: cannot have a root with multiplicity >= 12/2
```

An example where Newton’s Method does not find the right root:

```sage
R.<x,y> = PolynomialRing(QQ)
sage: F = x^6 + 3*x^5*y - 8*x^4*y^2 - 2*x^3*y^3 - 44*x^2*y^4 - 8*x*y^5
sage: F.reduced_form(smallest_coeffs=False, prec=400)
Traceback (most recent call last):
... ArithmeticError: Newton's method converged to z not in the upper half plane
```

An example with covariant on the boundary, therefore a non-unique form:

```sage
R.<x,y> = PolynomialRing(QQ)
sage: F = 5*x^2*y - 5*x*y^2 - 30*y^3
sage: F.reduced_form(smallest_coeffs=False)
([1 1],
 5*x^2*y + 5*x*y^2 - 30*y^3, [0 1])
```

An example where precision needs to be increased:

```sage
R.<x,y> = PolynomialRing(QQ)
sage: F=-16*x^7 - 114*x^6*y - 345*x^5*y^2 - 599*x^4*y^3 - 666*x^3*y^4 - 481*x^2*y^5 - 207*x*y^6 - 40*y^7
```

(continues on next page)
sage: F.reduced_form(prec=50, smallest_coeffs=False)
Traceback (most recent call last):
...
ValueError: accuracy of Newton’s root not within tolerance(0.000012... > 1e-06), → increase precision
sage: F.reduced_form(prec=100, smallest_coeffs=False)
( [-1 -1]
- x^5*y^2 - 24*x^3*y^4 - 3*x^2*y^5 - 2*x*y^6 + 16*y^7, [ 1 0] )

sage: R.<x,y> = PolynomialRing(QQ)
sage: F = - 8*x^4 - 3933*x^3*y - 725085*x^2*y^2 - 59411592*x*y^3 - 1825511633*y^4
sage: F.reduced_form(return_conjugation=False)
x^4 + 9*x^3*y - 3*x*y^3 - 8*y^4

sage: R.<x,y> = QQ[]
sage: F = -2*x^3 + 2*x^2*y + 3*x*y^2 + 127*y^3
sage: F.reduced_form(norm_type='height')
( [5 4]
- 58*x^3 - 47*x^2*y + 52*x*y^2 + 43*y^3, [1 1] )

sage: R.<x,y,z> = PolynomialRing(QQ)
sage: F = x^4 + x^3*y*z + y^2*z
sage: F.reduced_form()
Traceback (most recent call last):
...
ValueError: (=x^3*y*z + x^4 + y^2*z) must have two variables

sage: R.<x,y> = PolynomialRing(ZZ)
sage: F = - 8*x^6 - 3933*x^3*y - 725085*x^2*y^2 - 59411592*x*y^3 - 99*y^6
sage: F.reduced_form(return_conjugation=False)
Traceback (most recent call last):
...
ValueError: (=8*x^6 - 99*y^6 - 3933*x^3*y - 725085*x^2*y^2 - 59411592*x*y^3) must be homogeneous

sage: R.<x,y> = PolynomialRing(RR)
sage: F = 217.992172373276*x^3 + 96023.1505442490*x^2*y + 1.
Polynomials, Release 10.0

(...)

\[40987971253579e7*x*y^2\]
+ 6.90016027113216e8*y^3

**sage:** F.reduced_form(smallest_coeffs=False)  # tol le-8

\((-39.5673942565918*x^3 + 111.874026298523*x^2*y + 231.052762985229*x*y^2 - 138.\]
\rightarrow 38829811096*y^3,\)

**sage:** R.<x,y> = PolynomialRing(CC)

**sage:** F = (0.759099196558145 + 0.845425869641446*CC.0)*x^3 + (84.8317207268542 +
\rightarrow 93.8846848648033*CC.0)*x^2*y\]
+ (3159.07040755858 + 3475.33037377779*CC.0)*x*y^2 + (39202.5965389079 + 42882.
\rightarrow 5139724962*CC.0)*y^3

**sage:** F.reduced_form(smallest_coeffs=False)  # tol le-11

\((-0.759099196558145 - 0.845425869641446*I)*x^3 + (-0.571709908900118 - 0.
\rightarrow 0.04181333460279299*I)*x^2*y\]
+ (0.856525964330103 - 0.0721403997649759*I)*x*y^2 + (-0.965531044130330 + 0.
\rightarrow 754252314465703*I)*y^3,

\([-147 -148]
[ 1 1])

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

Specialization of this polynomial.

Given a family of polynomials 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:**

\(\cdot D\) – dictionary (optional)

\(\cdot\) phi – SpecializationMorphism (optional)

**OUTPUT:** a new polynomial

**EXAMPLES:**

**sage:** R.<c> = PolynomialRing(QQ)

**sage:** S.<x,y> = PolynomialRing(R)

**sage:** F = x^2 + c*y^2

**sage:** F.specialization({c:2})

\(x^2 + 2*y^2\)

**sage:** S.<a,b> = PolynomialRing(QQ)

**sage:** P.<x,y,z> = PolynomialRing(S)

**sage:** RR.<c,d> = PolynomialRing(P)

**sage:** f = a*x^2 + b*y^3 + c*y^2 - b*a*d + d^2 - a*c*b*z^2

**sage:** f.specialization({a:2, z:4, d:2})

\((y^2 - 32*b)*c + b*y^3 + 2*x^2 - 4*b + 4\)

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Check that we preserve multi- versus uni-variate:

```python
sage: R.<l> = PolynomialRing(QQ, 1)
sage: S.<k> = PolynomialRing(R)
sage: K.<a, b, c> = PolynomialRing(S)
sage: F = a*k^2 + b*l + c^2
sage: F.specialization({b:56, c:5}).parent()
Univariate Polynomial Ring in a over Univariate Polynomial Ring in k
over Multivariate Polynomial Ring in l over Rational Field
```

**subresultants**(*other, variable=None*)

Return the nonzero subresultant polynomials of self and other.

**INPUT:**

- other — a polynomial

**OUTPUT:** a list of polynomials in the same ring as self

**EXAMPLES:**

```python
sage: R.<x,y> = QQ[]
sage: p = (y^2 + 6)*(x - 1) - y*(x^2 + 1)
sage: q = (x^2 + 6)*(y - 1) - x*(y^2 + 1)
sage: p.subresultants(q, y)
[2*x^6 - 22*x^5 + 102*x^4 - 274*x^3 + 488*x^2 - 552*x + 288,
 -x^3 - x^2*y + 6*x^2 + 5*x*y - 11*x - 6*y + 6]
sage: p.subresultants(q, x)
[2*y^6 - 22*y^5 + 102*y^4 - 274*y^3 + 488*y^2 - 552*y + 288,
 x*y^2 + y^3 - 5*x*y - 6*y^2 + 6*x + 11*y - 6]
```

**sylvester_matrix**(*right, variable=None*)

Given two nonzero polynomials self and right, returns the Sylvester matrix of the polynomials with respect to a given variable.

Note that the Sylvester matrix is not defined if one of the polynomials is zero.

**INPUT:**

- self, right: multivariate polynomials
- variable: optional, compute the Sylvester matrix with respect to this variable. If variable is not provided, the first variable of the polynomial ring is used.

**OUTPUT:**

- The Sylvester matrix of self and right.

**EXAMPLES:**

```python
sage: R.<x, y> = PolynomialRing(ZZ)
sage: f = (y + 1)*x + 3*x**2
sage: g = (y + 2)*x + 4*x**2
sage: M = f.sylvester_matrix(g, x)
sage: M
[ 3 y + 1 0 0]
[ 0 3 y + 1 0]
[ 4 y + 2 0 0]
[ 0 4 y + 2 0]
```
If the polynomials share a non-constant common factor then the determinant of the Sylvester matrix will be zero:

```
sage: M.determinant()
0
sage: f.sylvester_matrix(1 + g, x).determinant()
y^2 - y + 7
```

If both polynomials are of positive degree with respect to variable, the determinant of the Sylvester matrix is the resultant:

```
sage: f = R.random_element(4) or (x^2 * y^2)
sage: g = R.random_element(4) or (x^2 * y^2)
sage: f.sylvester_matrix(g, x).determinant() == f.resultant(g, x)
True
```

`truncate(var, n)`

Returns a new multivariate polynomial obtained from self by deleting all terms that involve the given variable to a power at least n.

`weighted_degree(*weights)`

Return the weighted degree of self, which is the maximum weighted degree of all monomials in self; the weighted degree of a monomial is the sum of all powers of the variables in the monomial, each power multiplied with its respective weight in weights.

This method is given for convenience. It is faster to use polynomial rings with weighted term orders and the standard degree function.

INPUT:

- weights - Either individual numbers, an iterable or a dictionary, specifying the weights of each variable. If it is a dictionary, it maps each variable of self to its weight. If it is a sequence of individual numbers or a tuple, the weights are specified in the order of the generators as given by `self.parent().gens()`.

EXAMPLES:

```
sage: R.<x,y,z> = GF(7)[]
sage: p = x^3 + y + x*z^2
sage: p.weighted_degree({z:0, x:1, y:2})
3
sage: p.weighted_degree(1, 2, 0)
3
sage: p.weighted_degree((1, 4, 2))
5
sage: p.weighted_degree((1, 4, 1))
4
sage: p.weighted_degree(2**64, 2**50, 2**128)
689564733841876926945195958937245974528
sage: q = R.random_element(100, 20) #random
sage: q.weighted_degree(1, 1, 1) == q.total_degree()
True
```

You may also work with negative weights
Polynomials, Release 10.0

```
sage: p.weighted_degree(-1, -2, -1)
-2
```

Note that only integer weights are allowed

```
sage: p.weighted_degree(x,1,1)
Traceback (most recent call last):
...
TypeError: unable to convert non-constant polynomial x to Integer Ring
```

```
sage: p.weighted_degree(2/1,1,1)
6
```

The `weighted_degree` coincides with the `degree` of a weighted polynomial ring, but the later is faster.

```
sage: K = PolynomialRing(QQ, ['x','y'], order=TermOrder('wdegrevlex', (2,3)))
sage: p = K.random_element(10)
sage: p.degree() == p.weighted_degree(2,3)
True
```

### class sage.rings.polynomial.multi_polynomial.MPolynomial_libsingular

Bases: `MPolynomial`

Abstract base class for `MPolynomial_libsingular`

This class is defined for the purpose of `isinstance()` tests. It should not be instantiated.

**EXAMPLES:**

```
sage: R1.<x> = QQ[]
sage: isinstance(x, sage.rings.polynomial.multi_polynomial.MPolynomial_libsingular)
False
sage: R2.<y,z> = QQ[]
sage: isinstance(y, sage.rings.polynomial.multi_polynomial.MPolynomial_libsingular)
True
```

By design, there is a unique direct subclass:

```
sage: len(sage.rings.polynomial.multi_polynomial.MPolynomial_libsingular.__subclasses__()) <= 1
True
```

`sage.rings.polynomial.multi_polynomial.is_MPolynomial(x)`

### 3.1.4 Multivariate Polynomial Rings over Generic Rings

Sage implements multivariate polynomial rings through several backends. This generic implementation uses the classes `PolyDict` and `ETuple` to construct a dictionary with exponent tuples as keys and coefficients as values.

**AUTHORS:**

- David Joyner and William Stein
- Kiran S. Kedlaya (2006-02-12): added Macaulay2 analogues of Singular features
- Martin Albrecht (2006-04-21): reorganize class hierarchy for singular rep
- Martin Albrecht (2007-04-20): reorganized class hierarchy to support Pyrex implementations

EXAMPLES:

We construct the Frobenius morphism on \( F_5[x, y, z] \) over \( F_5 \):

```python
sage: R.<x,y,z> = GF(5)[]
sage: frob = R.hom([x^5, y^5, z^5])
sage: frob(x^2 + 2*y - z^4)
-z^20 + x^10 + 2*y^5
sage: frob((x + 2*y)^3)
x^15 + x^10*y^5 + 2*x^5*y^10 - 2*y^15
sage: (x^5 + 2*y^5)^3
x^15 + x^10*y^5 + 2*x^5*y^10 - 2*y^15
```

We make a polynomial ring in one variable over a polynomial ring in two variables:

```python
sage: R.<x, y> = PolynomialRing(QQ, 2)
sage: S.<t> = PowerSeriesRing(R)
sage: t*(x+y)
(x + y)*t
```

### class `sage.rings.polynomial.multi_polynomial_ring.MPolynomialRing_macaulay2_repr`

Bases: object

A mixin class for polynomial rings that support conversion to Macaulay2.

### class `sage.rings.polynomial.multi_polynomial_ring.MPolynomialRing_polydict(base_ring, n, names, order)`

Bases: `MPolynomialRing_macaulay2_repr`, `PolynomialRing_singular_repr`, `MPolynomialRing_base`

Multivariable polynomial ring.

EXAMPLES:

```python
sage: R = PolynomialRing(Integers(12), 'x', 5); R
Multivariate Polynomial Ring in x0, x1, x2, x3, x4 over Ring of integers modulo 12
sage: loads(R.dumps()) == R
True
```

`Element_hidden`

alias of `MPolynomial_polydict`

`monomial_all_divisors(t)`

Return a list of all monomials that divide \( t \), coefficients are ignored.

INPUT:

- \( t \) - a monomial.

OUTPUT: a list of monomials.

EXAMPLES:

```python
sage: from sage.rings.polynomial.multi_polynomial_ring import MPolynomialRing_polydict_domain
sage: P.<x,y,z> = MPolynomialRing_polydict_domain(QQ, 3, order='degrevlex')
```
ALGORITHM: addwithcarry idea by Toon Segers

**monomial_divides**(a, b)

Return False if a does not divide b and True otherwise.

**INPUT:**
- a – monomial
- b – monomial

**OUTPUT:** Boolean

**EXAMPLES:**

```
sage: P.<x,y,z> = PolynomialRing(ZZ,3, order='degrevlex')
sage: P.monomial_divides(x*y*z, x^3*y^2*z^4)
True
sage: P.monomial_divides(x^3*y^2*z^4, x*y*z)
False
```

**monomial_lcm**(f, g)

LCM for monomials. Coefficients are ignored.

**INPUT:**
- f - monomial.
- g - monomial.

**OUTPUT:** monomial.

**EXAMPLES:**

```
sage: from sage.rings.polynomial.multi_polynomial_ring import MPolynomialRing_polydict_domain
sage: P.<x,y,z> = MPolynomialRing_polydict_domain(QQ,3, order='degrevlex')
sage: P.monomial_lcm(3/2*x*y, x)
x*y
```

**monomial_pairwise_prime**(h, g)

Return True if h and g are pairwise prime.

Both are treated as monomials.

**INPUT:**
- h - monomial.
- g - monomial.

**OUTPUT:** Boolean.

**EXAMPLES:**
```
sage: from sage.rings.polynomial.multi_polynomial_ring import MPolynomialRing_polydict_domain
sage: P.<x,y,z> = MPolynomialRing_polydict_domain(QQ,3, order='degrevlex')
sage: P.monomial_pairwise_prime(x^2*z^3, y^4)
True
sage: P.monomial_pairwise_prime(1/2*x^3*y^2, 3/4*y^3)
False
```
\texttt{sage: G = [3/2*x^3 + y^2 + 1/2, 1/4*x*y + 2/7, P(1/2)]}
\texttt{sage: P.monomial_reduce(f,G)}
\texttt{(y, 1/4*x*y + 2/7)}

\texttt{sage: from sage.rings.polynomial.multi_polynomial_ring import MPolynomialRing_}
\texttt{˓→polydict_domain}
\texttt{sage: P.<x,y,z> = MPolynomialRing_polydict_domain(Zmod(23432), 3, order='degrevlex')}
\texttt{sage: f = x*y^2}
\texttt{sage: G = [3*x^3 + y^2 + 2, 4*x*y + 7, P(2)]}
\texttt{sage: P.monomial_reduce(f,G)}
\texttt{(y, 4*x*y + 7)}

\texttt{sum(terms)}

Return a sum of elements of this multipolynomial ring.

This is method is much faster than the Python builtin sum.

\textbf{EXAMPLES:}

\texttt{sage: R = QQ['x']}
\texttt{sage: S = R['y, z']}
\texttt{sage: x = R.gen()}
\texttt{sage: y, z = S.gens()}
\texttt{sage: S.sum([x*y, 2*x^2*z - 2*x*y, 1 + y + z])}
\texttt{(-x + 1)*y + (2*x^2 + 1)*z + 1}

Comparison with builtin sum:

\texttt{sage: sum([x*y, 2*x^2*z - 2*x*y, 1 + y + z])}
\texttt{(-x + 1)*y + (2*x^2 + 1)*z + 1}

\textbf{class} \texttt{sage.rings.polynomial.multi_polynomial_ring.MPolynomialRing_polydict_domain(base_ring, n, names, order)}

\textbf{Bases:} \texttt{IntegralDomain, MPolynomialRing_polydict}

\textbf{ideal(*gens, **kwsds)}

Create an ideal in this polynomial ring.

\textbf{is_field(proof=True)}

\textbf{is_integral_domain(proof=True)}
3.1.5 Generic Multivariate Polynomials

AUTHORS:

- David Joyner: first version
- William Stein: use dict's instead of lists
- Martin Albrecht malb@informatik.uni-bremen.de: some functions added
- Kiran S. Kedlaya (2006-02-12): added Macaulay2 analogues of some Singular features
- William Stein (2006-04-19): added e.g., f[1,3] to get coeff of \( xy^3 \); added examples of the new \( R.x,y = \text{PolynomialRing}(\mathbb{Q},2) \) notation.
- Martin Albrecht: improved singular coercions (restructured class hierarchy) and added ETuples
- Robert Bradshaw (2007-08-14): added support for coercion of polynomials in a subset of variables (including multi-level univariate rings)

EXAMPLES:

We verify Lagrange’s four squares identity:

```python
sage: R.<a0,a1,a2,a3,b0,b1,b2,b3> = QQbar[]
sage: (a0^2 + a1^2 + a2^2 + a3^2)*(b0^2 + b1^2 + b2^2 + b3^2) == (a0*b0 - a1*b1 - a2*b2 - a3*b3)^2 + (a0*b1 + a1*b0 + a2*b3 - a3*b2)^2 + (a0*b2 - a1*b3 + a2*b0 + a3*b1)^2 + (a0*b3 + a1*b2 - a2*b1 + a3*b0)^2
```

```python
True
```

class `sage.rings.polynomial.multi_polynomial_element.MPolynomial_element` (`parent`, `x`)

Bases: `MPolynomial`

Generic multivariate polynomial.

This implementation is based on the `PolyDict`.

**Todo:** As mentioned in their docstring, `PolyDict` objects never clear zeros. In all arithmetic operations on `MPolynomial_element` there is an additional call to the method `remove_zeros` to clear them. This is not ideal because of the presence of inexact zeros, see github issue #35174.

`change_ring(R)`

Change the base ring of this polynomial to \( R \).

**INPUT:**

- \( R \) – ring or morphism.

**OUTPUT:** a new polynomial converted to \( R \).

**EXAMPLES:**

```python
sage: R.<x,y> = QQ[]
sage: f = x^2 + 5*y
sage: f.change_ring(GF(5))
x^2
```
element()  

hamming_weight()  

Return the number of non-zero coefficients of this polynomial.  

This is also called weight, `hamming_weight()` or sparsity.

EXAMPLES:

```python
sage: R.<x, y> = CC[]
sage: f = x^3 - y
sage: f.number_of_terms()
2
sage: R(0).number_of_terms()
0
sage: f = (x+y)^100
sage: f.number_of_terms()
101
```

The method `hamming_weight()` is an alias:

```python
sage: f.hamming_weight()
101
```

number_of_terms()  

Return the number of non-zero coefficients of this polynomial.  

This is also called weight, `hamming_weight()` or sparsity.

EXAMPLES:

```python
sage: R.<x, y> = CC[]
sage: f = x^3 - y
sage: f.number_of_terms()
2
sage: R(0).number_of_terms()
0
sage: f = (x+y)^100
sage: f.number_of_terms()
101
```

The method `hamming_weight()` is an alias:

```python
sage: f.hamming_weight()
101
```

class sage.rings.polynomial.multi_polynomial_element.MPolynomial_polydict(parent, x)  

Bases: `Polynomial_singular_repr, MPolynomial_element`

Multivariate polynomials implemented in pure python using polydicts.
Polynomials, Release 10.0

**coefficient** (*degrees*)

Return the coefficient of the variables with the degrees specified in the python dictionary *degrees*. Mathematically, this is the coefficient in the base ring adjoined by the variables of this ring not listed in *degrees*. However, the result has the same parent as this polynomial.

This function contrasts with the function **monomial_coefficient** which returns the coefficient in the base ring of a monomial.

**INPUT:**

- **degrees** - Can be any of:
  - a dictionary of degree restrictions
  - a list of degree restrictions (with None in the unrestricted variables)
  - a monomial (very fast, but not as flexible)

**OUTPUT:** element of the parent of self

**See also:**

For coefficients of specific monomials, look at **monomial_coefficient()**.

**EXAMPLES:**

```python
sage: R.<x, y> = QQbar[]
sage: f = 2 * x * y
sage: c = f.coefficient({x:1,y:1}); c
2
sage: c.parent()
Multivariate Polynomial Ring in x, y over Algebraic Field
sage: c in PolynomialRing(QQbar, 2, names = ['x','y'])
True
sage: f = y^2 - x^9 - 7*x + 5*x*y
sage: f.coefficient({y:1})
5*x
sage: f.coefficient({y:0})
-x^9 + (-7)*x
sage: f.coefficient({x:0,y:0})
0
sage: f=(1+y+y^2)*(1+x+x^2)
sage: f.coefficient([0,None])
y^2 + y + 1
sage: f.coefficient(x)
y^2 + y + 1
sage: # Be aware that this may not be what you think!
sage: # The physical appearance of the variable x is deceiving -- particularly...
sage: f.coefficient(x^0) # outputs the full polynomial
x^2*y^2 + x^2*y + x*y^2 + x^2 + x*y + y^2 + x + y + 1
```

```python
sage: R.<x,y> = RR[]
sage: f=x*y+5
sage: c=f.coefficient({x:0,y:0}); c
5.00000000000000
```

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AUTHORS:

• Joel B. Mohler (2007-10-31)

c\text{constant\_coefficient}() 

Return the constant coefficient of this multivariate polynomial.

EXAMPLES:

\begin{verbatim}
sage: R.<x,y> = QQbar[]
sage: f = 3*x^2 - 2*y + 7*x^2*y^2 + 5
sage: f.constant_coefficient()
5
sage: f = 3*x^2
sage: f.constant_coefficient()
0
\end{verbatim}

c\text{degree}(x=None, \text{std\_grading}=False)

Return the degree of self in x, where x must be one of the generators for the parent of self.

INPUT:

• x - multivariate polynomial (a generator of the parent
  of self). If x is not specified (or is None), return the total degree, which is the maximum degree
  of any monomial. Note that a weighted term ordering alters the grading of the generators of the
  ring; see the tests below. To avoid this behavior, set the optional argument \text{std\_grading}=True.

OUTPUT: integer

EXAMPLES:

\begin{verbatim}
sage: R.<x,y> = RR[]
sage: f = y^2 - x^9 - x
sage: f.degree(x)
9
sage: f.degree(y)
2
sage: (y^10*x - 7*x^2*y^5 + 5*x^3).degree(x)
3
sage: (y^10*x - 7*x^2*y^5 + 5*x^3).degree(y)
10
\end{verbatim}

Note that total degree takes into account if we are working in a polynomial ring with a weighted term order.

\begin{verbatim}
sage: R = PolynomialRing(QQ,\'x,y\',order=TermOrder(\'wdeglex\',(2,3)))
sage: x,y = R.gens()
sage: x.degree()
2
sage: y.degree()
3
sage: x.degree(y),x.degree(x),y.degree(x),y.degree(y)
(0, 1, 0, 1)
sage: f = (x^2*y+x*y^2)
\end{verbatim}

sage: f.degree(x)
2
sage: f.degree(y)
2
sage: f.degree()
8
sage: f.degree(std_grading=True)
3

Note that if \( x \) is not a generator of the parent of self, for example if it is a generator of a polynomial algebra which maps naturally to this one, then it is converted to an element of this algebra. (This fixes the problem reported in github issue #17366.)

sage: x, y = ZZ['x', 'y'].gens()
sage: GF(3037000453)['x', 'y'].gen(0).degree(x)
1
sage: x0, y0 = QQ['x', 'y'].gens()
sage: GF(3037000453)['x', 'y'].gen(0).degree(x0)
Traceback (most recent call last):
  ...TypeError: x must canonically coerce to parent
sage: GF(3037000453)['x', 'y'].gen(0).degree(x^2)
Traceback (most recent call last):
  ...TypeError: x must be one of the generators of the parent

\texttt{degrees()}

Returns a tuple (precisely - an ETuple) with the degree of each variable in this polynomial. The list of degrees is, of course, ordered by the order of the generators.

\texttt{EXAMPLES:}

sage: R.<x,y,z>=PolynomialRing(QQbar)
sage: f = 3*x^2 - 2*y + 7*x^2*y^2 + 5
sage: f.degrees()
(2, 2, 0)
sage: f = x^2+z^2
sage: f.degrees()
(2, 0, 2)
sage: f.total_degree()  # this simply illustrates that total degree is not the sum of the degrees
2
sage: R.<x,y,z,u>=PolynomialRing(QQbar)
sage: f=(1-x)*(1+y+z*x^3)^5
sage: f.degrees()
(16, 5, 5, 0)
sage: R(0).degrees()
(0, 0, 0, 0)

\texttt{dict()}

Return underlying dictionary with keys the exponents and values the coefficients of this polynomial.
**exponents** (*as_ETuples=True*)

Return the exponents of the monomials appearing in *self*.

**INPUT:**

- *as_ETuples* – (default: True): return the list of exponents as a list of ETuples

**OUTPUT:**

The list of exponents as a list of ETuples or tuples.

**EXAMPLES:**

```sage
sage: R.<a,b,c> = PolynomialRing(QQbar, 3)
sage: f = a^3 + b + 2*b^2
sage: f.exponents()
[(3, 0, 0), (0, 2, 0), (0, 1, 0)]
```

By default the list of exponents is a list of ETuples:

```sage
sage: type(f.exponents()[0])
<class 'sage.rings.polynomial.polydict.ETuple'>
sage: type(f.exponents(as_ETuples=False)[0])
<... 'tuple'>
```

**factor** (*proof=None*)

Compute the irreducible factorization of this polynomial.

**INPUT:**

- *proof* - insist on provably correct results (default: `True` unless explicitly disabled for the “polynomial” subsystem with `sage.structure.proof.proof.WithProof`)

**global_height** (*prec=None*)

Return the (projective) global height of the polynomial.

This returns the absolute logarithmic height of the coefficients thought of as a projective point.

**INPUT:**

- *prec* – desired floating point precision (default: default RealField precision).

**OUTPUT:**

- a real number.

**EXAMPLES:**

```sage
sage: R.<x,y> = PolynomialRing(QQbar, 2)
sage: f = QQbar(i)*x^2 + 3*x*y
sage: f.global_height()
1.09861228866811
```

Scaling should not change the result:

```sage
sage: R.<x, y> = PolynomialRing(QQbar, 2)
sage: f = 1/25*x^2 + 25/3*x + 1 + QQbar(sqrt(2))*y^2
sage: f.global_height()
6.43775164973640
sage: g = 100 * f
```

(continues on next page)
sage: g.global_height()
6.43775164973640

sage: R.<x> = QQ[]
sage: K.<k> = NumberField(x^2 + 1)
sage: Q.<q,r> = PolynomialRing(K, implementation='generic')
sage: f = 12*q
sage: f.global_height()
0.000000000000000

sage: R.<x,y> = PolynomialRing(QQ, implementation='generic')
sage: f = 1/123*x*y + 12
sage: f.global_height(prec=2)
8.0

integral(var=None)
Integrate self with respect to variable var.

Note: The integral is always chosen so the constant term is 0.

If var is not one of the generators of this ring, integral(var) is called recursively on each coefficient of this polynomial.

EXAMPLES:
On polynomials with rational coefficients:

sage: x, y = PolynomialRing(QQ, 'x, y').gens()
sage: ex = x*y + x - y
sage: it = ex.integral(x); it
1/2*x^2*y + 1/2*x^2 - x*y
sage: it.parent() == x.parent()
True

sage: R = ZZ['x']['y, z']
sage: y, z = R.gens()
sage: R.an_element().integral(y).parent()
Multivariate Polynomial Ring in y, z over Univariate Polynomial Ring in x over
˓
→ Rational Field

On polynomials with coefficients in power series:

sage: R.<t> = PowerSeriesRing(QQbar)
sage: S.<x, y> = PolynomialRing(R)
sage: f = (t^2 + O(t^3))*x^2*y^3 + (37*t^4 + O(t^5))*x^3
sage: f.parent()
Multivariate Polynomial Ring in x, y over Power Series Ring in t over Algebraic Field

```
sage: f.integral(x)    # with respect to x
(1/3*t^2 + O(t^3))*x^3*y^3 + (37/4*t^4 + O(t^5))*x^4
sage: f.integral(x).parent()
Multivariate Polynomial Ring in x, y over Power Series Ring in t over Algebraic Field

sage: f.integral(y)    # with respect to y
(1/4*t^2 + O(t^3))*x^2*y^4 + (37*t^4 + O(t^5))*x^3*y
sage: f.integral(t)    # with respect to t (recurses into base ring)
(1/3*t^3 + O(t^4))*x^2*y^3 + (37/5*t^5 + O(t^6))*x^3
```

**inverse_of_unit()**

Return the inverse of a unit in a ring.

**is_constant()**

Return True if self is a constant and False otherwise.

EXAMPLES:

```
sage: R.<x,y> = QQbar[]
sage: f = 3*x^2 - 2*y + 7*x^2*y^2 + 5
sage: f.is_constant()
False
sage: g = 10*x^0
sage: g.is_constant()
True
```

**is_generator()**

Return True if self is a generator of its parent.

EXAMPLES:

```
sage: R.<x,y>=QQbar[

sage: x.is_generator()
True
sage: (x+y-y).is_generator()
True
sage: (x*y).is_generator()
False
```

**is_homogeneous()**

Return True if self is a homogeneous polynomial.

EXAMPLES:

```
sage: R.<x,y> = QQbar[

sage: (x+y).is_homogeneous()
True
sage: (x.parent()(0)).is_homogeneous()
True
sage: (x+y^2).is_homogeneous()
False
```
Polynomials, Release 10.0

(continued from previous page)

```python
sage: (x^2 + y^2).is_homogeneous()
True
sage: (x^2 + y^2*x).is_homogeneous()
False
sage: (x^2*y + y^2*x).is_homogeneous()
True
```

**is_homogeneous()**

- **Return** True if self is a homogeneous polynomial, which means that all monomials have the same degree.
- **Use** `is_term()` to allow for non-homogeneous polynomials.

**EXAMPLES:**

```python
sage: (x^2 + y^2).is_homogeneous()
True
sage: (x^2 + y^2*x).is_homogeneous()
False
sage: (x^2*y + y^2*x).is_homogeneous()
True
```

**is_monomial()**

- **Return** True if self is a monomial, which we define to be a product of generators with coefficient 1.
- **Use** `is_term()` to allow the coefficient to not be 1.

**EXAMPLES:**

```python
sage: R.<x,y>=QQbar[]
sage: x.is_monomial()
True
sage: (x+2*y).is_monomial()
False
sage: (2*x).is_monomial()
False
sage: (x*y).is_monomial()
True
```

To allow a non-1 leading coefficient, use `is_term()`:

```python
sage: (2*x*y).is_term()
True
sage: (2*x*y).is_monomial()
False
```

**is_term()**

- **Return** True if self is a term, which we define to be a product of generators times some coefficient, which need not be 1.
- **Use** `is_monomial()` to require that the coefficient be 1.

**EXAMPLES:**

```python
sage: R.<x,y>=QQbar[]
sage: x.is_term()
True
sage: (x+2*y).is_term()
False
sage: (2*x).is_term()
True
sage: (7*x^5*y).is_term()
True
```

To require leading coefficient 1, use `is_monomial()`:

```python
sage: (2*x*y).is_monomial()
False
sage: (2*x*y).is_term()
True
```

3.1. Multivariate Polynomials and Polynomial Rings
is_univariate()

Returns True if this multivariate polynomial is univariate and False otherwise.

EXAMPLES:

```
sage: R.<x,y> = QQbar[]
sage: f = 3*x^2 - 2*y + 7*x^2*y^2 + 5
sage: f.is_univariate()
False
sage: g = f.subs({x:10}); g
700*y^2 + (-2)*y + 305
sage: g.is_univariate()
True
sage: f = x^0
sage: f.is_univariate()
True
```

iterator_exp_coeff(as_ETuples=True)

Iterate over self as pairs of ((E)Tuple, coefficient).

INPUT:

- as_ETuples – (default: True) if True iterate over pairs whose first element is an ETuple, otherwise as a tuples

EXAMPLES:

```
sage: R.<x,y,z> = PolynomialRing(QQbar, order='lex')
sage: f = (x^1*y^5*z^2 + x^2*z + x^4*y^1*z^3)
sage: list(f.iterator_exp_coeff())
[[(4, 1, 3), 1], [(2, 0, 1), 1], [(1, 5, 2), 1]]

sage: R.<x,y,z> = PolynomialRing(QQbar, order='deglex')
sage: f = (x^1*y^5*z^2 + x^2*z + x^4*y^1*z^3)
sage: list(f.iterator_exp_coeff(as_ETuples=False))
[[(4, 1, 3), 1], [(1, 5, 2), 1], [(2, 0, 1), 1]]
```

lc()

Returns the leading coefficient of self i.e., self.coefficient(self.lm())

EXAMPLES:

```
sage: R.<x,y,z>=QQbar[]
sage: f=3*x^2-y^2-x*y
sage: f.lc()
3
```

lift(I)

given an ideal I = (f_1,...,f_r) and some g (== self) in I, find s_1,...,s_r such that g = s_1 f_1 + ... + s_r f_r

ALGORITHM: Use Singular.

EXAMPLES:
```python
sage: A.<x,y> = PolynomialRing(CC, 2, order='degrevlex')
sage: I = A.ideal([x^10 + x^9*y^2, y^8 - x^2*y^7])
sage: f = x*y^13 + y^12
sage: M = f.lift(I)
sage: M
[y^7, x^7*y^2 + x^8 + x^5*y^3 + x^6*y + x^3*y^4 + x^4*y^2 + x*y^5 + x^2*y^3 + y^4]
sage: sum(map(mul, zip(M, I.gens()))) == f
True
```

**lm()**

Returns the lead monomial of self with respect to the term order of self.parent().

**EXAMPLES:**

```python
sage: R.<x,y,z>=PolynomialRing(GF(7),3,order='lex')
sage: (x^1*y^2 + y^3*z^4).lm()
x*y^2
sage: (x^3*y^2*z^4 + x^3*y^2*z^1).lm()
x^3*y^2*z^4
sage: R.<x,y,z>=PolynomialRing(CC,3,order='deglex')
sage: (x^1*y^2*z^3 + x^3*y^2*z^0).lm()
x*y^2*z^3
sage: (x^1*y^2*z^4 + x^1*y^1*z^5).lm()
x*y^2*z^4
sage: R.<x,y,z>=PolynomialRing(QQbar,3,order='degrevlex')
sage: (x^1*y^5*z^2 + x^4*y^1*z^3).lm()
x*y^5*z^2
sage: (x^4*y^7*z^1 + x^4*y^2*z^3).lm()
x^4*y^7*z
```

**local_height(v, prec=None)**

Return the maximum of the local height of the coefficients of this polynomial.

**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:**

```python
sage: R.<x,y> = PolynomialRing(QQ, implementation='generic')
sage: f = 1/1331*x^2 + 1/4000*y
sage: f.local_height(1331)
7.19368581839511
sage: R.<x> = QQ[]
sage: K.<k> = NumberField(x^2 - 5)
```

(continues on next page)
sage: T.<t,w> = PolynomialRing(K, implementation='generic')
sage: I = K.ideal(3)
sage: f = 1/3*t*w + 3
sage: f.local_height(I)
1.09861288668811

sage: R.<x,y> = PolynomialRing(QQ, implementation='generic')
sage: f = 1/2*x*y + 2
sage: f.local_height(2, prec=2)
0.75

local_height_arch(i, prec=None)
Return the maximum of the local height at the i-th infinite place of the coefficients of this polynomial.

INPUT:
• i – an integer.
• prec – desired floating point precision (default: default RealField precision).

OUTPUT:
• a real number.

EXAMPLES:

sage: R.<x,y> = PolynomialRing(QQ, implementation='generic')
sage: f = 210*x*y
sage: f.local_height_arch(0)
5.34710753071747

sage: R.<x> = QQ[]
sage: K.<k> = NumberField(x^2 - 5)
sage: T.<t,w> = PolynomialRing(K, implementation='generic')
sage: f = 1/2*t*w + 3
sage: f.local_height_arch(1, prec=52)
1.09861288668811

sage: R.<x,y> = PolynomialRing(QQ, implementation='generic')
sage: f = 1/2*x*y + 3
sage: f.local_height_arch(0, prec=2)
1.0

lt()
Returns the leading term of self i.e., self.lc()*self.lm(). The notion of “leading term” depends on the ordering defined in the parent ring.

EXAMPLES:

sage: R.<x,y,z> = PolynomialRing(QQbar)
sage: f=3*x^2-y^2-x*y
sage: f.lt()
3*x^2
sage: R.<x,y,z> = PolynomialRing(QQbar, order="invlex")
(continues on next page)
monomial_coefficient($\text{mon}$)

Return the coefficient in the base ring of the monomial $\text{mon}$ in self, where $\text{mon}$ must have the same parent as self.

This function contrasts with the function coefficient which returns the coefficient of a monomial viewing this polynomial in a polynomial ring over a base ring having fewer variables.

INPUT:

• $\text{mon}$ - a monomial

OUTPUT: coefficient in base ring

See also:

For coefficients in a base ring of fewer variables, look at coefficient().

EXAMPLES:

The parent of the return is a member of the base ring.

```
sage: R.<x,y>=QQbar[]
sage: f = 2 * x * y
sage: c = f.monomial_coefficient(x*y); c
2
sage: c.parent()
Algebraic Field
```

The parent of the return is a member of the base ring.

```
sage: f = y^2 + y^2*x - x^9 + 7*x + 5*x*y
sage: f.monomial_coefficient(y^2)
1
sage: f.monomial_coefficient(x*y)
5
sage: f.monomial_coefficient(x^9)
-1
sage: f.monomial_coefficient(x^10)
0
```

```
sage: var('a')
a
sage: K.<a> = NumberField(a^2+a+1)
sage: P.<x,y> = K[]
sage: f=(a*x-1)*(a+1)*y-1); f
-x*y + (-a)*x + (-a - 1)*y + 1
sage: f.monomial_coefficient(x)
a
```

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monomials()

Returns the list of monomials in self. The returned list is decreasingly ordered by the term ordering of self.parent().

OUTPUT: list of MPolynomials representing Monomials

EXAMPLES:

```sage
R.<x,y> = QQbar[]
f = 3*x^2 - 2*y + 7*x^2*y^2 + 5
f.monomials()
[x^2*y^2, x^2, y, 1]
```

```sage
R.<fx,fy,gx,gy> = QQbar[]
F = ((fx*gy - fy*gx)^3)
F
-fy^3*gx^3 + 3*fx*fy^2*gx^2*gy + (-3)*fx^2*fy*gx*gy^2 + fx^3*gy^3
F.monomials()
[fx^3*gx^3, fy*gx^2*gy, fx^2*fy*gx*gy^2, fx^3*gy^3]
F.coefficients()
[-1, 3, -3, 1]
sum(map(mul,zip(F.coefficients(),F.monomials()))) == F
True
```

nvariables()

Number of variables in this polynomial

EXAMPLES:

```sage
R.<x,y> = QQbar[]
f = 3*x^2 - 2*y + 7*x^2*y^2 + 5
f.nvariables ()
2
g = f.subs({x:10}); g
700*y^2 + (-2)*y + 305
g.nvariables ()
1
```

quo_rem(right)

Returns quotient and remainder of self and right.

EXAMPLES:

```sage
R.<x,y> = CC[]
f = y*x^2 + x + 1
f.quo_rem(x)
(x*y + 1.00000000000000, 1.00000000000000)
```

```sage
R = QQ['a', 'b'] ['x', 'y', 'z']
p1 = R('a + (1+2*b)*x*y + (3-a^2)*z')
p2 = R('x-1')
p1.quo_rem(p2)
((2*b + 1)*y, (2*b + 1)*y + (-a^2 + 3)*z + a)
```

```sage
R.<x,y> = Qp(5)[]
```
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(continued from previous page)

```
sage: x.quo_rem(y)
Traceback (most recent call last):
...
TypeError: no conversion of this ring to a Singular ring defined
```

ALGORITHM: Use Singular.

**reduce(I)**

Reduce this polynomial by the polynomials in \( I \).

**INPUT:**
- \( I \) - a list of polynomials or an ideal

**EXAMPLES:**

```
sage: P.<x,y,z> = QQbar[]
sage: f1 = -2 * x^2 + x^3
sage: f2 = -2 * y + x*y
sage: f3 = -x^2 + y^2
sage: F = Ideal([f1,f2,f3])
sage: g = x*y - 3*x^2*y^2
sage: g.reduce(F)
(-6)*y^2 + 2*y
sage: g.reduce(F.gens())
(-6)*y^2 + 2*y
sage: f = 3*x
sage: f.reduce([2*x,y])
0
sage: k.<w> = CyclotomicField(3)
sage: A.<y9,y12,y13,y15> = PolynomialRing(k)
sage: J = [ y9 + y12]
sage: f = y9 - y12; f.reduce(J)
-2*y12
sage: f = y13*y15; f.reduce(J)
y13*y15
sage: f = y13*y15 + y9 - y12; f.reduce(J)
y13*y15 - 2*y12
```

Make sure the remainder returns the correct type, fixing github issue #13903:

```
sage: R.<y1,y2>=PolynomialRing(Qp(5),2, order='lex')
sage: G=[y1^2 + y2^2, y1*y2 + y2^2, y2^3]
sage: type(y2^3).reduce(G))
<class 'sage.rings.polynomial.multi_polynomial_element.MPolynomial_polydict'>
```

**resultant(other, variable=None)**

Compute the resultant of \( self \) and \( other \) with respect to \( variable \).

If a second argument is not provided, the first variable of \( self.parent() \) is chosen.

For inexact rings or rings not available in Singular, this computes the determinant of the Sylvester matrix.

**INPUT:**

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• other – polynomial in self.parent()
• variable – (optional) variable (of type polynomial) in self.parent()

EXAMPLES:

```python
sage: P.<x,y> = PolynomialRing(QQ, 2)
sage: a = x + y
sage: b = x^3 - y^3
sage: a.resultant(b)
-2*y^3
sage: a.resultant(b, y)
2*x^3
```

**subresultants**(other, variable=None)

Return the nonzero subresultant polynomials of self and other.

INPUT:

• other – a polynomial

OUTPUT: a list of polynomials in the same ring as self

EXAMPLES:

```python
sage: R.<x,y> = QQbar[]
sage: p = (y^2 + 6)*(x - 1) - y*(x^2 + 1)
sage: q = (x^2 + 6)*(y - 1) - x*(y^2 + 1)
sage: p.subresultants(q, y)
[2*x^6 + (-22)*x^5 + 102*x^4 + (-274)*x^3 + 488*x^2 + (-552)*x + 288,
 -x^3 - x^2*y + 6*x^2 + 5*x*y + (-11)*x + (-6)*y + 6]
sage: p.subresultants(q, x)
[2*y^6 + (-22)*y^5 + 102*y^4 + (-274)*y^3 + 488*y^2 + (-552)*y + 288,
 x*y^2 + y^3 + (-5)*x*y + (-6)*y^2 + 6*x + 11*y - 6]
```

**subs**(fixed=None, **kw)

Fixes some given variables in a given multivariate polynomial and returns the changed multivariate polynomials. The polynomial itself is not affected. The variable,value pairs for fixing are to be provided as a dictionary of the form {variable:value}.

This is a special case of evaluating the polynomial with some of the variables constants and the others the original variables.

INPUT:

• fixed - (optional) dictionary of inputs
• **kw - named parameters

OUTPUT: new MPolynomial

EXAMPLES:

```python
sage: R.<x,y> = QQbar[]
sage: f = x^2 + y + x^2*y^2 + 5
sage: f((5,y))
25*y^2 + y + 30
sage: f.subs({x:5})
25*y^2 + y + 30
```
total_degree()

Return the total degree of self, which is the maximum degree of any monomial in self.

EXAMPLES:

```
sage: R.<x,y,z> = QQbar[]
sage: f=2*x*y^3*z^2
sage: f.total_degree()
6
sage: f=4*x^2*y^2*z^3
sage: f.total_degree()
7
sage: f=99*x^6*y^3*z^9
sage: f.total_degree()
18
sage: f=x^y^3*z^6+3*x^2
sage: f.total_degree()
10
sage: f=z^9+10*x^4*y^5*z
sage: f.total_degree()
10
```

univariate_polynomial($R=None$)

Returns a univariate polynomial associated to this multivariate polynomial.

INPUT:

* $R$ - (default: None) PolynomialRing

If this polynomial is not in at most one variable, then a ValueError exception is raised. This is checked using the is_univariate() method. The new Polynomial is over the same base ring as the given MPolynomial.

EXAMPLES:

```
sage: R.<x,y> = QQbar[]
sage: f = 3*x^2 - 2*y + 7*x^2*y^2 + 5
sage: f.univariate_polynomial()
Traceback (most recent call last):
  ...    TypeError: polynomial must involve at most one variable
sage: g = f.subs({x:10}); g
700*y^2 + (-2)*y + 305
sage: g.univariate_polynomial()
700*y^2 - 2*y + 305
sage: g.univariate_polynomial(PolynomialRing(QQ, 'z'))
700*z^2 - 2*z + 305
```

variable($i$)

Returns $i$-th variable occurring in this polynomial.

EXAMPLES:
variables()

Returns the tuple of variables occurring in this polynomial.

EXAMPLES:

```python
sage: R.<x,y> = QQbar[]
sage: f = 3*x^2 - 2*y + 7*x^2*y^2 + 5
sage: f.variables()
(x, y)
```

`sage.rings.polynomial.multi_polynomial_element.degree_lowest_rational_function(r, x)`

Return the difference of valuations of \( r \) with respect to variable \( x \).

**INPUT:**

- \( r \) – a multivariate rational function
- \( x \) – a multivariate polynomial ring generator \( x \)

**OUTPUT:**

- integer – the difference \( \text{val}_x(p) - \text{val}_x(q) \) where \( r = p/q \)

**Note:** This function should be made a method of the FractionFieldElement class.

**EXAMPLES:**

```python
sage: R1 = PolynomialRing(FiniteField(5), 3, names = ['a','b','c'])
sage: F = FractionField(R1)
sage: a,b,c = R1.gens()
sage: f = 3*a*b^2*c^3+4*a*b*c
sage: g = a^2*b*c^2+2*a^2*b^4*c^7
```

Consider the quotient \( f/g = \frac{4+3bc^2}{ac+2ab^2c^6} \) (note the cancellation).

```python
sage: r = f/g; r
(-2*b^2*c^2 - 1)/(2*a*b^3*c^6 + a*c)
sage: degree_lowest_rational_function(r,a)
-1
sage: degree_lowest_rational_function(r,b)
0
sage: degree_lowest_rational_function(r,c)
-1
```
3.1.6 Ideals in multivariate polynomial rings

Sage has a powerful system to compute with multivariate polynomial rings. Most algorithms dealing with these ideals are centered on the computation of **Groebner bases**. Sage mainly uses Singular to implement this functionality. Singular is widely regarded as the best open-source system for Groebner basis calculation in multivariate polynomial rings over fields.

**EXAMPLES:**

We compute a Groebner basis for some given ideal. The type returned by the `groebner_basis` method is `PolynomialSequence`, i.e. it is not a `MPolynomialIdeal`:

```
sage: x,y,z = QQ['x,y,z'].gens()
sage: I = ideal(x^5 + y^4 + z^3 - 1, x^3 + y^3 + z^2 - 1)
sage: B = I.groebner_basis()
sage: type(B)
<class 'sage.rings.polynomial.multi_polynomial_sequence.PolynomialSequence_generic'>
```

Groebner bases can be used to solve the ideal membership problem:

```
sage: f,g,h = B
sage: (2*x*f + g).reduce(B)
0
sage: (2*x*f + g) in I
True
sage: (2*x*f + 2*z*h + y^3).reduce(B)
y^3
sage: (2*x*f + 2*z*h + y^3) in I
False
```

We compute a Groebner basis for Cyclic 6, which is a standard benchmark and test ideal.

```
sage: R.<x,y,z,t,u,v> = QQ['x,y,z,t,u,v']
sage: I = sage.rings.ideal.Cyclic(R,6)
sage: B = I.groebner_basis()
sage: len(B)
45
```

We compute in a quotient of a polynomial ring over $\mathbb{Z}/17\mathbb{Z}$:

```
sage: R.<x,y> = ZZ[]
sage: S.<a,b> = R.quotient((x^2 + y^2, 17))
sage: S
Quotient of Multivariate Polynomial Ring in x, y over Integer Ring by the ideal (x^2 + y^2, 17)
sage: a^2 + b^2 == 0
True
sage: a^3 - b^2
-a*b^2 - b^2
```

Note that the result of a computation is not necessarily reduced:
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```
sage: (a+b)^17
a*b^16 + b^17
sage: S(17) == 0
True

Or we can work with $\mathbb{Z}/17\mathbb{Z}$ directly:

```
sage: R.<x,y> = Zmod(17)[]
sage: S.<a,b> = R.quotient((x^2 + y^2,))
sage: S
Quotient of Multivariate Polynomial Ring in x, y over Ring of integers modulo 17 by the ideal (x^2 + y^2)

sage: a^2 + b^2 == 0
True
sage: a^3 - b^2 == -a*b^2 - b^2 == 16*a*b^2 + 16*b^2
True
sage: (a+b)^17
a*b^16 + b^17
sage: S(17) == 0
True
```

Working with a polynomial ring over $\mathbb{Z}$:

```
sage: R.<x,y,z,w> = ZZ[]
sage: I = ideal(x^2 + y^2 - z^2 - w^2, x-y)
sage: J = I^2
sage: J.groebner_basis()
[4*y^4 - 4*y^2*z^2 + z^4 - 4*y^2*w^2 + 2*z^2*w^2 + w^4,
  2*x*y^2 - 2*y^3 - x*z^2 + y*z^2 - x*w^2 + y*w^2,
  x^2 - 2*x*y + y^2]

sage: y^2 - 2*x*y + x^2 in J
True
sage: 0 in J
True
```

We do a Groebner basis computation over a number field:

```
sage: K.<zeta> = CyclotomicField(3)
sage: R.<x,y,z> = K[]; R
Multivariate Polynomial Ring in x, y, z over Cyclotomic Field of order 3 and degree 2

sage: i = ideal(x - zeta*y + 1, x^3 - zeta*y^3); i
Ideal (x + (-zeta)*y + 1, x^3 + (-zeta)*y^3) of Multivariate Polynomial Ring in x, y, z over Cyclotomic Field of order 3 and degree 2

sage: i.groebner_basis()
[y^3 + (2*zeta + 1)*y^2 + (zeta - 1)*y + (-1/3*zeta - 2/3), x + (-zeta)*y + 1]

sage: S = R.quotient(i); S
Quotient of Multivariate Polynomial Ring in x, y, z over Cyclotomic Field of order 3 and degree 2 by the ideal (x +
```

(continues on next page)
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(-zeta)*y + 1, x^3 + (-zeta)*y^3)

sage: S.0 - zeta*S.1
-1

sage: S.0^3 - zeta*S.1^3
0

Two examples from the Mathematica documentation (done in Sage):

We compute a Groebner basis:

sage: R.<x,y> = PolynomialRing(QQ, order='lex')
sage: ideal(x^2 - 2*y^2, x*y - 3).groebner_basis()  
[x - 2/3*y^3, y^4 - 9/2]

We show that three polynomials have no common root:

sage: R.<x,y> = QQ[]
sage: ideal(x+y, x^2 - 1, y^2 - 2*x).groebner_basis()  
[1]

The next example shows how we can use Groebner bases over \( \mathbb{Z} \) to find the primes modulo which a system of equations has a solution, when the system has no solutions over the rationals.

We first form a certain ideal \( I \) in \( \mathbb{Z}[x, y, z] \), and note that the Groebner basis of \( I \) over \( \mathbb{Q} \) contains 1, so there are no solutions over \( \mathbb{Q} \) or an algebraic closure of it (this is not surprising as there are 4 equations in 3 unknowns).

sage: P.<x,y,z> = PolynomialRing(ZZ,order='lex')
sage: I = ideal(-y^2 - 3*y + z^2 + 3, -2*y*z + z^2 + 2*z + 1, 
            x*z + y*z + z^2, -3*x*y + 2*y*z + 6*z^2)  
sage: I.change_ring(P.change_ring(QQ)).groebner_basis()  
[1]

However, when we compute the Groebner basis of \( I \) (defined over \( \mathbb{Z} \)), we note that there is a certain integer in the ideal which is not 1.

sage: I.groebner_basis()  
[x + y + 57119*z + 4, y^2 + 3*y + 17220, y*z + ..., 2*y + 158864, z^2 + 17223, 2*z + 41856, 164878]

Now for each prime \( p \) dividing this integer 164878, the Groebner basis of \( I \) modulo \( p \) will be non-trivial and will thus give a solution of the original system modulo \( p \).

sage: factor(164878)  
2 * 7 * 11777

sage: I.change_ring(P.change_ring( GF(2) )).groebner_basis()  
[x + y + z, y^2 + y, y*z + y, z^2 + 1]

sage: I.change_ring(P.change_ring( GF(7) )).groebner_basis()  
[x - 1, y + 3, z - 2]

sage: I.change_ring(P.change_ring( GF(11777) )).groebner_basis()  
[x + 5633, y - 3007, z - 2626]

The Groebner basis modulo any product of the prime factors is also non-trivial.
Modulo any other prime the Groebner basis is trivial so there are no other solutions. For example:

```
sage: I.change_ring( P.change_ring( GF(3) ) ).groebner_basis()
[1]
```

**Note:** Sage distinguishes between lists or sequences of polynomials and ideals. Thus an ideal is not identified with a particular set of generators. For sequences of multivariate polynomials see `sage.rings.polynomial.multi_polynomial_sequence.PolynomialSequence_generic`.

**AUTHORS:**
- William Stein: initial version
- Kiran S. Kedlaya (2006-02-12): added Macaulay2 analogues of some Singular features
- Martin Albrecht (2009): added Groebner basis over rings functionality from Singular 3.1
- John Perry (2012): bug fixing equality & containment of ideals

```python
class sage.rings.polynomial.multi_polynomial_ideal.MPolynomialIdeal(ring, gens, coerce=True)
```

Create an ideal in a multivariate polynomial ring.

**INPUT:**
- `ring` - the ring the ideal is defined in
- `gens` - a list of generators for the ideal
- `coerce` - coerce elements to the ring?

**EXAMPLES:**

```
sage: R.<x,y> = PolynomialRing(IntegerRing(), 2, order='lex')
sage: I = Ideal([x,y+1])
Ideal (x, y + 1) of Multivariate Polynomial Ring in x, y over Integer Ring
```

**property basis**
Shortcut to `gens()`.

**EXAMPLES:**

```
sage: P.<x,y> = PolynomialRing(QQ,2)
sage: I = Ideal([x,y+1])
sage: I.basis
[x, y + 1]
```
**change_ring**\((P)\)

Return the ideal \(I\) in \(P\) spanned by the generators \(g_1, ..., g_n\) of self as returned by `self.gens()`.

**INPUT:**

- \(P\) - a multivariate polynomial ring

**EXAMPLES:**

```python
sage: P.<x,y,z> = PolynomialRing(QQ,3,order='lex')
sage: I = sage.rings.ideal.Cyclic(P)
sage: I
Ideal (x + y + z, x*y + x*z + y*z, x*y*z - 1) of Multivariate Polynomial Ring in x, y, z over Rational Field

sage: I.groebner_basis()
[x + y + z, y^2 + y*z + z^2, z^3 - 1]
```

```python
sage: Q.<x,y,z> = P.change_ring(order='degrevlex'); Q
Multivariate Polynomial Ring in x, y, z over Rational Field
sage: Q.term_order()
Degree reverse lexicographic term order

sage: J = I.change_ring(Q); J
Ideal (x + y + z, x*y + x*z + y*z, x*y*z - 1) of Multivariate Polynomial Ring in x, y, z over Rational Field

sage: J.groebner_basis()
[z^3 - 1, y^2 + y*z + z^2, x + y + z]
```

**degree_of_semi_regularity**\()

Return the degree of semi-regularity of this ideal under the assumption that it is semi-regular.

Let \(\{f_1, ..., f_m\} \subset K[x_1, ..., x_n]\) be homogeneous polynomials of degrees \(d_1, ..., d_m\) respectively. This sequence is semi-regular if:

- \(\{f_1, ..., f_m\} \neq K[x_1, ..., x_n]\)
- for all \(1 \leq i \leq m\) and \(g \in K[x_1, ..., x_n]\): \(deg(g \cdot p_i) < D\) and \(g \cdot f_i < f_1, ..., f_i - 1 >\) implies that \(g \in f_1, ..., f_i - 1 >\) where \(D\) is the degree of regularity.

This notion can be extended to affine polynomials by considering their homogeneous components of highest degree.

The degree of regularity of a semi-regular sequence \(f_1, ..., f_m\) of respective degrees \(d_1, ..., d_m\) is given by the index of the first non-positive coefficient of:

\[
\sum c_k z^k = \prod (1-z^{-d_i})^{n_i}
\]

**EXAMPLES:**

We consider a homogeneous example:

```python
sage: n = 8
sage: K = GF(127)
sage: P = PolynomialRing(K,n,'x')
sage: s = [K.random_element() for _ in range(n)]
(continues on next page)
From this, we expect a Groebner basis computation to reach at most degree 4. For homogeneous systems this is equivalent to the largest degree in the Groebner basis:

```
sage: max(f.degree() for f in I.groebner_basis())
4
```

We increase the number of polynomials and observe a decrease the degree of regularity:

```
sage: for i in range(2*n):
    ....:     f = P.random_element(degree=2, terms=binomial(n,2))
    ....:     f -= f(*s)
    ....:     L.append(f.homogenize())
sage: I = Ideal(L)
sage: I.degree_of_semi_regularity()
3
sage: max(f.degree() for f in I.groebner_basis())
3
```

The degree of regularity approaches 2 for quadratic systems as the number of polynomials approaches $n^2$:

```
sage: for i in range((n-4)*n):
    ....:     f = P.random_element(degree=2, terms=binomial(n,2))
    ....:     f -= f(*s)
    ....:     L.append(f.homogenize())
sage: I = Ideal(L)
sage: I.degree_of_semi_regularity()
2
sage: max(f.degree() for f in I.groebner_basis())
2
```

**Note:** It is unknown whether semi-regular sequences exist. However, it is expected that random systems are semi-regular sequences. For more details about semi-regular sequences see [BFS2004].

**gens()**

Return a set of generators / a basis of this ideal. This is usually the set of generators provided during object creation.

**EXAMPLES:**

```
sage: P.<x,y> = PolynomialRing(QQ,2)
sage: I = Ideal([x,y+1]); I
```
Ideal (x, y + 1) of Multivariate Polynomial Ring in x, y over Rational Field

\begin{verbatim}
sage: I.gens()
[x, y + 1]
\end{verbatim}

\texttt{groebner_basis(algorithm="", deg_bound=None, mult_bound=None, prot=False, *args, **kwds)}

Return the reduced Groebner basis of this ideal.

A Groebner basis $g_1, ..., g_n$ for an ideal $I$ is a generating set such that $\langle LM(g_i) \rangle = LM(I)$, i.e., the leading monomial ideal of $I$ is spanned by the leading terms of $g_1, ..., g_n$. Groebner bases are the key concept in computational ideal theory in multivariate polynomial rings which allows a variety of problems to be solved.

Additionally, a reduced Groebner basis $G$ is a unique representation for the ideal $\langle G \rangle$ with respect to the chosen monomial ordering.

INPUT:

- \texttt{algorithm} - determines the algorithm to use, see below
  for available algorithms.
- \texttt{deg_bound} - only compute to degree \texttt{deg_bound}, that is, ignore all S-polynomials of higher degree.
  (default: None)
- \texttt{mult_bound} - the computation is stopped if the ideal is zero-dimensional in a ring with local ordering
  and its multiplicity is lower than \texttt{mult_bound}. Singular only. (default: None)
- \texttt{prot} - if set to True the computation protocol of the underlying implementation is printed. If an
  algorithm from the singular: or magma: family is used, \texttt{prot} may also be sage in which case
  the output is parsed and printed in a common format where the amount of information printed can be
  controlled via calls to set_verbose().
- \texttt{*args} - additional parameters passed to the respective
  implementations
- \texttt{**kwds} - additional keyword parameters passed to the
  respective implementations

ALGORITHMS:

- `'autoselect'` (default)
  - autoselect (default)
- `'singular:groebner'`
  - Singular’s groebner command
- `'singular:std'`
  - Singular’s std command
- `'singular:stdhilb'`
  - Singular’s stdhilb command
- `'singular:stdfglm'`
  - Singular’s stdfglm command
- `'singular:slimgb'`
  - Singular’s slimgb command
- `'libSingular:groebner'`
  - libSingular’s groebner command
Polynomials, Release 10.0

'libsingular:std'
libSingular's std command

'libsingular:slimgb'
libSingular's slimgb command

'libsingular:stdhilb'
libSingular's stdhilb command

'libsingular:stdfglm'
libSingular's stdfglm command

'toy:buchberger'
Sage's toy/educational buchberger without Buchberger criteria

'toy:buchberger2'
Sage's toy/educational buchberger with Buchberger criteria

'toy:d_basis'
Sage's toy/educational algorithm for computation over PIDs

'macaulay2:gb'
Macaulay2's gb command (if available)

'macaulay2:f4'
Macaulay2's GroebnerBasis command with the strategy “F4” (if available)

'macaulay2:mgb'
Macaulay2's GroebnerBasis command with the strategy “MGB” (if available)

'msolve'
optional package msolve (degrevlex order, prime fields)

'magma:GroebnerBasis'
Magma's Groebnerbasis command (if available)

'ginv:TQ', 'ginv:TQBlockHigh', 'ginv:TQBlockLow' and 'ginv:TQDegree'
One of GINV's implementations (if available)

'giac:gbasis'
Giac's gbasis command (if available)

If only a system is given - e.g. ‘magma’ - the default algorithm is chosen for that system.

Note: The Singular and libSingular versions of the respective algorithms are identical, but the former calls an external Singular process while the latter calls a C function, i.e. the calling overhead is smaller. However, the libSingular interface does not support pretty printing of computation protocols.

EXAMPLES:
Consider Katsura-3 over \( \mathbb{Q} \) with lexicographical term ordering. We compute the reduced Groebner basis using every available implementation and check their equality.

```python
sage: P.<a,b,c> = PolynomialRing(QQ,3, order='lex')
sage: I = sage.rings.ideal.Katsura(P,3) # regenerate to prevent caching
sage: I.groebner_basis()
[a - 60*c^3 + 158/7*c^2 + 8/7*c - 1, b + 30*c^3 - 79/7*c^2 + 3/7*c, c^4 - 10/
   21*c^3 + 1/84*c^2 + 1/84*c]
```
Although Giac does support lexicographical ordering, we use degree reverse lexicographical ordering here, in order to test against github issue #21884:

```
sage: I = sage.rings.ideal.Katsura(P,3) # regenerate to prevent caching
sage: I.groebner_basis('libsingular:groebner')
[a - 60*c^3 + 158/7*c^2 + 8/7*c - 1, b + 30*c^3 - 79/7*c^2 + 3/7*c, c^4 - 10/21*c^3 + 1/84*c^2 + 1/84*c]
sage: I = sage.rings.ideal.Katsura(P,3) # regenerate to prevent caching
sage: I.groebner_basis('libsingular:std')
[a - 60*c^3 + 158/7*c^2 + 8/7*c - 1, b + 30*c^3 - 79/7*c^2 + 3/7*c, c^4 - 10/21*c^3 + 1/84*c^2 + 1/84*c]
sage: I = sage.rings.ideal.Katsura(P,3) # regenerate to prevent caching
sage: I.groebner_basis('libsingular:stdhilb')
[a - 60*c^3 + 158/7*c^2 + 8/7*c - 1, b + 30*c^3 - 79/7*c^2 + 3/7*c, c^4 - 10/21*c^3 + 1/84*c^2 + 1/84*c]
sage: I = sage.rings.ideal.Katsura(P,3) # regenerate to prevent caching
sage: I.groebner_basis('libsingular:stdfglm')
[a - 60*c^3 + 158/7*c^2 + 8/7*c - 1, b + 30*c^3 - 79/7*c^2 + 3/7*c, c^4 - 10/21*c^3 + 1/84*c^2 + 1/84*c]
sage: I = sage.rings.ideal.Katsura(P,3) # regenerate to prevent caching
sage: I.groebner_basis('libsingular:slimgb')
[a - 60*c^3 + 158/7*c^2 + 8/7*c - 1, b + 30*c^3 - 79/7*c^2 + 3/7*c, c^4 - 10/21*c^3 + 1/84*c^2 + 1/84*c]
```

Giac’s gbasis over \(\mathbb{Q}\) can benefit from a probabilistic lifting and multi threaded operations:

```
sage: A9=PolynomialRing(QQ,9,'x')
sage: I9=sage.rings.ideal.Katsura(A9)
sage: print("possible output from giac", flush=True); I9.groebner_basis("giac", proba_epsilon=1e-7) # long time (3s) possible output...
Polynomial Sequence with 143 Polynomials in 9 Variables
```

The list of available Giac options is provided at `sage.libs.giac.groebner_basis()`.

Note that `toy:buchberger` does not return the reduced Groebner basis,
Polynomials, Release 10.0

```
sage: I = sage.rings.ideal.Katsura(P,3)  # regenerate to prevent caching
sage: gb = I.groebner_basis('toy:buchberger')
sage: gb.is_groebner()
True
sage: gb == gb.reduced()
False
```

but that `toy:buchberger2` does.

```
sage: I = sage.rings.ideal.Katsura(P,3)  # regenerate to prevent caching
sage: gb = I.groebner_basis('toy:buchberger2'); gb
[a - 60*c^3 + 158/7*c^2 + 8/7*c - 1, b + 30*c^3 - 79/7*c^2 + 3/7*c, c^4 - 10/21*c^3 + 1/84*c^2 + 1/84*c]
sage: gb == gb.reduced()
True
```

Here we use Macaulay2 with three different strategies over a finite field.

```
sage: R.<a,b,c> = PolynomialRing(GF(101), 3)
sage: I = sage.rings.ideal.Katsura(R,3)  # regenerate to prevent caching
sage: I.groebner_basis('macaulay2:gb')  # optional - macaulay2
[c^3 + 28*c^2 - 37*b + 13*c, b^2 - 41*c^2 + 20*b - 20*c, b*c - 19*c^2 + 10*b + 40*c, a + 2*b + 2*c - 1]
sage: I = sage.rings.ideal.Katsura(R,3)  # regenerate to prevent caching
sage: I.groebner_basis('macaulay2:f4')  # optional - macaulay2
[c^3 + 28*c^2 - 37*b + 13*c, b^2 - 41*c^2 + 20*b - 20*c, b*c - 19*c^2 + 10*b + 40*c, a + 2*b + 2*c - 1]
sage: I = sage.rings.ideal.Katsura(R,3)  # regenerate to prevent caching
sage: I.groebner_basis('macaulay2:mgb')  # optional - macaulay2
[c^3 + 28*c^2 - 37*b + 13*c, b^2 - 41*c^2 + 20*b - 20*c, b*c - 19*c^2 + 10*b + 40*c, a + 2*b + 2*c - 1]
```

Over prime fields of small characteristic, we can also use the optional package msolve:

```
sage: R.<a,b,c> = PolynomialRing(GF(101), 3)
sage: I = sage.rings.ideal.Katsura(R,3)  # regenerate to prevent caching
sage: I.groebner_basis('msolve')  # optional - msolve
[a + 2*b + 2*c - 1, b*c - 19*c^2 + 10*b + 40*c, b^2 - 41*c^2 + 20*b - 20*c, c^3 + 28*c^2 - 37*b + 13*c]
```

Singular and libSingular can compute Groebner basis with degree restrictions.

```
sage: R.<x,y> = QQ[]
sage: I = R*[x^3+y^2,x^2*y+1]
sage: I.groebner_basis(algorithm='singular')
[x^3 + y^2, x^2*y + 1, y^3 - x]
```

(continues on next page)
sage: I.groebner_basis(algorithm='singular', deg_bound=2)
[x^3 + y^2, x^2*y + 1]
sage: I.groebner_basis()
[x^3 + y^2, x^2*y + 1, y^3 - x]
sage: I.groebner_basis(deg_bound=2)
[x^3 + y^2, x^2*y + 1]

A protocol is printed, if the verbosity level is at least 2, or if the argument prot is provided. Historically, the protocol did not appear during doctests, so we skip the examples with protocol output.

sage: from sage.misc.verbose import set_verbose
sage: set_verbose(2)
sage: I = R*[x^3+y^2,x^2*y+1]
sage: I.groebner_basis()
# not tested
std in (QQ),(x,y),(dp(2),C)
[...:2]3ss4s6
(S:2)--
product criterion:1 chain criterion:0
[x^3 + y^2, x^2*y + 1, y^3 - x]
sage: I.groebner_basis(prot=False)
std in (QQ),(x,y),(dp(2),C)
[...:2]3ss4s6
(S:2)--
product criterion:1 chain criterion:0
[x^3 + y^2, x^2*y + 1, y^3 - x]
sage: set_verbose(0)
sage: I.groebner_basis(prot=True)
# not tested
std in (QQ),(x,y),(dp(2),C)
[...:2]3ss4s6
(S:2)--
product criterion:1 chain criterion:0
[x^3 + y^2, x^2*y + 1, y^3 - x]

The list of available options is provided at LibSingularOptions.

Note that Groebner bases over \( \mathbb{Z} \) can also be computed.

sage: P.<a,b,c> = PolynomialRing(ZZ,3)
sage: I = P * (a + 2*b + 2*c - 1, a^2 - a + 2*b^2 + 2*c^2, 2*a*b + 2*b*c - b)
sage: I.groebner_basis()
[b^3 + b*c^2 + 12*c^3 + b^2 + b*c - 4*c^2,
2*b*c^2 - 6*c^3 - b^2 - b*c + 2*c^2,
42*c^3 + b^2 + 2*b*c - 14*c^2 + b,
2*b^2 + 6*b*c + 6*c^2 - b - 2*c,
10*b*c + 12*c^2 - b - 4*c,
a + 2*b + 2*c - 1]

sage: I.groebner_basis('macaulay2')  # optional - macaulay2
[b^3 + b*c^2 + 12*c^3 + b^2 + b*c - 4*c^2,
2*b*c^2 - 6*c^3 + b^2 + 5*b*c + 8*c^2 - b - 2*c,
42*c^3 + b^2 + 2*b*c - 14*c^2 + b,
2*b^2 - 4*b*c - 6*c^2 + 2*c, 10*b*c + 12*c^2 - b - 4*c,
a + 2*b + 2*c - 1]
Groebner bases over $\mathbb{Z}/n\mathbb{Z}$ are also supported:

```python
sage: P.<a,b,c> = PolynomialRing(Zmod(1000),3)
sage: I = P * (a + 2*b + 2*c - 1, a^2 - a + 2*b^2 + 2*c^2, 2*a*b + 2*b*c - b)
sage: I.groebner_basis()
[b*c^2 + 732*b*c + 808*b,
 2*c^3 + 884*b*c + 666*c^2 + 320*b,
  b^2 + 438*b*c + 281*b,
  5*b*c + 156*c^2 + 112*b + 948*c,
 50*c^2 + 600*b + 650*c,
  a + 2*b + 2*c + 999,
  125*b]
```

```python
sage: R.<x,y,z> = PolynomialRing(Zmod(2233497349584))
sage: I = R.ideal([z*(x-3*y), 3^2*x^2-y*z, z^2+y^2])
sage: I.groebner_basis()
[2*z^4, y*z^2 + 81*z^3, 248166372176*z^3, 9*x^2 - y*z, y^2 + z^2, x*z + 2233497349581*y*z, 248166372176*y*z]
```

Sage also supports local orderings:

```python
sage: P.<x,y,z> = PolynomialRing(QQ,3,order='negdegrevlex')
sage: I = P * ( x*y*z + z^5, 2*x^2 + y^3 + z^7, 3*z^5 +y ^5 )
sage: I.groebner_basis()
[x^2 + 1/2*y^3, x*y*z + z^5, y^5 + 3*z^5, y^4*z - 2*x*z^5, z^6]
```

We can represent every element in the ideal as a combination of the generators using the `lift()` method:

```python
sage: P.<x,y,z> = PolynomialRing(QQ,3)
sage: I = Ideal(I.groebner_basis())
sage: f = sum(P.random_element(terms=2)*f for f in I.gens())
sage: f
1/2*y^2*z^7 - 1/4*y*z^8 + 2*x*z^5 + 95*z^6 + 1/2*y^5 - 1/4*y^4*z + x^2*y^2 + 3/ →2*x^2*y*z + 95*x*y*z^2
sage: f.lift(I.gens())  # random
[2*x + 95*z, 1/2*y^2 - 1/4*y*z, 0]
sage: l = f.lift(J.gens()); l  # random
[0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, -1/2*y^2 + 1/4*y*z, 1/2*y^2*z^2 - 1/ →4*y^2*z^3 + 2*x + 95*z]
sage: sum(map(mul, zip(l,J.gens()))) == f
True
```

Groebner bases over fraction fields of polynomial rings are also supported:

```python
sage: P.<t> = QQ[]
sage: F = Frac(P)
sage: R.<X,Y,Z> = F[]
sage: I = Ideal([f + P.random_element() for f in sage.rings.ideal.Katsura(R).gens()])
sage: I.groebner_basis().ideal() == I
True
```

In cases where a characteristic cannot be determined, we use a toy implementation of Buchberger’s algorithm (see github issue #6581):
sage: R.<a,b> = QQ[]; I = R.ideal(a^2+b^2-1)
sage: Q = QuotientRing(R,I); K = Frac(Q)
sage: R2.<x,y> = K[]; J = R2.ideal([(a^2+b^2)*x + y, x+y])
sage: J.groebner_basis()
verbose 0 (...: multi_polynomial_ideal.py, groebner_basis) Warning: falling...
[x + y]

ALGORITHM:

Uses Singular, one of the other systems listed above (if available), or a toy implementation.

groebner_cover()

Compute the Gröbner cover of the ideal, over a field with parameters.

The Groebner cover is a partition of the space of parameters, such that the Groebner basis in each part is given by the same expression.

EXAMPLES:

sage: F = PolynomialRing(QQ,'a').fraction_field()
sage: F.inject_variables()
Defining a
sage: R.<x,y,z> = F[]  

sage: I = R.ideal([-x+3*y+z-5,2*x+a*z+4,4*x-3*z-1/a])
sage: I.groebner_cover()
{Quasi-affine subscheme X - Y of Affine Space of dimension 1 over Rational...
- Field, where X is defined by:
  ∅
  and Y is defined by:
  2*a^2 + 3*a: [(2*a^2 + 3*a)*z + (8*a + 1), (12*a^2 + 18*a)*y + (-20*a^2 -...
- Field, where X is defined by:
  ...
  and Y is defined by:
  1: [1],
Quasi-affine subscheme X - Y of Affine Space of dimension 1 over Rational...
- Field, where X is defined by:
  ...
  and Y is defined by:
  1: [1]}

groebner_fan(is_groebner_basis=False, symmetry=None, verbose=False)

Return the Groebner fan of this ideal.

The base ring must be $\mathbb{Q}$ or a finite field $\mathbb{F}_p$ of with $p \leq 32749$.

EXAMPLES:

sage: P.<x,y> = PolynomialRing(QQ)
sage: i = ideal(x^2 - y^2 + 1)
sage: g = i.groebner_fan()
sage: g.reduced_groebner_bases()
[[[x^2 - y^2 + 1], [-x^2 + y^2 - 1]]}
INPUT:

- **is_groebner_basis** - bool (default False). if True, then I.gens() must be a Groebner basis with respect to the standard degree lexicographic term order.
- **symmetry** - default: None; if not None, describes symmetries of the ideal
- **verbose** - default: False; if True, printout useful info during computations

**homogenize**(*var='h'*)

Return homogeneous ideal spanned by the homogeneous polynomials generated by homogenizing the generators of this ideal.

INPUT:

- **h** - variable name or variable in cover ring (default: ‘h’)

**EXAMPLES:**

```python
sage: P.<x,y,z> = PolynomialRing(GF(2))
sage: I = Ideal([x^2*y + z + 1, x + y^2 + 1]); I
Ideal (x^2*y + z + 1, y^2 + x + 1) of Multivariate Polynomial Ring in x, y, z over Finite Field of size 2

sage: I.homogenize()
Ideal (x^2*y + z*h^2 + h^3, y^2 + x*h + h^2) of Multivariate Polynomial Ring in x, y, z, h over Finite Field of size 2

sage: I.homogenize(y)
Ideal (x^2*y + y^3 + y^2*z, x*y) of Multivariate Polynomial Ring in x, y, z over Finite Field of size 2
```

**is_homogeneous**()

Return True if this ideal is spanned by homogeneous polynomials, i.e. if it is a homogeneous ideal.

**EXAMPLES:**

```python
sage: P.<x,y,z> = PolynomialRing(QQ,3)
sage: I = sage.rings.ideal.Katsura(P)
sage: I
Ideal (x + 2*y + 2*z - 1, x^2 + 2*y^2 + 2*z^2 - x, 2*x*y + 2*y*z - y) of Multivariate Polynomial Ring in x, y, z over Rational Field

sage: I.is_homogeneous()
False

sage: J = I.homogenize()
sage: J
```

Ideal \((x + 2y + 2z - h, x^2 + 2y^2 + 2z^2 - x^h, 2xy + 2yz - y^h)\) of Multivariate Polynomial Ring in \(x, y, z, h\) over Rational Field

\[\text{sage: } J\text{.is_homogeneous()}
\]
\[\text{True}\]

\[\text{plot(*args, **kwds)}\]
Plot the real zero locus of this principal ideal.

**INPUT:**

- `self` - a principal ideal in 2 variables
- `algorithm` - set this to ‘surf’ if you want ‘surf’ to plot the ideal (default: None)
- `*args` - optional tuples `(variable, minimum, maximum)` for plotting dimensions
- `**kwds` - optional keyword arguments passed on to `implicit_plot`

**EXAMPLES:**

Implicit plotting in 2-d:

\[\text{sage: } R.<x,y> = PolynomialRing(QQ,2)
\]
\[\text{sage: } I = R.ideal([y^3 - x^2])
\]
\[\text{sage: } I\text{.plot()} \quad \# \text{ cusp}
\]
Graphics object consisting of 1 graphics primitive

\[\text{sage: } I = R.ideal([y^2 - x^2 - 1])
\]
\[\text{sage: } I\text{.plot((x,-3, 3), (y, -2, 2))} \quad \# \text{ hyperbola}
\]
Graphics object consisting of 1 graphics primitive

\[\text{sage: } I = R.ideal([y^2 + x^2*(1/4) - 1])
\]
\[\text{sage: } I\text{.plot()} \quad \# \text{ ellipse}
\]
Graphics object consisting of 1 graphics primitive

\[\text{sage: } I = R.ideal([y^2-(x^2-1)*(x-2)])
\]
\[\text{sage: } I\text{.plot()} \quad \# \text{ elliptic curve}
\]
Graphics object consisting of 1 graphics primitive

\[\text{sage: } f = ((x+3)^3 + 2*(x+3)^2 - y^2)*(x^3 - y^2)*((x-3)^3-2*(x-3)^2-y^2)
\]
\[\text{sage: } I = R.ideal(f)
\]
\[\text{sage: } I\text{.plot()} \quad \# \text{ the Singular logo}
\]
Graphics object consisting of 1 graphics primitive

\[\text{sage: } R.<x,y> = PolynomialRing(QQ,2)
\]
\[\text{sage: } I = R.ideal([x - 1])
\]
\[\text{sage: } I\text{.plot((y, -2, 2))} \quad \# \text{ vertical line}
\]
Graphics object consisting of 1 graphics primitive
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```python
sage: I = R.ideal([-x^2*y + 1])
sage: I.plot()  # blow up
Graphics object consisting of 1 graphics primitive
```

**random_element**(degree, compute_gb=False, *args, **kwds)

Return a random element in this ideal as \( r = \sum h_i \cdot f_i \).

**INPUT:**

- compute_gb - if True then a Gröbner basis is computed first and \( f_i \) are the elements in the Gröbner basis. Otherwise whatever basis is returned by self.gens() is used.

- *args and **kwds are passed to R.random_element() with \( R = \text{self.ring()} \).

**EXAMPLES:**

We compute a uniformly random element up to the provided degree.

```python
sage: P.<x,y,z> = GF(127)[]
sage: I = sage.rings.ideal.Katsura(P)
sage: f = I.random_element(degree=4, compute_gb=True, terms=infinity)
sage: f.degree() <= 4
True
sage: len(list(f)) <= 35
True
```

Note that sampling uniformly at random from the ideal at some large enough degree is equivalent to computing a Gröbner basis. We give an example showing how to compute a Gröbner basis if we can sample uniformly at random from an ideal:

```python
sage: n = 3; d = 4
sage: P = PolynomialRing(GF(127), n, 'x')
sage: I = sage.rings.ideal.Cyclic(P)
```

1. We sample \( n^d \) uniformly random elements in the ideal:

```python
sage: F = Sequence(I.random_element(degree=d, compute_gb=True, terms=infinity) for _ in range(n^d))
```

2. We linearize and compute the echelon form:

```python
sage: A,v = F.coefficient_matrix()
sage: A.echelonize()
```

3. The result is the desired Gröbner basis:

```python
sage: G = Sequence((A*v).list())
sage: G.is_groebner()
True
sage: Ideal(G) == I
True
```

We return some element in the ideal with no guarantee on the distribution:
sage: P = PolynomialRing(GF(127), 10, 'x')
sage: I = sage.rings.ideal.Katsura(P)
sage: f = I.random_element(degree=3)
sage: f  # random
-25*x0^2*x1 + 14*x1^3 + 57*x0*x1*x2 + ... + 19*x7*x9 + 40*x8*x9 + 49*x1
sage: f.degree()
3

We show that the default method does not sample uniformly at random from the ideal:

sage: P.<x,y,z> = GF(127)[]
sage: G = Sequence([x+7, y-2, z+110])
sage: I = Ideal([sum(P.random_element() * g for g in G) for _ in range(4)])
sage: all(I.random_element(degree=1) == 0 for _ in range(100))
True

If degree equals the degree of the generators a random linear combination of the generators is returned:

sage: P.<x,y> = QQ[

sage: I = P.ideal([x^2,y^2])
sage: set_random_seed(5)
sage: I.random_element(degree=2)
-2*x^2 + 2*y^2

reduce(f)

Reduce an element modulo the reduced Groebner basis for this ideal. This returns 0 if and only if the element is in this ideal. In any case, this reduction is unique up to monomial orders.

EXAMPLES:

sage: R.<x,y> = PolynomialRing(QQ, 2)
sage: I = (x^3 + y, y)*R
sage: I.reduce(y)
0
sage: I.reduce(x^3)
0
sage: I.reduce(x - y)
x
sage: I = (y^2 - (x^3 + x))*R
sage: I.reduce(x^3)
y^2 - x
sage: I.reduce(x^6)
y^4 - 2*x^6*y^2 + x^2
sage: (y^2 - x)^2
y^4 - 2*x^6*y^2 + x^2

Note: Requires computation of a Groebner basis, which can be a very expensive operation.

subs(in_dict=None, **kwds)
Substitute variables.

3.1. Multivariate Polynomials and Polynomial Rings 369
This method substitutes some variables in the polynomials that generate the ideal with given values. Variables that are not specified in the input remain unchanged.

**INPUT:**
- `in_dict` – (optional) dictionary of inputs
- `**kwds` – named parameters

**OUTPUT:**
A new ideal with modified generators. If possible, in the same polynomial ring. Raises a `TypeError` if no common polynomial ring of the substituted generators can be found.

**EXAMPLES:**

```python
sage: R.<x,y> = PolynomialRing(ZZ,2, 'xy')
sage: I = R.ideal(x^5+y^5, x^2 + y + x^2*y^2 + 5); I
Ideal (x^5 + y^5, x^2*y^2 + x^2 + y + 5) of Multivariate Polynomial Ring in x, y over Integer Ring
sage: I.subs(x=y)
Ideal (2*y^5, y^4 + y^2 + y + 5) of Multivariate Polynomial Ring in x, y over Integer Ring
sage: I.subs({x:y})  # same substitution but with dictionary
Ideal (2*y^5, y^4 + y^2 + y + 5) of Multivariate Polynomial Ring in x, y over Integer Ring
```

The new ideal can be in a different ring:

```python
sage: R.<a,b> = PolynomialRing(QQ,2)
sage: S.<x,y> = PolynomialRing(QQ,2)
sage: I = R.ideal(a^2+b^2+a-b+2); I
Ideal (a^2 + b^2 + a - b + 2) of Multivariate Polynomial Ring in a, b over Rational Field
sage: I.subs(a=x, b=y)
Ideal (x^2 + y^2 + x - y + 2) of Multivariate Polynomial Ring in x, y over Rational Field
```

The resulting ring need not be a multivariate polynomial ring:

```python
sage: T.<t> = PolynomialRing(QQ)
sage: I = R.ideal(t^2 + 1); I
Principal ideal (t^2 + 1) of Univariate Polynomial Ring in t over Rational Field
sage: var("z")
z
sage: I.subs(a=z, b=z)
Principal ideal (2*z^2 + 2) of Symbolic Ring
```

Variables that are not substituted remain unchanged:

```python
sage: R.<x,y> = PolynomialRing(QQ,2)
sage: I = R.ideal(x^2+y^2-x-y+2); I
Ideal (x^2 + y^2 + x - y + 2) of Multivariate Polynomial Ring in x, y over Rational Field
sage: I.subs(x=1)
Ideal (y^2 - y + 4) of Multivariate Polynomial Ring in x, y over Rational Field
```
weil_restriction()  
Compute the Weil restriction of this ideal 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 $\text{Res}_{L/k}$ - is a functor which, for any finite extension of fields $L/k$  
and any algebraic variety $X$ over $L$, produces another corresponding variety $\text{Res}_{L/k}(X)$, 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: MPolynomial Ideal  
EXAMPLES:

```python
sage: k.<a> = GF(2^2)
sage: P.<x,y> = PolynomialRing(k,2)
sage: I = Ideal([x*y + 1, a*x + 1])
sage: I.variety()
[{y: a, x: a + 1}]
sage: J = I.weil_restriction()
sage: J
Ideal (x0*y0 + x1*y1 + 1, x1*y0 + x0*y1, x1 + 1, x0 + x1) of 
Multivariate Polynomial Ring in x0, x1, y0, y1 over Finite Field of size 2
sage: J += sage.rings.ideal.FieldIdeal(J.ring())  # ensure radical ideal
sage: J.variety()
[{y1: 1, y0: 0, x1: 1, x0: 1}]
sage: J.weil_restriction()  # returns J
Ideal (x0*y0 + x1*y1 + 1, x1*y0 + x0*y1, x1 + 1, x0 + x1, x0^2 + 
x0, x1^2 + x1, y0^2 + y0, y1^2 + y1) of Multivariate Polynomial Ring in 
x0, x1, y0, y1 over Finite Field of size 2
sage: k.<a> = GF(3^5)
sage: P.<x,y,z> = PolynomialRing(k)
sage: I = sage.rings.ideal.Katsura(P)
sage: I.dimension()
0
sage: I.variety()
[{z: 0, y: 0, x: 1}]
sage: J = I.weil_restriction(); J
Ideal (x0 - y0 - z0 - 1, x1 - y1 - z1, x2 - y2 - z2, x3 - y3 - z3, x4 -
```
(continues on next page)
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(continued from previous page)

\[ \begin{align*}
y_4 - z_4, & \quad x_0^2 + x_2^2 - x_1^2 x_3 + x_1 x_4 - y_0^2 - y_2^2 y_3 - y_1 y_4 - z_0^2 - z_2^2 z_3 - z_1^2 z_4 - x_0, -x_0 x_1 - x_2 x_3 - x_3^2 - x_1 x_4 + x_2 x_4 + y_0 y_1 + y_2 y_3 + y_3^2 + y_1 y_4 - y_2 y_4 - y_3 y_4 - z_0^2 - z_2^2 z_4 - z_1 x_2 + z_0^2 z_2 - z_3^2 + z_2^2 z_4 - z_3 z_4 - x_2, -x_1 x_2 - x_0 x_3 - x_3 x_4 - x_4^2 + y_1 y_2 + y_0 y_3 + y_3^2 + y_2 y_4 - y_3 y_4 - z_0^2 - z_4^2 - x_4, -x_0 y_0 + x_4 y_1 + x_3 y_2 + x_2 y_3 + x_1 y_4 - y_0 z_0 + y_4 z_1 + y_3 z_2 + y_2 z_3 + y_1 z_4 - y_0, -x_1 y_0 - x_0 y_1 - x_4 y_1 - x_3 y_2 + x_4 y_2 - x_2 y_3 + x_3 y_3 - x_1 y_4 + x_2 y_4 - y_1 z_0 - y_0 z_1 - y_4 z_1 + y_3 z_2 + y_4 z_2 - y_2 z_3 - y_3 z_3 - y_1 z_4 - y_2 z_4 - y_1, -x_2 y_0 - x_1 y_1 - x_0 y_2 - x_4 y_2 - x_3 y_3 + x_4 y_3 - x_2 y_4 + x_3 y_4 - y_2 z_0 - y_1 z_1 - y_0 z_2 - y_4 z_2 - y_3 z_3 + y_4 z_3 - y_2 z_4 + y_3 z_4 - y_2, -x_3 y_0 - x_2 y_1 - x_1 y_2 - x_0 y_3 - x_4 y_3 - x_3 y_4 + x_4 y_4 - y_3 z_0 - y_2 z_1 - y_1 z_2 - y_0 z_3 - y_4 z_3 - y_3 z_4 + y_4 z_4 - y_3, -x_4 y_0 - x_3 y_1 - x_2 y_2 - y_1 z_3 - x_0 y_4 - x_4 y_4 - y_4 z_0 - y_3 z_1 + y_2 z_2 + y_1 z_3 - y_0 z_4 - y_4 z_4 - y_4) \text{ of Multivariate Polynomial Ring in } x_0, x_1, x_2, x_3, x_4, y_0, y_1, y_2, y_3, y_4, z_0, z_1, z_2, z_3, z_4 \text{ over Finite Field of size 3.

sage: J += sage.rings.ideal.FieldIdeal(J.ring()) \# ensure radical ideal
sage: from sage.doctest.fixtures import reproducible_repr
sage: print(reproducible_repr(J.variety()))
\{x_0: 1, x_1: 0, x_2: 0, x_3: 0, x_4: 0, y_0: 0, y_1: 0, y_2: 0, y_3: 0, y_4: 0, z_0: 0, z_1: 0, z_2: 0, z_3: 0, z_4: 0\}

Weil restrictions are often used to study elliptic curves over extension fields so we give a simple example involving those:

\begin{verbatim}sage: K.<a> = QuadraticField(1/3)
to EllipticCurve(K,[1,2,3,4,5])
\end{verbatim}

We pick a point on E:

\begin{verbatim}sage: p = E.lift_x(1); p
(1 : 2 : 1)
sage: I = E.defining_ideal(); I
Ideal (-x^3 - 2*x^2*z + x*y*z + y^2*z - 4*x*z^2 + 3*y*z^2 - 5*z^3) of
\text{Multivariate Polynomial Ring in } x, y, z \text{ over Number Field in } a \text{ with defining polynomial } x^2 - 1/3 \text{ with } a = 0.5773502691896258?
\end{verbatim}

Of course, the point p is a root of all generators of I:

\begin{verbatim}sage: I.subs(x=1,y=2,z=1)
Ideal (0) of Multivariate Polynomial Ring in x, y, z over Number Field in a with defining polynomial x^2 - 1/3 with a = 0.5773502691896258?
\end{verbatim}

I is also radical:

\begin{verbatim}sage: I.radical() == I
True
\end{verbatim}

So we compute its Weil restriction:
\texttt{sage: } J = I\textunderscore weil\textunderscore restriction()
\texttt{sage: } J
Ideal (-x0^3 - x0*x1^2 - 2*x0^2*z0 - 2/3*x1^2*z0 + x0*y0*z0 + y0^2*z0 +
1/3*x1*y1*z0 + 1/3*y1^2*z0 - 4*x0*y0*z0^2 + 3*y0^2*z0^2 - 5*z0^3 -
4/3*x0^3*x1*z1 + 1/3*x1*y0^2*z1 + 1/3*x0*y1*z1 + 2/3*y0*y1*z1 - 8/3*x1^2*z0^2 -
+ 2*y1*z0^2*z1 - 4/3*x0^2*z1^2 + y0^2*z1^2 - 5*z0^2*z1^2, 1/3*x1*y1^2*z1 + 1/3*y1^2*z1 -
+ 1/3*x0^2*y0*z1 + 1/3*y0^2*y1*z1 + 2/3*y0*y1*z0 - 4*x1*z0^2 + 3*y1*z0^2 +
- 2*x0^2*z1 + 2/3*x1^2*z1 + x0^2*y0*z1 + y0^2*z1^2 + 1/3*x1*y1^2*z1 + 1/3*y1^2*z1 +
+ 1/3*x0^2*z0^2 + 8*x0^2*y0^2*z1 + 6*y0^2*z0^2*z1 + 15*z0^2^2*z1 + 4/3*x1^2*z1^2 +
y1^2*z1^2 - 5/3*z1^3) of Multivariate Polynomial Ring in x0, x1, y0, y1,
z0, z1 over Rational Field

We can check that the point $p$ is still a root of all generators of $J$:

\texttt{sage: } J\textunderscore subs(x0=1,y0=2,z0=1,x1=0,y1=0,z1=0)
Ideal (0, 0) of Multivariate Polynomial Ring in x0, x1, y0, y1, z0, z1 over Rational Field

Example for relative number fields:

\texttt{sage: } R.<x> = QQ[]
\texttt{sage: } K.<w> = NumberField(x^5-2)
\texttt{sage: } R.<x> = K[]
\texttt{sage: } L.<v> = K.extension(x^2+1)
\texttt{sage: } S.<x,y> = L[]
\texttt{sage: } I = S.ideal([y^2-x^3-1])
\texttt{sage: } I\textunderscore weil\textunderscore restriction()
Ideal (-x0^3 + 3*x0*x1^2 + y0^2 - y1^2 - 1, -3*x0^2*x1 + x1^3 + 2*y0*y1)
of Multivariate Polynomial Ring in x0, x1, y0, y1 over Number Field in w
with defining polynomial $x^5 - 2$

\textbf{Note:} Based on a Singular implementation by Michael Brickenstein

\texttt{class} sage\textunderscore rings\textunderscore polynomial\textunderscore multi\textunderscore polynomial\textunderscore ideal.MPolynomialIdeal\textunderscore macaulay2\textunderscore repr
Bases: object

An ideal in a multivariate polynomial ring, which has an underlying Macaulay2 ring associated to it.

EXAMPLES:

\texttt{sage: } R.<x,y,z,w> = PolynomialRing(ZZ, 4)
\texttt{sage: } I = ideal(x*y-z^2, y^2-w^2)
\texttt{sage: } I
Ideal (x*y - z^2, y^2 - w^2) of Multivariate Polynomial Ring in x, y, z, w over ..
→ Integer Ring

\texttt{class} sage\textunderscore rings\textunderscore polynomial\textunderscore multi\textunderscore polynomial\textunderscore ideal.MPolynomialIdeal\textunderscore magma\textunderscore repr
Bases: object

\texttt{class} sage\textunderscore rings\textunderscore polynomial\textunderscore multi\textunderscore polynomial\textunderscore ideal.MPolynomialIdeal\textunderscore quotient\texttt{(ring, gens,}
\texttt{ coerce=True)}

Bases: MPolynomialIdeal

An ideal in a quotient of a multivariate polynomial ring.

\subsection{3.1. Multivariate Polynomials and Polynomial Rings}
EXAMPLES:

```python
sage: Q.<x,y,z,w> = QQ['x,y,z,w'].quotient([x*y-z^2, y^2-w^2])
sage: I = ideal(x + y^2 + z - 1)
sage: I
Ideal (w^2 + x + z - 1) of Quotient of Multivariate Polynomial Ring in x, y, z, w over Rational Field by the ideal (x*y - z^2, y^2 - w^2)
```

reduce(f)

Reduce an element modulo a Gröbner basis for this ideal. This returns 0 if and only if the element is in this ideal. In any case, this reduction is unique up to monomial orders.

EXAMPLES:

```python
sage: R.<T,U,V,W,X,Y,Z> = PolynomialRing(QQ, order='lex')
sage: I = R.ideal([T^2+U^2-1, V^2+W^2-1, X^2+Y^2+Z^2-1])
sage: Q.<t,u,v,w,x,y,z> = R.quotient(I)
sage: J = Q.ideal([u*v-x, u*w-y, t-z])
sage: J.reduce(t^2 - z^2)
0
sage: J.reduce(u^2)
-z^2 + 1
sage: t^2 - z^2 in J
True
sage: u^2 in J
False
```

class sage.rings.polynomial.multi_polynomial_ideal.MPolynomialIdeal_singular_base_repr

Bases: object

syzygy_module()

Computes the first syzygy (i.e., the module of relations of the given generators) of the ideal.

EXAMPLES:

```python
sage: R.<x,y> = PolynomialRing(QQ)
sage: f = 2*x^2 + y
sage: g = y
sage: h = 2*f + g
sage: I = Ideal([f,g,h])
sage: M = I.syzygy_module(); M
[ -2  -1  1]
[  y 2*x^2 + y  0]
sage: G = vector(I.gens())
sage: M*G
(0, 0)
```

ALGORITHM: Uses Singular’s syz command

class sage.rings.polynomial.multi_polynomial_ideal.MPolynomialIdeal_singular_repr

Bases: MPolynomialIdeal_singular_base_repr

An ideal in a multivariate polynomial ring, which has an underlying Singular ring associated to it.

associated_primes(algorithm='sy')

Return a list of the associated primes of primary ideals of which the intersection is \( I = \texttt{self} \).
An ideal $Q$ is called primary if it is a proper ideal of the ring $R$ and if whenever $ab \in Q$ and $a \notin Q$ then $b^n \in Q$ for some $n \in \mathbb{Z}$.

If $Q$ is a primary ideal of the ring $R$, then the radical ideal $P$ of $Q$, i.e. $P = \{a \in R, a^n \in Q\}$ for some $n \in \mathbb{Z}$, is called the associated prime of $Q$.

If $I$ is a proper ideal of the ring $R$ then there exists a decomposition in primary ideals $Q_i$ such that
- their intersection is $I$
- none of the $Q_i$ contains the intersection of the rest, and
- the associated prime ideals of $Q_i$ are pairwise different.

This method returns the associated primes of the $Q_i$.

INPUT:
- algorithm - string:
  - 'sy' - (default) use the Shimoyama-Yokoyama algorithm
  - 'gtz' - use the Gianni-Trager-Zacharias algorithm

OUTPUT:
- list - a list of associated primes

EXAMPLES:

```
sage: R.<x,y,z> = PolynomialRing(QQ, 3, order='lex')
sage: p = z^2 + 1; q = z^3 + 2
sage: I = (p*q^2, y-z^2)*R
sage: pd = I.associated_primes(); sorted(pd, key=str)
[Ideal (z^2 + 1, y + 1) of Multivariate Polynomial Ring in x, y, z over...
 Ideal (z^3 + 2, y - z^2) of Multivariate Polynomial Ring in x, y, z over...
]```

ALGORITHM:
Uses Singular.

REFERENCES:
Polynomials, Release 10.0

sage: R.<a,b,c,d,e,f,g,h,i,j> = PolynomialRing(GF(127),10)
sage: I = sage.rings.ideal.Cyclic(R,4)
sage: I.basis_is_groebner()
False
sage: I2 = Ideal(I.groebner_basis())
sage: I2.basis_is_groebner()
True

A more complicated example:

sage: R.<U6,U5,U4,U3,U2, u6,u5,u4,u3,u2, h> = PolynomialRing(GF(7583))
sage: l = [u6 + u5 + u4 + u3 + u2 - 3791*h, \
    U6 + U5 + U4 + U3 + U2 - 3791*h, \ 
    U2*u2 - h^2, U3*u3 - h^2, U4*u4 - h^2, \ 
    U5*u5 + U4*u4 + U3*u3 + U2*u2 + U4*u2 + U5*u2 - 3791*U5*h - \ 
    3791*U4*h - 3791*U3*h - 3791*U2*h - 2842*h^2, \ 
    U4*u5 + U3*u5 + U2*u5 + U3*u4 + U2*u4 + U2*u3 - 3791*u5*h - \ 
    3791*u4*h - 3791*u3*h - 3791*u2*h - 2842*h^2, \ 
    U5*u5 - h^2, U4*U2*u3 + U5*U3*u2 + U4*U3*u2 + U3^2*u2 - 3791*U5*U3*h, \ 
    → 3791*U4*U3*h - 3791*U3^2*h - 3791*U5*U2*h \ 
    - 3791*U4*U2*h + U3*U2*h - 3791*U2^2*h - 3791*U4*u3*h - \ 
    3791*U4*u2*h - 3791*U3*u2*h - 2843*U5*h^2 + 1897*U4*h^2 - 946*U3*h^2 - \ 
    947*U2*h^2 + 2370*h^3, \ 
    U3*u5*u4 + U2*u5*u4 + U3*u4^2 + U2*u4^2 + U2*u4*u3 - 3791*u5*u4*h - \ 
    3791*u4^2*h - 3791*u4*u3*h - 3791*u4*u2*h - 2842*u4*h^2, \ 
    U2*u5*u4 + U4*u4^2 + U2*u4*u3 + U2*u4*u3^2 - 3791*u5*u4*h - 3791*u4^2*h - \ 
    2*u3^2*h - 3791*u4*u3*u2*h + U5*u4*u2*h + U4^2*h^2 + U5*u3*h^2 - \ 
    2842*u4*u3*h^2, \ 
    U5^2*U4*u3 + U5*U4^2*u3 + U5*U4*u3^2 - 3791*U5^2*U4*h - 3791*U5*U4^2*h - \ 
    3791*U5^2*U3*h \ 
    → + U5*U4*U3*h - 3791*U5*U3^2*h - 3791*U5*U2^2*h + U5*U4*U2*h + \ 
    U5*U3*U2*h - 3791*U5*U2^2*h - 3791*U5*U3*u2*h - 2842*U5*U2*h^2 + 1897*U5*U4*h^2 \ 
    → 2 \ 
    - U4^2*h^2 - 947*U5*U3*h^2 - 948*U5*U2*h^2 - 2842*U5*h^2 + 1897*U5*U4*h^2 \ 
    → 1422*U5*h^3 + 3791*U4*h^3, \ 
    u5*u4*u3*u2*h + u4^2*u3^2*u2*h + u4*u3^2*u2*h + u4^2*u3^2*u2*h + \ 
    2*u5*u4*u3*h^2 + 2*u4^2*u3*h^2 + 2*u4^2*u3*h^2 + 2*u5*u4*u2*h^2 + 2*u4^2*u2*h^2 \ 
    → 2 \ 
    + 2*u5*u3*u2*h^2 + 1899*u4*u3*u2*h^2, \ 
    U5^2*U4*U3*u2 + U5*U4^2*U3*u2 + U5*U4*U3^2*u2 - 3791*U5*U2*U4*U3*h - \ 
    3791*U5*U4^2*U3*h - 3791*U5*U4*U3^2*h - 3791*U5*U4*U3*U2*h \ 
    + 3791*U5*U4*U3*U2^2*h + U5^2*U4*U4*h^2 + U5^2*U3*U3*h^2 - U4^2*U3*h^2 - U5*U3^2*U2*h^2 - U5*U4*U2*U2*h^2 \ 
    - U5*U3*U2^2*h + U4*U3^2*u2*h + 3791*U5*U4*U3*h^3 + 3791*U5*U3*h^3 + \ 
    3791*U4*U3*h^3, \ 
    U4^2*u3^2*u2*h^2 + 1515*u5*u3^2*u2*h^2 + u4^2*u3^2*u2*h^2 + \ 
    1515*u5*u4*u3*h^3 + 3028*u4^2*u3^2*h^3 - 3028*u4^2*u3^2*h^3 + \ 
    1521*u5*u4*u2^2*h^3 - 3208*u4^2*u2^2*h^3 + 3028*u4^2*u2^2*h^3 + 3420*u4*u3^2*u2^2*h^3, \ 
    → \ 
    U5^2*U4*U3*U2*h + U5^4*U2^2*U3^2*h + U5^2*U4*U3*U2*h + U5*U4*U3*U2^2*h \ 
    → 2*h + 2*U5^2*U4*U3*h^2 + 2*U5*U4*U3^2*h^2 + 2*U5*U4*U3*U2^2*h^2 \ 
(continues on next page)
+ 2*U5^2*U4*U2*h^2 + 2*U5*U4^2*U2*h^2 + 2*U5^2*U3*U2*h^2 - 2*U4^-
˓→2*U3*U2*h^2 - 2*U5*U3^2*U2*h^2 - 2*U4*U3^2*U2*h^2 - 2*U5*U4*U2^2*h^2 - 2*U5*U3*U2^2*h^2 - 2*U4*U3*U2^2*h^2 - ˓→U5*U4*U3*h^3 - U5*U4*U2*h^3 - U5*U3*U2*h^3 - U4*U3*U2*h^3

sage: Ideal(l).basis_is_groebner()  
False
sage: gb = Ideal(l).groebner_basis()  
sage: Ideal(gb).basis_is_groebner()  
True

Note: From the Singular Manual for the reduce function we use in this method: ‘The result may have no meaning if the second argument (self) is not a standard basis’. I (malb) believe this refers to the mathematical fact that the results may have no meaning if self is no standard basis, i.e., Singular doesn’t ‘add’ any additional ‘nonsense’ to the result. So we may actually use reduce to determine if self is a Groebner basis.

complete_primary_decomposition()  
A decorator that creates a cached version of an instance method of a class.

Note: For proper behavior, the method must be a pure function (no side effects). Arguments to the method must be hashable or transformed into something hashable using key or they must define sage.structure.sage_object.SageObject._cache_key().

EXAMPLES:

sage: class Foo():  
.....:     def f(self, t, x=2):  
.....:         print('computing')  
.....:         return t**x  

sage: a = Foo()  

The example shows that the actual computation takes place only once, and that the result is identical for equivalent input:

sage: res = a.f(3, 2); res  
computing 9  
sage: a.f(t = 3, x = 2) is res  
True  
sage: a.f(3) is res  
True

Note, however, that the CachedMethod is replaced by a CachedMethodCaller or CachedMethodCallerNoArgs as soon as it is bound to an instance or class:

sage: P.<a,b,c,d> = QQ[]  
sage: I = P*[a,b]
So, you would hardly ever see an instance of this class alive.

The parameter `key` can be used to pass a function which creates a custom cache key for inputs. In the following example, this parameter is used to ignore the `algorithm` keyword for caching:

```python
sage: class A:
    ....:    def _f_normalize(self, x, algorithm): return x
    ....:    @cached_method(key=_f_normalize)
    ....:    def f(self, x, algorithm='default'): return x
sage: a = A()
sage: a.f(1, algorithm='default') is a.f(1) is a.f(1, algorithm='algorithm')
True
```

The parameter `do_pickle` can be used to enable pickling of the cache. Usually the cache is not stored when pickling:

```python
sage: class A:
    ....:    @cached_method
def f(self, x):
    return None
import __main__
sage: __main__.A = A
sage: a = A()
sage: a.f(1)
sage: len(a.f.cache)
1
sage: b = loads(dumps(a))
sage: len(b.f.cache)
0
```

When `do_pickle` is set, the pickle contains the contents of the cache:

```python
sage: class A:
    ....:    @cached_method(do_pickle=True)
    ....:    def f(self, x):
    return None
sage: __main__.A = A
sage: a = A()
sage: a.f(1)
sage: len(a.f.cache)
1
sage: b = loads(dumps(a))
sage: len(b.f.cache)
1
```

Cached methods cannot be copied like usual methods, see github issue #12603. Copying them can lead to very surprising results:

```python
sage: class A:
    ....:    @cached_method
    ....:    def f(self):
    ....:        return 1
(continues on next page)
```
sage: class B:
......:     g=A.f
......:     def f(self):
......:         return 2

sage: b=B()
sage: b.f()
2
sage: b.g()
1
sage: b.f()
1

**dimension** *(singular='singular_default')*

The dimension of the ring modulo this ideal.

**EXAMPLES:**

```
sage: P.<x,y,z> = PolynomialRing(GF(32003),order='degrevlex')
sage: I = ideal(x^2-y,x^3)
sage: I.dimension()
1
```

If the ideal is the total ring, the dimension is $-1$ by convention.

For polynomials over a finite field of order too large for Singular, this falls back on a toy implementation of Buchberger to compute the Groebner basis, then uses the algorithm described in Chapter 9, Section 1 of Cox, Little, and O’Shea’s “Ideals, Varieties, and Algorithms”.

**EXAMPLES:**

```
sage: R.<x,y> = PolynomialRing(GF(2147483659^2),order='lex')
sage: I = R.ideal([x*y,x*y+1])
sage: I.dimension()
-1
```

```
sage: I=ideal([x^(x+y+1),y^(x+y+1)])
sage: I.dimension()
1
```

```
sage: I = R.ideal([x^3*y,x^y^2])
sage: I.dimension()
1
```

```
sage: R.<x,y> = PolynomialRing(GF(2147483659^2),order='lex')
sage: I = R.ideal(0)
sage: I.dimension()
2
```

---

3.1. Multivariate Polynomials and Polynomial Rings 379
ALGORITHM:
Uses Singular, unless the characteristic is too large.

**Note:** Requires computation of a Groebner basis, which can be a very expensive operation.

**elimination_ideal**(variables, algorithm=None, *args, **kwds)

Return the elimination ideal of this ideal with respect to the variables given in variables.

**INPUT:**
- variables – a list or tuple of variables in self.ring()
- algorithm - determines the algorithm to use, see below
  for available algorithms.

**ALGORITHMS:**
- 'libsingular:eliminate' – libSingular's eliminate command (default)
- 'giac:eliminate' – Giac’s eliminate command (if available)

If only a system is given - e.g. 'giac' - the default algorithm is chosen for that system.

**EXAMPLES:**

```python
sage: R.<x,y,t,s,z> = PolynomialRing(QQ,5)
sage: I = R * [x-t,y-t^2,z-t^3,s-x+y^3]
sage: J = I.elimination_ideal([t,s]); J
Ideal (y^2 - x*z, x*y - z, x^2 - y) of Multivariate Polynomial Ring in x, y, t, s, z over Rational Field
```

You can use Giac to compute the elimination ideal:

```python
sage: print("possible output from giac", flush=True); I.elimination_ideal([t,˓→s], algorithm="giac") == J
possible output...
True
```

The list of available Giac options is provided at `sage.libs.giac.groebner_basis()`.

**ALGORITHM:**
Uses Singular, or Giac (if available).

**Note:** Requires computation of a Groebner basis, which can be a very expensive operation.

**free_resolution**(args, **kwds)

Return a free resolution of self.

For input options, see `FreeResolution`.

**EXAMPLES:**

```python
sage: R.<x,y> = PolynomialRing(QQ)
sage: f = 2*x^2 + y
sage: g = y
sage: h = 2*f + g
```
sage: I = R.ideal([f,g,h])
sage: res = I.free_resolution()
sage: res
S^1 <-- S^2 <-- S^1 <-- 0
sage: ascii_art(res.chain_complex())
[-x^2]
[ y x^2] [ y]
0 <-- C_0 <-------- C_1 <------- C_2 <-- 0
sage: q = ZZ['q'].fraction_field().gen()
sage: R.<x,y,z> = q.parent()[]
sage: I = R.ideal([x^2+y^2+z^2, x*y*z^4])
sage: I.free_resolution()
Traceback (most recent call last):
  ... Not ImplementedError: the ring must be a polynomial ring using Singular

`genus()`
A decorator that creates a cached version of an instance method of a class.

**Note:** For proper behavior, the method must be a pure function (no side effects). Arguments to the method must be hashable or transformed into something hashable using `key` or they must define `sage.structure.sage_object.SageObject._cache_key()`.

**EXAMPLES:**

```
sage: class Foo():
    ....:     @cached_method
    ....:     def f(self, t, x=2):
    ....:         print('computing')
    ....:         return t**x
sage: a = Foo()
```

The example shows that the actual computation takes place only once, and that the result is identical for equivalent input:

```
sage: res = a.f(3, 2); res
computing
9
sage: a.f(t = 3, x = 2) is res
True
sage: a.f(3) is res
True
```

Note, however, that the `CachedMethod` is replaced by a `CachedMethodCaller` or `CachedMethodCallerNoArgs` as soon as it is bound to an instance or class:

```
sage: P.<a,b,c,d> = QQ[]
sage: I = P[[a,b]]
sage: type(I.__class__.gens)
<class 'sage.misc.cachefunc.CachedMethodCallerNoArgs'>
```
So, you would hardly ever see an instance of this class alive.

The parameter `key` can be used to pass a function which creates a custom cache key for inputs. In the following example, this parameter is used to ignore the `algorithm` keyword for caching:

```python
sage: class A():
    ....:     def _f_normalize(self, x, algorithm): return x
    ....:     @cached_method(key=_f_normalize)
    ....:     def f(self, x, algorithm='default'): return x
sage: a = A()
sage: a.f(1, algorithm="default") is a.f(1) is a.f(1, algorithm="algorithm")
True
```

The parameter `do_pickle` can be used to enable pickling of the cache. Usually the cache is not stored when pickling:

```python
sage: class A():
    ....:     @cached_method
    ....:     def f(self, x): return None
sage: import __main__
sage: A = __main__.A
sage: a = A()
sage: a.f(1)
sage: len(a.f.cache)
1
sage: b = loads(dumps(a))
sage: len(b.f.cache)
0
```

When `do_pickle` is set, the pickle contains the contents of the cache:

```python
sage: class A():
    ....:     @cached_method(do_pickle=True)
    ....:     def f(self, x): return None
sage: A = __main__.A
sage: a = A()
sage: a.f(1)
sage: len(a.f.cache)
1
sage: b = loads(dumps(a))
sage: len(b.f.cache)
1
```

Cached methods cannot be copied like usual methods, see github issue #12603. Copying them can lead to very surprising results:

```python
sage: class A:
    ....:     @cached_method
    ....:     def f(self):
    ....:         return 1
sage: class B:
    ....:     g=A.f
    ....:     def f(self):
    ....:         return 2
```

(continues on next page)
sage: b=B()
sage: b.f()
2
sage: b.g()
1
sage: b.f()
1

graded_free_resolution(*args, **kwds)

Return a graded free resolution of self.

For input options, see GradedFreeResolution.

EXAMPLES:

sage: R.<x,y> = PolynomialRing(QQ)
sage: f = 2*x^2 + y^2
sage: g = y^2
sage: h = 2*f + g
sage: I = R.ideal([f,g,h])
sage: I.graded_free_resolution(shifts=[1])
S(-1) <-- S(-3)⊕S(-3) <-- S(-5) <-- 0
sage: f = 2*x^2 + y
sage: g = y
sage: h = 2*f + g
sage: I = R.ideal([f,g,h])
sage: I.graded_free_resolution(degrees=[1,2])
S(0) <-- S(-2)⊕S(-2) <-- S(-4) <-- 0

hilbert_numerator(grading=None, algorithm='sage')

Return the Hilbert numerator of this ideal.

INPUT:

- grading – (optional) a list or tuple of integers
- algorithm – (default: 'sage') must be either 'sage' or 'singular'

Let \( I \) (which is self) be a homogeneous ideal and \( R = \bigoplus_d R_d \) (which is self.ring()) be a graded commutative algebra over a field \( K \). Then the Hilbert function is defined as \( H(d) = \dim_K R_d \) and the Hilbert series of \( I \) is defined as the formal power series \( HS(t) = \sum_{d=0}^{\infty} H(d)t^d \).

This power series can be expressed as \( HS(t) = Q(t)/(1 - t)^n \) where \( Q(t) \) is a polynomial over \( Z \) and \( n \) the number of variables in \( R \). This method returns \( Q(t) \), the numerator; hence the name, hilbert_numerator. An optional grading can be given, in which case the graded (or weighted) Hilbert numerator is given.

EXAMPLES:
hilbert_polynomial(algorithm='sage')

Return the Hilbert polynomial of this ideal.

INPUT:

• algorithm – (default: 'sage') must be either 'sage' or 'singular'

Let \( I \) (which is self) be a homogeneous ideal and \( R = \bigoplus_d R_d \) (which is self.ring()) be a graded commutative algebra over a field \( K \). The Hilbert polynomial is the unique polynomial \( HP(t) \) with rational coefficients such that \( HP(d) = \text{dim}_K R_d \) for all but finitely many positive integers \( d \).

EXAMPLES:

sage: P.<x,y,z> = PolynomialRing(QQ)
sage: I = Ideal([x^3*y^2 + 3*x^2*y^2*z + y^3*z^2 + z^5])
sage: I.hilbert_polynomial()
5*t - 5

Of course, the Hilbert polynomial of a zero-dimensional ideal is zero:

sage: J0 = Ideal([x^3*y^2 + 3*x^2*y^2*z + y^3*z^2 + z^5, y^3-2*x*z^2+x*y,x^4-x*y+y^2*z])
sage: J = P*[m.lm() for m in J0.groebner_basis()]
sage: J.dimension()
0
sage: J.hilbert_polynomial()
0

It is possible to request a computation using the Singular library:

sage: I.hilbert_polynomial(algorithm = 'singular') == I.hilbert_polynomial()
True
sage: J.hilbert_polynomial(algorithm = 'singular') == J.hilbert_polynomial()
True

Here is a bigger examples:

sage: n = 4; m = 11; P = PolynomialRing(QQ, n * m, "x"); x = P.gens(); M = Matrix(n, x)
sage: Minors = P.ideal(M.minors(2))
sage: hp = Minors.hilbert_polynomial(); hp
1/21772800*t^13 + 61/21772800*t^12 + 1661/21772800*t^11
+ 26681/21772800*t^10 + 93841/7257600*t^9 + 685421/7257600*t^8
+ 1524809/3110400*t^7 + 39780323/21772800*t^6 + 6638071/1360800*t^5

(continues on next page)
Because Singular uses 32-bit integers, the above example would fail with Singular. We don’t test it here, as it has a side-effect on other tests that is not understood yet (see github issue #26300):

```sage
sage: Minors.hilbert_polynomial(algorithm = 'singular') # not tested
Traceback (most recent call last):
  ... 
RuntimeError: error in Singular function call 'hilbPoly':
int overflow in hilb 1
error occurred in or before poly.lib::hilbPoly line 58: ` intvec v=hilb(I,2);`
expected intvec-expression. type 'help intvec';
```

Note that in this example, the Hilbert polynomial gives the coefficients of the Hilbert-Poincaré series in all degrees:

```sage
sage: P.<x,y,z> = PolynomialRing(QQ, 't', default_prec = 50)
sage: hs = Minors.hilbert_series()
sage: list(P(hs.numerator()) / P(hs.denominator())) == [hp(t = k) for k in range(50)]
True
```

**hilbert_series** *(grading=None, algorithm='sage')*

Return the Hilbert series of this ideal.

**INPUT:**

- **grading** – (optional) a list or tuple of integers
- **algorithm** – (default: 'sage') must be either 'sage' or 'singular'

Let $I$ (which is self) be a homogeneous ideal and $R = \bigoplus_d R_d$ (which is self.ring()) be a graded commutative algebra over a field $K$. Then the Hilbert function is defined as $H(d) = \dim_K R_d$ and the Hilbert series of $I$ is defined as the formal power series $HS(t) = \sum_{d=0}^{\infty} H(d)t^d$.

This power series can be expressed as $HS(t) = Q(t)/(1 - t)^n$ where $Q(t)$ is a polynomial over $\mathbb{Z}$ and $n$ the number of variables in $R$. This method returns $Q(t)/(1 - t)^n$, normalised so that the leading monomial of the numerator is positive.

An optional grading can be given, in which case the graded (or weighted) Hilbert series is given.

**EXAMPLES:**

```sage
sage: P.<x,y,z> = PolynomialRing(QQ)
sage: I = Ideal([x^3*y^2 + 3*x^2*y^2*z + y^3*z^2 + z^5])
sage: I.hilbert_series()
(t^4 + t^3 + t^2 + t + 1)/(t^2 - 2*t + 1)
sage: R.<a,b> = PolynomialRing(QQ)
sage: J = R.ideal([a^2*b,a*b^2])
sage: J.hilbert_series()
(t^3 - t^2 - t - 1)/(t - 1)
sage: J.hilbert_series(grading=(10,3))
(t^25 + t^24 + t^23 + t^22 + t^15 - t^14 - t^13 + t^12 - t^11 - t^10 - t^9 - t^8 - t^7 - t^6 - t^5 - t^4 - t^3 - t^2 - t - 1)/(t^12 + t^11 + t^10 - t^2 - t - 1)
```

(continues on next page)
integral_closure(p=0, r=True, singular='singular_default')

Let $I = \text{self}$.

Return the integral closure of $I, \ldots, I^p$, where $sI$ is an ideal in the polynomial ring $R = k[x(1), \ldots, x(n)]$. If $p$ is not given, or $p = 0$, compute the closure of all powers up to the maximum degree in $t$ occurring in the closure of $R[I^t]$ (so this is the last power whose closure is not just the sum/product of the smaller). If $r$ is given and $r$ is True, $I$.integral_closure() starts with a check whether $I$ is already a radical ideal.

**INPUT:**

- $p$ - powers of $I$ (default: 0)
- $r$ - check whether self is a radical ideal first (default: True)

**EXAMPLES:**

```python
sage: R.<x,y> = QQ[]
sage: I = ideal([x^2,x*y^4,y^5])
sage: I.integral_closure()
[x^2, x*y^4, y^5, x*y^3]
```

**ALGORITHM:**

Uses libSINGULAR.

interreduced_basis()

If this ideal is spanned by $(f_1, \ldots, f_n)$ this method returns $(g_1, \ldots, g_s)$ such that:

- $(f_1, \ldots, f_n) = (g_1, \ldots, g_s)$
- $LT(g_i)! = LT(g_j)$ for all $i! = j$
- $LT(g_i)$ does not divide $m$ for all monomials $m$ of \( \{g_1, \ldots, g_i-1, g_i+1, \ldots, g_s\} \)
- $LC(g_i) == 1$ for all $i$ if the coefficient ring is a field.

**EXAMPLES:**

```python
sage: R.<x,y,z> = PolynomialRing(QQ)
sage: I = Ideal([z*x+y^3,z+y^3,z+x*y])
sage: I.interreduced_basis()
[y^3 + z, x*y + z, x*z - z]
```

Note that tail reduction for local orderings is not well-defined:

```python
sage: R.<x,y,z> = PolynomialRing(QQ,order='negdegrevlex')
sage: I = Ideal([z*x+y^3,z+y^3,z+x*y])
sage: I.interreduced_basis()
[z + x*y, x*y - y^3, x^2*y - y^3]
```

A fixed error with nonstandard base fields:
sage: R.<t> = QQ['t']
sage: K.<x, y> = R.fraction_field()['x, y']
sage: I = t*x*K
sage: I.interreduced_basis()
[x]

The interreduced basis of 0 is 0:

sage: P.<x, y, z> = GF(2)[]
sage: Ideal(P(0)).interreduced_basis()
[0]

**ALGORITHM:**

Uses Singular’s interred command or `sage.rings.polynomial.toy_buchberger.inter_reduction()` if conversion to Singular fails.

**intersection(** `*others` **)**

Return the intersection of the arguments with this ideal.

**EXAMPLES:**

sage: R.<x, y> = PolynomialRing(QQ, 2, order='lex')
sage: I = x^R
sage: J = y^R
sage: I.intersection(J)
Ideal (x*y) of Multivariate Polynomial Ring in x, y over Rational Field

The following simple example illustrates that the product need not equal the intersection.

sage: I = (x^2, y)^R
sage: J = (y^2, x)^R
sage: K = I.intersection(J); K
Ideal (y^2, x*y, x^2) of Multivariate Polynomial Ring in x, y over Rational Field
sage: I*J
Ideal (x^2*y^2, x^3, y^3, x*y) of Multivariate Polynomial Ring in x, y over Rational Field
sage: I*J == K
False

Intersection of several ideals:

sage: R.<x, y, z> = PolynomialRing(QQ, 3, order='lex')
sage: I1 = x^R
sage: I2 = y^R
sage: I3 = (x, y)^R
sage: I4 = (x^2 + x*y*z, y^2 - z^3*y, z^3 + y^5*x*z)^R
sage: I1.intersection(I2, I3, I4).groebner_basis()
[x^2*y + x*y*z^4, x*y^2 - x*y*z^3, x*y*z^20 - x*y*z^3]

The ideals must share the same ring:

sage: R2.<x, y> = PolynomialRing(QQ, 2, order='lex')
sage: R3.<x, y, z> = PolynomialRing(QQ, 3, order='lex')
sage: I2 = x*R2
sage: I3 = x*R3
sage: I2.intersection(I3)
Traceback (most recent call last):
  ...  
TypeError: Intersection is only available for ideals of the same ring.

**is_prime(**kwds**)

Return True if this ideal is prime.

**INPUT:**

- keyword arguments are passed on to complete_primary_decomposition; in this way you can specify the algorithm to use.

**EXAMPLES:**

```sage
sage: R.<x, y> = PolynomialRing(QQ, 2)
sage: I = (x^2 - y^2 - 1)*R
sage: I.is_prime()
True
sage: (I^2).is_prime()
False
sage: J = (x^2 - y^2)*R
sage: J.is_prime()
False
sage: (J^3).is_prime()
False
sage: (I * J).is_prime()
False
```

The following is github issue #5982. Note that the quotient ring is not recognized as being a field at this time, so the fraction field is not the quotient ring itself:

```sage
sage: Q = R.quotient(I); Q
Quotient of Multivariate Polynomial Ring in x, y over Rational Field by the ideal (x^2 - y^2 - 1)
sage: Q.fraction_field()
Fraction Field of Quotient of Multivariate Polynomial Ring in x, y over Rational Field by the ideal (x^2 - y^2 - 1)
```

**minimal_associated_primes()**

**OUTPUT:**

- list - a list of prime ideals

**EXAMPLES:**

```sage
sage: R.<x,y,z> = PolynomialRing(QQ, 3, 'xyz')
sage: p = z^2 + 1; q = z^3 + 2
sage: I = (p*q^2, y-z^2)*R
sage: sorted(I.minimal_associated_primes(), key=str)
[Ideal (z^2 + 1, -z^2 + y) of Multivariate Polynomial Ring in x, y, z over QQ]
```
ALGORITHM:

Uses Singular.

normal_basis(degree=None, algorithm='libsingular', singular='singular_default')

Return a vector space basis of the quotient ring of this ideal.

INPUT:

• degree – integer (default: None)

• algorithm – string (default: "libsingular"); if not the default, this will use the kbase() or weightKB() command from Singular

• singular – the singular interpreter to use when algorithm is not "libsingular" (default: the default instance)

OUTPUT:

Monomials in the basis. If degree is given, only the monomials of the given degree are returned.

EXAMPLES:

sage: R.<x,y,z> = PolynomialRing(QQ)

sage: I = R.ideal(x^2+y^2+z^2-4, x^2+2*y^2-5, x*z-1)

sage: I.normal_basis()
y*z^2, z^2, y*z, z, x*y, y, x, 1

sage: I.normal_basis(algorithm='singular')
y*z^2, z^2, y*z, z, x*y, y, x, 1

The result can be restricted to monomials of a chosen degree, which is particularly useful when the quotient ring is not finite-dimensional as a vector space.

sage: J = R.ideal(x^2+y^2+z^2-4, x^2+2*y^2-5)

sage: J.dimension()
1
sage: [J.normal_basis(d) for d in (0..3)]
[[1], [z, y, x], [z^2, y*z, x*z, x*y], [z^3, y^2*z^2, x*y*z^2, x^2*y*z]]

In case of a polynomial ring with a weighted term order, the degree of the monomials is taken with respect to the weights.

sage: T = TermOrder('wdegrevlex', (1, 2, 3))

sage: R.<x,y,z> = PolynomialRing(QQ, order=T)

sage: B = R.ideal(x*y^2 + x^5, z*y + x^3*y).normal_basis(9); B
[x^2*y^2*z, x^3*z^2, x*y*z^2, z^3]

sage: all(f.degree() == 9 for f in B)
True

If you somehow manage to install surf, perhaps you can use this function to implicitly plot the real zero locus of this ideal (if principal).
INPUT:

- self - must be a principal ideal in 2 or 3 vars over $\mathbb{Q}$.

EXAMPLES:

Implicit plotting in 2-d:

```
sage: R.<x,y> = PolynomialRing(QQ,2)
sage: I = R.ideal([y^3 - x^2])
sage: I.plot()         # cusp
Graphics object consisting of 1 graphics primitive
sage: I = R.ideal([y^2 - x^2 - 1])
sage: I.plot()         # hyperbola
Graphics object consisting of 1 graphics primitive
sage: I = R.ideal([y^2 + x^2*(1/4) - 1])
sage: I.plot()         # ellipse
Graphics object consisting of 1 graphics primitive
sage: I = R.ideal([y^2-(x^2-1)*(x-2)])
sage: I.plot()         # elliptic curve
Graphics object consisting of 1 graphics primitive
```

Implicit plotting in 3-d:

```
sage: R.<x,y,z> = PolynomialRing(QQ,3)
sage: I = R.ideal([y^2 + x^2*(1/4) - z])
sage: I.plot()         # a cone; optional - surf
sage: I = R.ideal([y^2 + z^2*(1/4) - x])
sage: I.plot()         # same code, from a different angle; optional - surf
sage: I = R.ideal([x^2*y^2+x^2*z^2+y^2*z^2-16*x*y*z])
sage: I.plot()         # Steiner surface; optional - surf
```

AUTHORS:

- David Joyner (2006-02-12)

**primary_decomposition**(algorithm='sy')

Return a list of primary ideals such that their intersection is self.

An ideal $Q$ is called primary if it is a proper ideal of the ring $R$, and if whenever $ab \in Q$ and $a \notin Q$, then $b^n \in Q$ for some $n \in \mathbb{Z}$.

If $Q$ is a primary ideal of the ring $R$, then the radical ideal $P$ of $Q$ (i.e. the ideal consisting of all $a \in R$ with $a^n$ in $Q$ for some $n \in \mathbb{Z}$), is called the associated prime of $Q$.

If $I$ is a proper ideal of a Noetherian ring $R$, then there exists a finite collection of primary ideals $Q_i$ such that the following hold:

- the intersection of the $Q_i$ is $I$;
- none of the $Q_i$ contains the intersection of the others;
- the associated prime ideals of the $Q_i$ are pairwise distinct.

INPUT:

- algorithm – string:
  - 'sy' – (default) use the Shimoyama-Yokoyama algorithm
  - 'gtz' – use the Gianni-Trager-Zacharias algorithm
OUTPUT:

• a list of primary ideals $Q_i$ forming a primary decomposition of `self`.

EXAMPLES:

```python
sage: R.<x,y,z> = PolynomialRing(QQ, 3, order='lex')
sage: p = z^2 + 1; q = z^3 + 2
sage: I = (p*q^2, y-z^2)*R
sage: pd = I.primary_decomposition(); sorted(pd, key=str)
[Ideal (z^2 + 1, y + 1) of Multivariate Polynomial Ring in x, y, z over Rational Field,
  Ideal (z^6 + 4*z^3 + 4, y - z^2) of Multivariate Polynomial Ring in x, y, z over Rational Field]
sage: from functools import reduce
sage: reduce(lambda Qi,Qj: Qi.intersection(Qj), pd) == I
True
```

ALGORITHM:

Uses Singular.

REFERENCES:


`primary_decomposition_complete()`

A decorator that creates a cached version of an instance method of a class.

Note: For proper behavior, the method must be a pure function (no side effects). Arguments to the method must be hashable or transformed into something hashable using `key` or they must define `sage.structure.sage_object.SageObject._cache_key()`.

EXAMPLES:

```python
sage: class Foo():
    ....: @cached_method
    ....: def f(self, t, x=2):
    ....:     print('computing')
    ....:     return t**x
sage: a = Foo()
```

The example shows that the actual computation takes place only once, and that the result is identical for equivalent input:

```python
sage: res = a.f(3, 2); res
computing
9
sage: a.f(t = 3, x = 2) is res
True
sage: a.f(3) is res
True
```
Note, however, that the `CachedMethod` is replaced by a `CachedMethodCaller` or `CachedMethodCallerNoArgs` as soon as it is bound to an instance or class:

```
sage: P.<a,b,c,d> = QQ[]
sage: I = P*[a,b]
sage: type(I.__class__.gens)
<class 'sage.misc.cachefunc.CachedMethodCallerNoArgs'>
```

So, you would hardly ever see an instance of this class alive.

The parameter `key` can be used to pass a function which creates a custom cache key for inputs. In the following example, this parameter is used to ignore the `algorithm` keyword for caching:

```
sage: class A():
    ....:    def _f_normalize(self, x, algorithm): return x
    ....:    @cached_method(key=_f_normalize)
    ....:    def f(self, x, algorithm='default'): return x
sage: a = A()
sage: a.f(1, algorithm='default') is a.f(1) is a.f(1, algorithm='algorithm')
True
```

The parameter `do_pickle` can be used to enable pickling of the cache. Usually the cache is not stored when pickling:

```
sage: class A():
    ....:    @cached_method
    ....:    def f(self, x):
    ....:        return None
sage: import __main__
sage: __main__.A = A
sage: a = A()
sage: a.f(1)
sage: len(a.f.cache)
1
sage: b = loads(dumps(a))
sage: len(b.f.cache)
0
```

When `do_pickle` is set, the pickle contains the contents of the cache:

```
sage: class A():
    ....:    @cached_method(do_pickle=True)
    ....:    def f(self, x):
    ....:        return None
sage: __main__.A = A
sage: a = A()
sage: a.f(1)
sage: len(a.f.cache)
1
sage: b = loads(dumps(a))
sage: len(b.f.cache)
1
```

Cached methods cannot be copied like usual methods, see github issue #12603. Copying them can lead to very surprising results:
```python
sage: class A:
....:     @cached_method
....:     def f(self):
....:         return 1
sage: class B:
....:     g = A.f
....:     def f(self):
....:         return 2
sage: b = B()
```

### quotient(J)

Given ideals $I = \text{self}$ and $J$ in the same polynomial ring $P$, return the ideal quotient of $I$ by $J$ consisting of the polynomials $a$ of $P$ such that \(\{aJ \subset I\}\).

This is also referred to as the colon ideal ($I:J$).

**INPUT:**

- $J$ - multivariate polynomial ideal

**EXAMPLES:**

```python
sage: R.<x,y,z> = PolynomialRing(GF(181),3)
sage: I = Ideal([x^2+x*y*z,y^2-z^3*y,z^3+y^5*x*z])
sage: J = Ideal([x])
sage: Q = I.quotient(J)
sage: y*z + x in I
False
sage: x in J
True
sage: x * (y*z + x) in I
True
```

### radical()

The radical of this ideal.

**EXAMPLES:**

This is an obviously not radical ideal:

```python
sage: R.<x,y,z> = PolynomialRing(QQ, 3)
sage: I = (x^2, y^3, (x*y*z)^4 + y^3 + 10*x^2)*R
sage: I.radical()
Ideal (y, x) of Multivariate Polynomial Ring in x, y, z over Rational Field
```

That the radical is correct is clear from the Groebner basis.

```python
sage: I.groebner_basis()
[y^3, x^2]
```

### 3.1. Multivariate Polynomials and Polynomial Rings
This is the example from the Singular manual:

```
sage: p = z^2 + 1; q = z^3 + 2
sage: I = (p*q^2, y-z^2)*R
sage: I.radical()
Ideal (z^2 - y, y^2*z + y*z + 2*y + 2) of Multivariate Polynomial Ring in x, y, z over Rational Field
```

**Note:** From the Singular manual: A combination of the algorithms of Krick/Logar and Kemper is used. Works also in positive characteristic (Kemper's algorithm).

```
sage: R.<x,y,z> = PolynomialRing(GF(37), 3)
sage: p = z^2 + 1; q = z^3 + 2
sage: I = (p*q^2, y - z^2)*R
sage: I.radical()
Ideal (z^2 - y, y^2*z + y*z + 2*y + 2) of Multivariate Polynomial Ring in x, y, z over Finite Field of size 37
```

**saturation**(other)

Return the saturation (and saturation exponent) of the ideal `self` with respect to the ideal `other`

**INPUT:**

- `other` – another ideal in the same ring

**OUTPUT:**

- a pair (ideal, integer)

**EXAMPLES:**

```
sage: R.<x, y, z> = QQ[]
sage: I = R.ideal(x^5*z^3, x*y*z, y*z^4)
sage: J = R.ideal(z)
sage: I.saturation(J)
(Ideal (y, x^5) of Multivariate Polynomial Ring in x, y, z over Rational Field, 4)
```

**syzygy_module()**

Computes the first syzygy (i.e., the module of relations of the given generators) of the ideal.

**EXAMPLES:**

```
sage: R.<x, y> = PolynomialRing(QQ)
sage: f = 2*x^2 + y
sage: g = y
sage: h = 2*f + g
sage: I = Ideal([f, g, h])
sage: M = I.syzygy_module(); M
[-2 -1 1]
[ -y 2*x^2 + y 0]
sage: G = vector(I.gens())
sage: M*G
(0, 0)
```
ALGORITHM:
Uses Singular’s syz command.

\texttt{transformed\_basis(algorithm='gwalk', other\_ring=None, singular='singular\_default')}

Return a lex or other\_ring Groebner Basis for this ideal.

INPUT:
\begin{itemize}
  \item \texttt{algorithm} - see below for options.
  \item \texttt{other\_ring} - only valid for algorithm ‘fglm’, if provided conversion will be performed to this ring. Otherwise a lex Groebner basis will be returned.
\end{itemize}

ALGORITHMS:
\begin{itemize}
  \item \texttt{fglm} - FGLM algorithm. The input ideal must be given with a reduced Groebner Basis of a zero-dimensional ideal
  \item \texttt{gwalk} - Groebner Walk algorithm (default)
  \item \texttt{awalk1} - ‘first alternative’ algorithm
  \item \texttt{awalk2} - ‘second alternative’ algorithm
  \item \texttt{twalk} - Tran algorithm
  \item \texttt{fwalk} - Fractal Walk algorithm
\end{itemize}

EXAMPLES:
\begin{verbatim}
sage: R.<x,y,z> = PolynomialRing(QQ,3)
sage: I = Ideal([y^3+x^2, x^2*y+x^2, x^3-x^2, z^4-x^2-y])
sage: I = Ideal(I.groebner_basis())
sage: S.<z,x,y> = PolynomialRing(QQ,3,order='lex')
sage: J = Ideal(I.transformed_basis('fglm',S))
sage: J Ideal (z^4 + y^3 - y, x^2 + y^3, x*y^3 - y^3, y^4 + y^3)
of Multivariate Polynomial Ring in z, x, y over Rational Field
\end{verbatim}

\begin{verbatim}
sage: R.<z,y,x>=PolynomialRing(GF(32003),3,order='lex')
sage: I=Ideal([y^3+x*y*z+y^2*z+x^2*z^3,3+x*y+x^2*y+y^2*z])
sage: I.transformed_basis('gwalk')
[z*y^2 + y*x^2 + y*x + 3,  
z*x + 8297*y^8*x^2 + 8297*y^8*x + 3556*y^7 - 8297*y^6*x^4 + 15409*y^6*x^3 - 8297*y^6*x^2  
- 8297*y^5*x^5 + 15409*y^5*x^4 - 8297*y^5*x^3 + 3556*y^5*x^2 + 3556*y^5*x + 3556*y^4*x^3  
+ 3556*y^4*x^2 - 10668*y^4 - 10668*y^3*x - 8297*y^2*x^9 - 1185*y^2*x^8  
- 10666*y^2*x^6 - 10666*y^2*x^5 - 14223*y*x^4  
+ x^5 + 2*x^4 + x^3,  
y^9 - y^7*x^2 - y^7*x - y^6*x^3 - y^6*x^2 - 3*y^6 - 3*y^5*x - y^3*x^7 - 3*y^2 - 3*y^x^6  
- 3*y^3*x^5 - y^3*x^4 - 9*y^2*x^5 - 18*y^2*x^4 - 9*y^2*x^3 - 27*y*x^3 - 27*y*x^2  
- 2 - 27*x]
\end{verbatim}

ALGORITHM:
Uses Singular.

3.1. Multivariate Polynomials and Polynomial Rings 395
triangular_decomposition(algorithm=None, singular='singular_default')

Decompose zero-dimensional ideal self into triangular sets.

This requires that the given basis is reduced w.r.t. to the lexicographical monomial ordering. If the basis of self does not have this property, the required Groebner basis is computed implicitly.

INPUT:
- algorithm - string or None (default: None)

ALGORITHMS:
- singular:triangL - decomposition of self into triangular systems (Lazard).
- singular:triangLfak - decomp. of self into tri. systems plus factorization.
- singular:triangM - decomposition of self into triangular systems (Moeller).

OUTPUT: a list \( T \) of lists \( t \) such that the variety of \( \text{self} \) is the union of the varieties of \( t \) in \( L \) and each \( t \) is in triangular form.

EXAMPLES:

\[
\begin{align*}
\text{sage: } & P.<e,d,c,b,a> = \text{PolynomialRing}(\text{QQ},5,\text{order='lex'}) \\
\text{sage: } & I = \text{sage.rings.ideal.Cyclic}(P) \\
\text{sage: } & GB = \text{Ideal}(I.\text{groebner\_basis}'\text{libsingular:stdfglm}') \\
\text{sage: } & GB.\text{triangular\_decomposition}'\text{singual:triangLfak}') \\
\text{[Ideal } (a - 1, b - 1, c - 1, d^2 + 3d + 1, e + d + 3) \text{ of Multivariate}_e, d, c, b, a \text{ over Rational Field,} \\
\text{Ideal } (a - 1, b - 1, c^2 + 3c + 1, d + c + 3, e - 1) \text{ of Multivariate}_e, d, c, b, a \text{ over Rational Field,} \\
\text{Ideal } (a - 1, b^2 + 3b + 1, c + b + 3, d - 1, e - 1) \text{ of Multivariate}_e, d, c, b, a \text{ over Rational Field,} \\
\text{Ideal } (a - 1, b^4 + b^3 + b^2 + b + 1, -c + b^2, -d + b^3, e + b^3 + b^2 + b + 1) \text{ of Multivariate}_e, d, c, b, a \text{ over Rational Field,} \\
\text{Ideal } (a^2 + 3a + 1, b - 1, c - 1, d + 3a, e - a) \text{ of Multivariate}_e, d, c, b, a \text{ over Rational Field,} \\
\text{Ideal } (a^4 + a^3 + a^2 + a + 1, b - 1, c + a^3 + a^2 + a + 1, -d + a^3, -e + a^2) \text{ of Multivariate}_e, d, c, b, a \text{ over Rational Field,} \\
\text{Ideal } (a^4 + a^3 + a^2 + a + 1, b - a, c - a, d^2 + 3d^2a + a^2e, d + e + 3a) \text{ of Multivariate}_e, d, c, b, a \text{ over Rational Field,} \\
\text{Ideal } (a^4 + a^3 + a^2 + a + 1, b - a, c^2 + 3c^3a + a^2d, d + c + 3a, e - a) \text{ of Multivariate}_e, d, c, b, a \text{ over Rational Field,} \\
\end{align*}
\]

(continues on next page)
→Polynomial Ring in e, d, c, b, a over Rational Field

sage: R.<x1,x2> = PolynomialRing(QQ, 2, order='lex')
sage: f1 = 1/2*((x1^2 + 2*x1 - 4)*x2^2 + 2*(x1^2 + x1)*x2 + x1^2)
sage: f2 = 1/2*((x1^2 + 2*x1 + 1)*x2^2 + 2*(x1^2 + x1)*x2 - 4*x1^2)
sage: I = Ideal(f1,f2)
sage: I.triangular_decomposition()

[Ideal (x2, x1^2) of Multivariate Polynomial Ring in x1, x2 over Rational Field, Ideal (x2, x1^2) of Multivariate Polynomial Ring in x1, x2 over Rational Field, Ideal (x2, x1^2) of Multivariate Polynomial Ring in x1, x2 over Rational Field, Ideal (x2^4 + 4*x2^3 - 6*x2^2 - 20*x2 + 5, 8*x1 - x2^3 + x2^2 + 13*x2 - 5) of...

variety(ring=None)

Return the variety of this ideal.

Given a zero-dimensional ideal \( I \) (== self) of a polynomial ring \( P \) whose order is lexicographic, return the variety of \( I \) as a list of dictionaries with (variable, value) pairs. By default, the variety of the ideal over its coefficient field \( K \) is returned; ring can be specified to find the variety over a different ring.

These dictionaries have cardinality equal to the number of variables in \( P \) and represent assignments of values to these variables such that all polynomials in \( I \) vanish.

If ring is specified, then a triangular decomposition of self is found over the original coefficient field \( K \); then the triangular systems are solved using root-finding over ring. This is particularly useful when \( K \) is QQ (to allow fast symbolic computation of the triangular decomposition) and ring is RR, AA, CC, or QQbar (to compute the whole real or complex variety of the ideal).

Note that with ring=RR or CC, computation is done numerically and potentially inaccurately; in particular, the number of points in the real variety may be miscomputed. With ring=AA or QQbar, computation is done exactly (which may be much slower, of course).

INPUT:

- ring - return roots in the ring instead of the base ring of this ideal (default: None)
- algorithm - algorithm or implementation to use; see below for supported values
- proof - return a provably correct result (default: True)

EXAMPLES:

sage: K.<w> = GF(27) # this example is from the MAGMA handbook
sage: P.<x, y> = PolynomialRing(K, 2, order='lex')
sage: I = Ideal([x^8 + y + 2, y^6 + x*y^5 + x^2 ])
sage: I = Ideal(I.groebner_basis()); I
Ideal (x - y^47 - y^45 + y^44 - y^43 + y^41 - y^39 - y^38 - y^37 - y^36 + y^35 - y^34 + y^33 + y^32 - y^31 + y^30 + y^28 + y^27 + y^26 + y^25 - y^23 + y^22 + y^21 - y^19 - y^18 - y^16 + y^15 + y^13 + y^12 - y^10 + y^9 + y^8 + y^7 - y^6 + y^4 + y^3 + y^2 + y - 1, y^48 + y^41 - y^40 + y^37 - y^36 - y^33 + y^32 - y^29 + y^28 - y^25 + y^24 + y^2 + y + 1) of Multivariate Polynomial Ring in x, y over Finite Field in w of size 3^3
sage: V = I.variety();
However, we only account for solutions in the ground field and not in the algebraic closure:

\[
\text{sage: I.vector_space_dimension()}
\]

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Here we compute the points of intersection of a hyperbola and a circle, in several fields:

\[
\text{sage: K.<x, y> = PolynomialRing(QQ, 2, order='lex')} \\
\text{sage: I = Ideal([x*y - 1, (x-2)^2 + (y-1)^2 - 1])} \\
\text{sage: I = Ideal(I.groebner_basis()); I} \\
\text{Ideal (x + y^3 - 2*y^2 + 4*y - 4, y^4 - 2*y^3 + 4*y^2 - 4*y + 1)} \\
\text{of Multivariate Polynomial Ring in x, y over Rational Field}
\]

These two curves have one rational intersection:

\[
\text{sage: I.variety()}
\]

\[
\{(y: 1, x: 1)\}
\]

There are two real intersections:

\[
\text{sage: sorted(I.variety(ring=RR), key=str)}
\]

\[
\{(y: 0.361103080528647, x: 2.76929235423863), \\
(y: 1.00000000000000, x: 1.00000000000000)\}
\]

and a total of four intersections:

\[
\text{sage: sorted(I.variety(ring=CC), key=str)}
\]

\[
\{(y: 0.31944845973567... + 1.6331702409152...*I, \\
x: 0.11535382288068... - 0.58974280502220...*I), \\
(y: 0.31944845973567... - 1.6331702409152...*I, \\
x: 0.11535382288068... + 0.58974280502220...*I), \\
(y: 0.36110308052864..., x: 2.7692923542386...), \\
(y: 1.00000000000000, x: 1.00000000000000)\}
\]

\[
\text{sage: sorted(I.variety(ring=QQbar), key=str)}
\]

\[
\{(y: 0.3194484597356763? + 1.633170240915238?*I, \\
x: 0.11535382288068429? - 0.5897428050222055?*I), \\
(y: 0.3194484597356763? - 1.633170240915238?*I, \\
x: 0.11535382288068429? + 0.5897428050222055?*I), \\
(y: 0.3611030805286474?, x: 2.769292354238632?), \\
(y: 1, x: 1)\}
\]

We can also use the optional package msolve to compute the variety. See msolve for more information.
Computation over floating point numbers may compute only a partial solution, or even none at all. Notice that x values are missing from the following variety:

```
sage: R.<x,y> = CC[]
sage: I = ideal([x^2+y^2-1,x*y-1])
sage: sorted(I.variety(), key=str)
verbose 0 (...: multi_polynomial_ideal.py, variety) Warning: computations in
→ the complex field are inexact; variety may be computed partially or
→ incorrectly.
verbose 0 (...: multi_polynomial_ideal.py, variety) Warning: falling back to
→ very slow toy implementation.
[[y: -0.86602540378443... + 0.500000000000000*I],
 {y: -0.86602540378443... - 0.500000000000000*I},
 {y: 0.86602540378443... + 0.500000000000000*I},
 {y: 0.86602540378443... - 0.500000000000000*I]}
```

This is due to precision error, which causes the computation of an intermediate Groebner basis to fail. If the ground field’s characteristic is too large for Singular, we resort to a toy implementation:

```
sage: R.<x,y> = PolynomialRing(GF(2147483659^3),order='lex')
sage: I = ideal([x^3-2*y^2,3*x+y^4])
sage: I.variety()
verbose 0 (...: multi_polynomial_ideal.py, groebner_basis) Warning: falling back to very slow toy implementation.
verbose 0 (...: multi_polynomial_ideal.py, dimension) Warning: falling back to very slow toy implementation.
verbose 0 (...: multi_polynomial_ideal.py, variety) Warning: falling back to very slow toy implementation.
[[y: 0, x: 0]]
```

The dictionary expressing the variety will be indexed by generators of the polynomial ring after changing to the target field. But the mapping will also accept generators of the original ring, or even generator names as strings, when provided as keys:

```
sage: K.<x,y> = QQ[]
sage: I = ideal([x^2+2*y-5,x+y+3])
sage: v = I.variety(AA)[0]; v[x], v[y]
(4.464101615137755?, -7.464101615137755?)
sage: list(v)[0].parent()
Multivariate Polynomial Ring in x, y over Algebraic Real Field
sage: v[x]
4.464101615137755?
sage: v[y]
-7.464101615137755?
```

msolve also works over finite fields:

```
sage: R.<x, y> = PolynomialRing(GF(536870909), 2, order='lex')
sage: I = Ideal([ x^2 - 1, y^2 - 1 ])```

(continues on next page)
sage: sorted(I.variety(algorithm='msolve', proof=False), key=str) # optional - msolve
[[x: 1, y: 1],
 {x: 1, y: 536870908},
 {x: 536870908, y: 1},
 {x: 536870908, y: 536870908}]

but may fail in small characteristic, especially with ideals of high degree with respect to the characteristic:

sage: R.<x, y> = PolynomialRing(GF(3), 2, order='lex')
sage: I = Ideal([ x^2 - 1, y^2 - 1 ])
sage: I.variety(algorithm='msolve', proof=False) # optional - msolve
Traceback (most recent call last):
... NotImplementedError: characteristic 3 too small

ALGORITHM:

• With algorithm = "triangular_decomposition" (default), uses triangular decomposition, via Singular if possible, falling back on a toy implementation otherwise.

• With algorithm = "msolve", uses the optional package msolve. Note that msolve uses heuristics and therefore requires setting the proof flag to False. See msolve for more information.

vector_space_dimension()

Return the vector space dimension of the ring modulo this ideal. If the ideal is not zero-dimensional, a TypeError is raised.

ALGORITHM:
Uses Singular.

EXAMPLES:

sage: R.<u,v> = PolynomialRing(QQ)
sage: g = u^4 + v^4 + u^3 + v^3
sage: I = ideal(g) + ideal(g.gradient())
sage: I.dimension()
0
sage: I.vector_space_dimension()
4

When the ideal is not zero-dimensional, we return infinity:

sage: R.<x,y> = PolynomialRing(QQ)
sage: I = R.ideal(x)
sage: I.dimension()
1
sage: I.vector_space_dimension()
+Infinity

Due to integer overflow, the result is correct only modulo $2^{32}$, see github issue #8586:

sage: P.<x,y,z> = PolynomialRing(GF(32003),3)
sage: sage.rings.ideal.FieldIdeal(P).vector_space_dimension() # known bug
32777216864027
class sage.rings.polynomial.multi_polynomial_ideal.NCPolynomialIdeal(ring, gens, coerce=True, side='left')

Bases: MPolynomialIdeal_singular_repr, Ideal_nc

Creates a non-commutative polynomial ideal.

INPUT:

- **ring** - the g-algebra to which this ideal belongs
- **gens** - the generators of this ideal
- **coerce** (optional - default True) - generators are coerced into the ring before creating the ideal
- **side** - optional string, either “left” (default) or “twosided”; defines whether this ideal is left of two-sided.

EXAMPLES:

```python
sage: A.<x,y,z> = FreeAlgebra(QQ, 3)
sage: H = A.g_algebra({y*x:x*y-z, z*x:x*z+2*x, z*y:y*z-2*y})
sage: H.inject_variables()
Defining x, y, z
sage: I = H.ideal([y^2, x^2, z^2-H.one()],coerce=False) # indirect doctest
sage: I
#random
Left Ideal (y^2, x^2, z^2 - 1) of Noncommutative Multivariate Polynomial
Ring in x, y, z over Rational Field, nc-relations: {z*x: x*z + 2*x, z*y: y*z - 2*y, y*x: x*y - z}
sage: sorted(I.gens(),key=str)
[x^2, y^2, z^2 - 1]
sage: H.ideal([y^2, x^2, z^2-H.one()], side="twosided")
Twosided Ideal (y^2, x^2, z^2 - 1) of Noncommutative Multivariate Polynomial
Ring in x, y, z over Rational Field, nc-relations: {z*x: x*z + 2*x, z*y: y*z - 2*y, y*x: x*y - z}
sage: sorted(H.ideal([y^2, x^2, z^2-H.one()], side="twosided").gens(),key=str)
[x^2, y^2, z^2 - 1]
sage: H.ideal([y^2, x^2, z^2-H.one()], side="right")
Traceback (most recent call last):
... ValueError: Only left and two-sided ideals are allowed.
```

**elimination_ideal**(variables)

Return the elimination ideal of this ideal with respect to the variables given in “variables”.

EXAMPLES:

```python
sage: A.<x,y,z> = FreeAlgebra(QQ, 3)
sage: H = A.g_algebra({y*x:x*y-z, z*x:x*z+2*x, z*y:y*z-2*y})
sage: H.inject_variables()
Defining x, y, z
sage: I = H.ideal([y^2, x^2, z^2-H.one()],coerce=False)
sage: I.elimination_ideal([x, z])
Left Ideal (y^2) of Noncommutative Multivariate Polynomial
Ring in x, y, z over Rational Field, nc-relations: {...}
sage: J = I.twostd()
sage: J
Twosided Ideal (z^2 - 1, y*z - y, x*z + x, y^2, 2*x*y - z - 1, x^2) of
Noncommutative Multivariate Polynomial Ring in x, y, z over Rational Field
```

(continues on next page)
ALGORITHM: Uses Singular’s eliminate command

reduce($p$)

Reduce an element modulo a Groebner basis for this ideal.

It returns 0 if and only if the element is in this ideal. In any case, this reduction is unique up to monomial orders.

NOTE:

There are left and two-sided ideals. Hence,

EXAMPLES:

```
sage: A.<x,y,z> = FreeAlgebra(QQ, 3)
sage: H.<x,y,z> = A.g_algebra({y*x:x*y-z, z*x:x*z+2*x, z*y:y*z-2*y})
sage: I = H.ideal([y^2, x^2, z^2-H.one()],coerce=False, side='twosided')
sage: Q = H.quotient(I); Q
#random
Quotient of Noncommutative Multivariate Polynomial Ring in x, y, z
over Rational Field, nc-relations: {z*x: x*z + 2*x,
  z*y: y*z - 2*y, y*x: x*y - z} by the ideal (y^2, x^2, z^2 - 1)
sage: Q.2^2 == Q.one()  # indirect doctest
True
```

Here, we see that the relation that we just found in the quotient is actually a consequence of the given relations:

```
sage: H.2^2-H.one() in I.std().gens()
True
```

Here is the corresponding direct test:

```
sage: I.reduce(z^2)
1
```

res($length$)

Compute the resolution up to a given length of the ideal.

NOTE:

Only left syzygies can be computed. So, even if the ideal is two-sided, then the resolution is only one-sided. In that case, a warning is printed.

EXAMPLES:

```
sage: A.<x,y,z> = FreeAlgebra(QQ, 3)
sage: H = A.g_algebra({y*x:x*y-z, z*x:x*z+2*x, z*y:y*z-2*y})
sage: H.inject_variables()
Defining x, y, z
sage: I = H.ideal([y^2, x^2, z^2-H.one()],coerce=False)
sage: I.res(3)
<Resolution>
```
std()

Computes a GB of the ideal. It is two-sided if and only if the ideal is two-sided.

EXAMPLES:

```sage
A.<x,y,z> = FreeAlgebra(QQ, 3)
sage: H = A.g_algebra({y*x:x*y-z, z*x:x*z+2*x, z*y:y*z-2*y})
sage: H.inject_variables()
Defining x, y, z
sage: I = H.ideal([y^2, x^2, z^2-H.one()],coerce=False)
sage: I.std()  #random
Left Ideal (z^2 - 1, y*z - y, x*z + x, y^2, 2*x*y - z - 1, x^2) of Noncommutative Multivariate Polynomial Ring in x, y, z over Rational Field, nc-relations: {z*x: x*z + 2*x, z*y: y*z - 2*y, y*x: x*y - z}
sage: sorted(I.std().gens(),key=str)
[2*x*y - z - 1, x*z + x, x^2, y*z - y, y^2, z^2 - 1]
```

If the ideal is a left ideal, then std returns a left Groebner basis. But if it is a two-sided ideal, then the output of std and `twostd()` coincide:

```sage
JL = H.ideal([x^3, y^3, z^3 - 4*z])
sage: JL  #random
Left Ideal (x^3, y^3, z^3 - 4*z) of Noncommutative Multivariate Polynomial Ring in x, y, z over Rational Field, nc-relations: {z*x: x*z + 2*x, z*y: y*z - 2*y, y*x: x*y - z}
sage: sorted(JL.gens(),key=str)
[x^3, y^3, z^3 - 4*z]
```

ALGORITHM: Uses Singular's std command

syzygy_module()

Computes the first syzygy (i.e., the module of relations of the given generators) of the ideal.

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NOTE:

Only left syzygies can be computed. So, even if the ideal is two-sided, then the syzygies are only one-sided. In that case, a warning is printed.

EXAMPLES:

```
sage: A.<x,y,z> = FreeAlgebra(QQ, 3)
sage: H = A.g_algebra({y*x:x*y-z, z*x:x*z+2*x, z*y:y*z-2*y})
sage: H.inject_variables()
Defining x, y, z
sage: I = H.ideal([y^2, x^2, z^2-H.one()], coerce=False)
sage: G = vector(I.gens()); G
d...: UserWarning: You are constructing a free module over a noncommutative ring. Sage does not have a concept of left/right and both sided modules, so be careful. It's also not guaranteed that all multiplications are done from the right side.
d...: UserWarning: You are constructing a free module over a noncommutative ring. Sage does not have a concept of left/right and both sided modules, so be careful.
(y^2, x^2, z^2 - 1)
sage: M = I.syzygy_module(); M
[ [ -z^2 - 8*z - 15 0 y^2 ]
 [ 0 -z^2 + 8*z - 15 x^2 ]
 [ 2*z + 15*x^2 2*z^2 + 8*y^2*z - 15*y^2 -4*x*y*z + 2*z^2 + 2*y^2*z - x^2*y^2*z^2 + 9*x^2*y^2*z - 6*x*y^2*z^2 + 20*x^2*y^2 - y^3*z^2 + 7*y^3*z - 12*y^3 6*y*z^2 ]
 [ 52*y^2*z - 224*y^2 + 320*y -6*x*y^2*z^2 + 288 -y^4*z + 4*y^4 0 ]
 [ -2*x*y^2*z^2 + 8*x*y^3*z + 9*x*y^3 - 20*x*y^2 + 27*x^2 -2*x*y^2*z^2 - 195*y^2 -36*x*y^2*z + 24*z^2 + 18*z ]
[ [ -x^2*y^2*z^2 + 9*x*y^2*z - 4*y^2*z^2 - 20*x*y^2 + 52*y^2*z^2 - 224*y^2 + 320*y -6*x*y^2*z^2 + 288 -y^4*z + 4*y^4 0 ]
 [ -2*x*y^2*z^2 + 8*x*y^3*z + 9*x*y^3 - 20*x*y^2 + 27*x^2 -2*x*y^2*z^2 - 195*y^2 -36*x*y^2*z + 24*z^2 + 18*z ]
```

(continues on next page)
\[4z + 4x^4 - x^2y^2z + 4x^2y^2 - 4x^2y^2z^2 + 32x^2y^2z - 6z^3 - 64xy + 66z^2 - 240z + 288\]
\[\begin{align*}
&x^3y^2z^2 + 4x^3y^2 + 18x^2yz - 36x^2y^3 - 432x^2z^2 - 1656x^2z - 2052x - x^4y^2z + 4x^4y - 8y^3z^2 + 62y^3z - 114y^33
&48y^2z^2 - 36yz
\end{align*}\]

```
sage: M*G
(0, 0, 0, 0, 0, 0, 0, 0, 0)
```

ALGORITHM: Uses Singular’s syz command

twostd()

Computes a two-sided GB of the ideal (even if it is a left ideal).

EXAMPLES:

```
sage: A.<x,y,z> = FreeAlgebra(QQ, 3)
sage: H = A.g_algebra({y*x:x*y-z, z*x:x*z+2*x, z*y:y*z-2*y})
sage: H.inject_variables()
Defining x, y, z
sage: I = H.ideal([y^2, x^2, z^2-H.one()],coerce=False)
sage: I.twostd()  # random
Twosided Ideal (z^2 - 1, y*z - y, x*z + x, y^2, 2*x*y - z - 1, x^2) of
Noncommutative Multivariate Polynomial Ring in x, y, z over Rational Field...
sage: sorted(I.twostd().gens(),key=str)
[2*x*y - z - 1, x*z + x, x^2, y*z - y, y^2, z^2 - 1]
```

ALGORITHM: Uses Singular’s twostd command

class sage.rings.polynomial.multi_polynomial_ideal.RequireField(f)

Bases: MethodDecorator

Decorator which throws an exception if a computation over a coefficient ring which is not a field is attempted.

Note: This decorator is used automatically internally so the user does not need to use it manually.

sage.rings.polynomial.multi_polynomial_ideal.is_MPolynomialIdeal(x)

Return True if the provided argument x is an ideal in the multivariate polynomial ring.

INPUT:

- x - an arbitrary object

EXAMPLES:

```
sage: from sage.rings.polynomial.multi_polynomial_ideal import is_MPolynomialIdeal
sage: P.<x,y,z> = PolynomialRing(QQ)
sage: I = [x + 2*y + 2*z - 1, x^2 + 2*y^2 + 2*z^2 - x, 2*x*y + 2*y*z - y]
```

Sage distinguishes between a list of generators for an ideal and the ideal itself. This distinction is inconsistent with Singular but matches Magma’s behavior.
Polynomials, Release 10.0

```python
sage: is_MPolynomialIdeal(I)
False

sage: I = Ideal(I)
sage: is_MPolynomialIdeal(I)
True
```

sage.rings.polynomial.multi_polynomial_ideal.require_field
alias of RequireField

### 3.1.7 Polynomial Sequences

We call a finite list of polynomials a Polynomial Sequence.

Polynomial sequences in Sage can optionally be viewed as consisting of various parts or sub-sequences. These kind of polynomial sequences which naturally split into parts arise naturally for example in algebraic cryptanalysis of symmetric cryptographic primitives. The most prominent examples of these systems are: the small scale variants of the AES [CMR2005] (cf. sage.crypto.mq.sr.SR()) and Flurry/Curry [BPW2006]. By default, a polynomial sequence has exactly one part.

AUTHORS:

- Martin Albrecht (2007ff): initial version
- Martin Albrecht (2009): refactoring, clean-up, new functions
- Martin Albrecht (2011): refactoring, moved to sage.rings.polynomial
- Alex Raichev (2011-06): added algebraic-dependence()
- Charles Bouillaguet (2013-1): added solve()

EXAMPLES:

As an example consider a small scale variant of the AES:

```python
sage: sr = mq.SR(2,1,2,4,gf2=True,polybori=True)
sage: sr
SR(2,1,2,4)

sage: F, s = sr.polynomial_system()
sage: r2 = F.part(2); r2
(w200 + k100 + x100 + x102 + x103,
 w201 + k101 + x100 + x101 + x103 + 1,
 w202 + k102 + x100 + x101 + x102 + 1,
(continues on next page)
```

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We separate the system in independent subsystems:

```
sage: C = Sequence(r2).connected_components(); C
[[w200 + k100 + x100 + x102 + x103,  
w201 + k101 + x100 + x101 + x103 + 1,  
w202 + k102 + x100 + x101 + x102 + 1,  
w203 + k103 + x101 + x102 + x103,  
x100*w100 + x100*w103 + x101*w102 + x102*w101 + x103*w100,  
x100*w100 + x100*w101 + x101*w100 + x102*w103 + x103*w102,  
x100*w100 + x100*w101 + x101*w100 + x102*w102 + x103*w101,  
x100*w100 + x100*w101 + x101*w100 + x102*w102 + x103*w101,  
x100*w100 + x100*w101 + x101*w100 + x102*w102 + x103*w101],  
[w100 + x100*w103 + x101*w102 + x102*w101 + x103*w100,  
x100*w100 + x100*w101 + x101*w100 + x102*w103 + x103*w102,  
x100*w100 + x100*w101 + x101*w100 + x102*w102 + x103*w101,  
x100*w100 + x100*w101 + x101*w100 + x102*w102 + x103*w101,  
x100*w100 + x100*w101 + x101*w100 + x102*w102 + x103*w101]],
```
x_{100}w_{100} + x_{100}w_{102} + x_{100}w_{103} + x_{101}w_{100} + x_{101}w_{101} + x_{102}w_{102} + x_{103}w_{100} + x_{100},
\rightarrow x_{100},
\rightarrow x_{101},
\rightarrow x_{100}w_{100} + x_{100}w_{102} + x_{101}w_{100} + x_{101}w_{102} + x_{102}w_{100} + x_{102}w_{101} + x_{103}w_{101} + x_{101},
\rightarrow x_{103}w_{102} + x_{102},
\rightarrow x_{100}w_{101} + x_{100}w_{102} + x_{100}w_{100} + x_{101}w_{103} + x_{102}w_{101} + x_{103}w_{103} + x_{103},
\rightarrow x_{100}w_{100} + x_{100}w_{101} + x_{101}w_{101} + x_{101}w_{102} + x_{102}w_{100} + x_{102}w_{102} + x_{103}w_{100} + x_{100},
\rightarrow w_{100},
\rightarrow x_{100}w_{102} + x_{101}w_{100} + x_{101}w_{101} + x_{102}w_{100} + x_{102}w_{101} + x_{103}w_{100} + x_{103}w_{102} + x_{101},
\rightarrow w_{101},
\rightarrow x_{100}w_{100} + x_{100}w_{101} + x_{100}w_{102} + x_{101}w_{100} + x_{102}w_{100} + x_{102}w_{101} + x_{102}w_{103} + x_{101},
\rightarrow x_{103}w_{101} + w_{102},
\rightarrow x_{100}w_{101} + x_{101}w_{100} + x_{102}w_{100} + x_{103}w_{101} + x_{103}w_{103} + w_{103},
\rightarrow x_{100}w_{102} + x_{101}w_{101} + x_{102}w_{100} + x_{103}w_{103} + 1],
[w_{110} + k_{110} + x_{110} + x_{112} + x_{113},
w_{111} + k_{111} + x_{110} + x_{111} + x_{113} + 1,\w_{112} + k_{112} + x_{110} + x_{111} + x_{112} + 1,\w_{113} + k_{113} + x_{111} + x_{112} + x_{113},\n_{110}w_{110} + x_{110}w_{113} + x_{111}w_{112} + x_{112}w_{111} + x_{113}w_{110},\n_{110}w_{110} + x_{110}w_{111} + x_{111}w_{110} + x_{111}w_{113} + x_{112}w_{112} + x_{113}w_{111},\n_{110}w_{111} + x_{110}w_{112} + x_{111}w_{110} + x_{111}w_{111} + x_{112}w_{110} + x_{112}w_{113} + x_{113}w_{112},\n_{110}w_{110} + x_{110}w_{112} + x_{110}w_{113} + x_{111}w_{110} + x_{111}w_{111} + x_{112}w_{112} + x_{113}w_{110} + x_{110},\n_{110}w_{111} + x_{110}w_{113} + x_{111}w_{111} + x_{111}w_{112} + x_{112}w_{110} + x_{112}w_{113} + x_{113}w_{111} + x_{111},\n_{110}w_{110} + x_{110}w_{112} + x_{110}w_{110} + x_{111}w_{112} + x_{111}w_{113} + x_{112}w_{110} + x_{112}w_{111} + x_{113}w_{111} + x_{113}w_{113} + x_{112},\n_{110}w_{111} + x_{110}w_{112} + x_{111}w_{110} + x_{111}w_{111} + x_{112}w_{110} + x_{112}w_{112} + x_{113}w_{111} + x_{111},\n_{110}w_{110} + x_{110}w_{112} + x_{110}w_{113} + x_{111}w_{110} + x_{111}w_{111} + x_{112}w_{112} + x_{113}w_{110} + x_{113}w_{111} + x_{112},\n_{110}w_{111} + x_{110}w_{112} + x_{111}w_{111} + x_{111}w_{112} + x_{112}w_{110} + x_{112}w_{111} + x_{113}w_{110} + x_{113}w_{112} + x_{111},\n_{110}w_{110} + x_{110}w_{111} + x_{110}w_{112} + x_{111}w_{111} + x_{111}w_{112} + x_{112}w_{110} + x_{112}w_{113} + x_{113}w_{111} + x_{112}w_{111} + x_{113}w_{112} + x_{111},\n_{110}w_{111} + x_{110}w_{111} + x_{110}w_{112} + x_{111}w_{111} + x_{111}w_{112} + x_{112}w_{110} + x_{112}w_{111} + x_{113}w_{110} + x_{113}w_{112} + x_{111},\n_{110}w_{110} + x_{110}w_{111} + x_{110}w_{111} + x_{111}w_{111} + x_{111}w_{112} + x_{112}w_{110} + x_{112}w_{111} + x_{113}w_{110} + x_{113}w_{111} + x_{112},\n_{110}w_{111} + x_{110}w_{111} + x_{110}w_{112} + x_{111}w_{111} + x_{111}w_{112} + x_{112}w_{110} + x_{112}w_{111} + x_{113}w_{110} + x_{113}w_{111} + x_{113}w_{112} + x_{111},\n_{110}w_{110} + x_{110}w_{112} + x_{111}w_{110} + x_{111}w_{112} + x_{112}w_{110} + x_{112}w_{111} + x_{113}w_{110} + x_{113}w_{111} + x_{113}w_{112} + 1]]
\textbf{sage:} \text{C[0].groebner\_basis()}
\text{Polynomial Sequence with 30 Polynomials in 16 Variables}

and compute the coefficient matrix:

\textbf{sage:} \text{A,v = Sequence(r2).coefficient\_matrix()}
\textbf{sage:} \text{A.rank()}
32

Using these building blocks we can implement a simple XL algorithm easily:

\textbf{sage:} \text{sr = mq.SR(1,1,4, gf2=True, polybori=True, order='lex')}
\textbf{sage:} \text{while True:}  # workaround (see \text{\texttt{:trac:31891}})
\text{....:} \text{try:}
\text{....:} \text{F, s = sr.polynomial\_system()}

(continues on next page)
....: break
....: except ZeroDivisionError:
....: pass

sage: monomials = [a*b for a in F.variables() for b in F.variables() if a<b]
sage: len(monomials)
190
sage: F2 = Sequence(map(mul, cartesian_product_iterator((monomials, F))))
sage: A,v = F2.coefficient_matrix(sparse=False)
sage: A.echelonize()
sage: A
6840 x 4474 dense matrix over Finite Field of size 2 (use the '.str()' method to see the entries)
sage: A.rank()
4056
sage: A[4055]*v
(k001*k003)

**Note:** In many other computer algebra systems (cf. Singular) this class would be called `Ideal` but an ideal is a very distinct object from its generators and thus this is not an ideal in Sage.

### Classes

`sage.rings.polynomial.multi_polynomial_sequence.PolynomialSequence(arg1, arg2=None, immutable=False, cr=False, cr_str=None)`

Construct a new polynomial sequence object.

**INPUT:**

- `arg1` - a multivariate polynomial ring, an ideal or a matrix
- `arg2` - an iterable object of parts or polynomials (default: None)
  - `immutable` - if True the sequence is immutable (default: False)
  - `cr` - print a line break after each element (default: False)
  - `cr_str` - print a line break after each element if `str` is called (default: None)

**EXAMPLES:**

```python
sage: P.<a,b,c,d> = PolynomialRing(GF(127),4)
sage: I = sage.rings.ideal.Katsura(P)
```

If a list of tuples is provided, those form the parts:

```python
sage: F = Sequence([I.gens(),I.gens()], I.ring()); F # indirect doctest
[a + 2*b + 2*c + 2*d - 1, a^2 + 2*b^2 + 2*c^2 + 2*d^2 - a, 2*a*b + 2*b*c + 2*c*d - b, b^2 + 2*a*c + 2*b*d - c, a + 2*b + 2*c + 2*d - 1,
```

(continues on next page)
a^2 + 2*b^2 + 2*c^2 + 2*d^2 - a,
2*a*b + 2*b*c + 2*c*d - b,
b^2 + 2*a*c + 2*b*d - c]
sage: F.nparts()
2

If an ideal is provided, the generators are used:

sage: Sequence(I)
[a + 2*b + 2*c + 2*d - 1,
a^2 + 2*b^2 + 2*c^2 + 2*d^2 - a,
2*a*b + 2*b*c + 2*c*d - b,
b^2 + 2*a*c + 2*b*d - c]

If a list of polynomials is provided, the system has only one part:

sage: F = Sequence(I.gens(), I.ring()); F
[a + 2*b + 2*c + 2*d - 1,
a^2 + 2*b^2 + 2*c^2 + 2*d^2 - a,
2*a*b + 2*b*c + 2*c*d - b,
b^2 + 2*a*c + 2*b*d - c]
sage: F.nparts()
1

We test that the ring is inferred correctly:

sage: P.<x,y,z> = GF(2)[]
sage: from sage.rings.polynomial.multi_polynomial_sequence import PolynomialSequence
sage: PolynomialSequence([[1,x,y]], [0]).ring()
Multivariate Polynomial Ring in x, y, z over Finite Field of size 2
sage: PolynomialSequence([[1,x,y], [0]]).ring()
Multivariate Polynomial Ring in x, y, z over Finite Field of size 2

class sage.rings.polynomial.multi_polynomial_sequence.PolynomialSequence_generic(parts, ring, immutable=False, cr=False, cr_str=None)

Bases: Sequence_generic

Construct a new system of multivariate polynomials.

INPUT:

• part - a list of lists with polynomials
• ring - a multivariate polynomial ring
• immutable - if True the sequence is immutable (default: False)
• cr - print a line break after each element (default: False)
• cr_str - print a line break after each element if 'str' is called (default: None)

EXAMPLES:
sage: P.<a,b,c,d> = PolynomialRing(GF(127),4)
sage: I = sage.rings.ideal.Katsura(P)

sage: Sequence([I.gens()], I.ring())  # indirect doctest
[a + 2*b + 2*c + 2*d - 1, a^2 + 2*b^2 + 2*c^2 + 2*d^2 - a, 2*a*b + 2*b*c + 2*c*d - b, b^2 + 2*a*c + 2*b*d - c]

If an ideal is provided, the generators are used:

sage: Sequence(I)
[a + 2*b + 2*c + 2*d - 1, a^2 + 2*b^2 + 2*c^2 + 2*d^2 - a, 2*a*b + 2*b*c + 2*c*d - b, b^2 + 2*a*c + 2*b*d - c]

If a list of polynomials is provided, the system has only one part:

sage: Sequence(I.gens(), I.ring())
[a + 2*b + 2*c + 2*d - 1, a^2 + 2*b^2 + 2*c^2 + 2*d^2 - a, 2*a*b + 2*b*c + 2*c*d - b, b^2 + 2*a*c + 2*b*d - c]

algebraic_dependence()

Returns the ideal of annihilating polynomials for the polynomials in self, if those polynomials are algebraically dependent. Otherwise, returns the zero ideal.

OUTPUT:

If the polynomials \( f_1, \ldots, f_r \) in self are algebraically dependent, then the output is the ideal \( \{ F \in K[T_1, \ldots, T_r] : F(f_1, \ldots, f_r) = 0 \} \) of annihilating polynomials of \( f_1, \ldots, f_r \). Here \( K \) is the coefficient ring of polynomial ring of \( f_1, \ldots, f_r \) and \( T_1, \ldots, T_r \) are new indeterminates. If \( f_1, \ldots, f_r \) are algebraically independent, then the output is the zero ideal in \( K[T_1, \ldots, T_r] \).

EXAMPLES:

sage: R.<x,y> = PolynomialRing(QQ)
sage: S = Sequence([x, x*y])
sage: I = S.algebraic_dependence(); I
Ideal (0) of Multivariate Polynomial Ring in T0, T1 over Rational Field

sage: R.<x,y> = PolynomialRing(QQ)
sage: S = Sequence([x, (x^2 + y^2 - 1)^2, x*y - 2])
sage: I = S.algebraic_dependence(); I
Ideal (16 + 32*T2 - 8*T0^2 + 24*T2^2 - 8*T0^2*T2 + T2^3 + 2*T0^4 - 2*T0^2*T2^2 + T2^4 - T0^4*T1 + T0^4*T2 - T0^6 + 2*T0^4*T2^2 + T0^8) of Multivariate Polynomial Ring in T0, T1, T2 over Rational Field

sage: [F(S) for F in I.gens()]
[0]

sage: R.<x,y> = PolynomialRing(GF(7))
sage: S = Sequence([x, (x^2 + y^2 - 1)^2, x*y - 2])
sage: I = S.algebraic_dependence(); I
Ideal (2 - 3*T2 - T0^2 + 3*T2^2 - T0^2*T2 + T2^3 + 2*T0^4 - 2*T0^2*T2^2 + T2^4 - T0^4*T1 + T0^4*T2 - 2*T0^6 + 2*T0^4*T2^2 + T0^8) of Multivariate Polynomial Ring in T0, T1, T2 over Finite Field of size 7

sage: [F(S) for F in I.gens()]
[0]
Note: This function’s code also works for sequences of polynomials from a univariate polynomial ring, but I don’t know where in the Sage codebase to put it to use it to that effect.

AUTHORS:
• Alex Raichev (2011-06-22)

coefficient_matrix(sparse=True)

Return tuple \((A,v)\) where \(A\) is the coefficient matrix of this system and \(v\) the matching monomial vector. Thus value of \(A[i,j]\) corresponds the coefficient of the monomial \(v[j]\) in the \(i\)-th polynomial in this system.

Monomials are order w.r.t. the term ordering of \(\text{self.ring()}\) in reverse order, i.e. such that the smallest entry comes last.

INPUT:
• \(\text{sparse}\) - construct a sparse matrix (default: True)

EXAMPLES:

```sage
P.<a,b,c,d> = PolynomialRing(GF(127),4)
sage: I = sage.rings.ideal.Katsura(P)
sage: I.gens()
[a + 2*b + 2*c + 2*d - 1,
a^2 + 2*b^2 + 2*c^2 + 2*d^2 - a,
2*a*b + 2*b*c + 2*c*d - b,
b^2 + 2*a*c + 2*b*d - c]
sage: F = Sequence(I)
sage: A,v = F.coefficient_matrix()
sage: A
[ 0 0 0 0 0 0 0 0 0 1 2 2 2 126]
[ 1 0 2 0 0 2 0 0 2 126 0 0 0 0]
[ 0 2 0 0 2 0 0 2 0 0 126 0 0 0]
[ 0 0 1 2 0 0 2 0 0 0 0 126 0 0]  
sage: v
[a^2]
[a*b]
[b^2]
[a*c]
[b*c]
[c^2]
[b*d]
[c*d]
[d^2]
[ a]
[ b]
[ c]
[ d]
[1]  
sage: A*v
```
connected_components()
Split the polynomial system in systems which do not share any variables.

EXAMPLES:

As an example consider one part of AES, which naturally splits into four subsystems which are independent:

```
sage: sr = mq.SR(2,4,4,8,gf2=True,polybori=True)
sage: while True:  # workaround (see :trac:`31891`)
    ....:     try:
    ....:         F, s = sr.polynomial_system()
    ....:         break
    ....:     except ZeroDivisionError:
    ....:         pass
sage: Fz = Sequence(F.part(2))
sage: Fz.connected_components()
[Polynomial Sequence with 128 Polynomials in 128 Variables,
 Polynomial Sequence with 128 Polynomials in 128 Variables,
 Polynomial Sequence with 128 Polynomials in 128 Variables,
 Polynomial Sequence with 128 Polynomials in 128 Variables]
```

collection_graph()
Return the graph which has the variables of this system as vertices and edges between two variables if they appear in the same polynomial.

EXAMPLES:

```
sage: B.<x,y,z> = BooleanPolynomialRing()
sage: F = Sequence([x*y + y + 1, z + 1])
sage: G = F.connection_graph(); G
Graph on 3 vertices
sage: G.is_connected()
False
sage: F = Sequence([x])
sage: F.connection_graph()
Graph on 1 vertex
```

groebner_basis(*args, **kwargs)
Compute and return a Groebner basis for the ideal spanned by the polynomials in this system.

INPUT:

- **args** - list of arguments passed to `MPolynomialIdeal.groebner_basis` call
- **kwargs** - dictionary of arguments passed to `MPolynomialIdeal.groebner_basis` call

EXAMPLES:

```
sage: sr = mq.SR(allow_zero_inversions=True)
sage: F,s = sr.polynomial_system()
```
ideal()

Return ideal spanned by the elements of this system.

EXAMPLES:

```python
sage: sr = mq.SR(allow_zero_inversions=True)
sage: F, s = sr.polynomial_system()
sage: P = F.ring()
sage: I = F.ideal()
sage: J = I.elimination_ideal(P.gens()[4:-4])
sage: J <= I
True
sage: set(J.gens().variables()).issubset(P.gens()[:4] + P.gens()[-4:])
True
```

is_groebner(singular=Singular)

Returns True if the generators of this ideal (self.gens()) form a Groebner basis.

Let $I$ be the set of generators of this ideal. The check is performed by trying to lift $\text{Syz}(LM(I))$ to $\text{Syz}(I)$ as $I$ forms a Groebner basis if and only if for every element $S$ in $\text{Syz}(LM(I))$:

$$S \ast G = \sum_{i=0}^{m} h_i g_i - G > 0.$$

EXAMPLES:

```python
sage: R.<a,b,c,d,e,f,g,h,i,j> = PolynomialRing(GF(127),10)
sage: I = sage.rings.ideal.Cyclic(R,4)
sage: I.basis.is_groebner()
False
sage: I2 = Ideal(I.groebner_basis())
sage: I2.basis.is_groebner()
True
```

maximal_degree()

Return the maximal degree of any polynomial in this sequence.

EXAMPLES:

```python
sage: P.<x,y,z> = PolynomialRing(GF(7))
sage: F = Sequence([x*y + x, x])
sage: F.maximal_degree()
2
sage: P.<x,y,z> = PolynomialRing(GF(7))
sage: F = Sequence([], universe=P)
sage: F.maximal_degree()
-1
```

monomials()

Return an unordered tuple of monomials in this polynomial system.

EXAMPLES:
```python
sage: sr = mq.SR(allow_zero_inversions=True)
sage: F,s = sr.polynomial_system()
sage: len(F.monomials())
49
```

**nmonomials()**

Return the number of monomials present in this system.

**EXAMPLES:**

```python
sage: sr = mq.SR(allow_zero_inversions=True)
sage: F,s = sr.polynomial_system()
sage: F.nmonomials()
49
```

**nparts()**

Return number of parts of this system.

**EXAMPLES:**

```python
sage: sr = mq.SR(allow_zero_inversions=True)
sage: F,s = sr.polynomial_system()
sage: F.nparts()
4
```

**nvariables()**

Return number of variables present in this system.

**EXAMPLES:**

```python
sage: sr = mq.SR(allow_zero_inversions=True)
sage: F,s = sr.polynomial_system()
sage: F.nvariables()
20
```

**part(i)**

Return \(i\)-th part of this system.

**EXAMPLES:**

```python
sage: sr = mq.SR(allow_zero_inversions=True)
sage: F,s = sr.polynomial_system()
sage: R0 = F.part(1)
sage: R0
(k000^2 + k001, k001^2 + k002, k002^2 + k003, k003^2 + k00)
```

**parts()**

Return a tuple of parts of this system.

**EXAMPLES:**

```python
sage: sr = mq.SR(allow_zero_inversions=True)
sage: F,s = sr.polynomial_system()
sage: l = F.parts()
sage: len(l)
4
```
reduced()

If this sequence is \((f_1, \ldots, f_n)\) then this method returns \((g_1, \ldots, g_s)\) such that:

- \((f_1, \ldots, f_n) = (g_1, \ldots, g_s)\)
- \(LT(g_i) = LT(g_j)\) for all \(i = j\)
- \(LT(g_i)\) does not divide \(m\) for all monomials \(m\) of \(\{g_1, \ldots, g_i-1, g_i+1, \ldots, g_s\}\)
- \(LC(g_i) = 1\) for all \(i\) if the coefficient ring is a field.

EXAMPLES:

```python
sage: R.<x,y,z> = PolynomialRing(QQ)
sage: F = Sequence([z*x+y^3,z+y^3,z+x*y])
sage: F.reduced()
[y^3 + z, x*y + z, x*z - z]
```

Note that tail reduction for local orderings is not well-defined:

```python
sage: R.<x,y,z> = PolynomialRing(QQ, order='negdegrevlex')
sage: F = Sequence([z*x+y^3,z+y^3,z+x*y])
sage: F.reduced()
[z + x*y, x*y - y^3, x^2*y - y^3]
```

A fixed error with nonstandard base fields:

```python
sage: R.<t> = QQ['t']
sage: K.<x,y> = R.fraction_field()['x,y']
sage: I = t*x*K
sage: I.basis.reduced()
[x]
```

The interreduced basis of 0 is 0:

```python
sage: P.<x,y,z> = GF(2)[]
sage: Sequence([P(0)]).reduced()
[0]
```

Leading coefficients are reduced to 1:

```python
sage: P.<x,y> = QQ[]
sage: Sequence([2*x,y]).reduced()
[x, y]
sage: P.<x,y> = CC[]
sage: Sequence([2*x,y]).reduced()
[x, y]
```

ALGORITHM:

Uses Singular’s interred command or `sage.rings.polynomial.toy_buchberger.inter_reduction()` if conversion to Singular fails.

ring()

Return the polynomial ring all elements live in.

EXAMPLES:
sage: sr = mq.SR(allow_zero_inversions=True, gf2=True, order='block')
sage: F, s = sr.polynomial_system()
sage: print(F.ring().repr_long())
Polynomial Ring
Base Ring : Finite Field of size 2
<table>
<thead>
<tr>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
</tr>
</tbody>
</table>
| Block 0:
| Ordering : deglex
| Names : k100, k101, k102, k103, x100, x101, x102, x103, w100, ...
| ... w101, w102, w103, s000, s001, s002, s003
| Block 1:
| Ordering : deglex
| Names : k000, k001, k002, k003

subs(*args, **kwargs)
Substitute variables for every polynomial in this system and return a new system. See MPolynomial.subs for calling convention.

INPUT:
- args - arguments to be passed to MPolynomial.subs
- kwargs - keyword arguments to be passed to MPolynomial.subs

EXAMPLES:

```python
sage: sr = mq.SR(allow_zero_inversions=True)
sage: F, s = sr.polynomial_system(); F
Polynomial Sequence with 40 Polynomials in 20 Variables
sage: F = F.subs(s); F
Polynomial Sequence with 40 Polynomials in 16 Variables
```

universe()
Return the polynomial ring all elements live in.

EXAMPLES:

```python
sage: sr = mq.SR(allow_zero_inversions=True, gf2=True, order='block')
sage: F, s = sr.polynomial_system()
sage: print(F.ring().repr_long())
Polynomial Ring
Base Ring : Finite Field of size 2
<table>
<thead>
<tr>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
</tr>
</tbody>
</table>
| Block 0:
| Ordering : deglex
| Names : k100, k101, k102, k103, x100, x101, x102, x103, w100, ...
| ... w101, w102, w103, s000, s001, s002, s003
| Block 1:
| Ordering : deglex
| Names : k000, k001, k002, k003
```

variables()
Return all variables present in this system. This tuple may or may not be equal to the generators of the ring of this system.

EXAMPLES:

```python
sage: sr = mq.SR(allow_zero_inversions=True)
sage: F, s = sr.polynomial_system()
```
class sage.rings.polynomial.multi_polynomial_sequence.PolynomialSequence_gf2(parts, ring, immutable=False, cr=False, cr_str=None):

    Bases: PolynomialSequence_generic

    Polynomial Sequences over \( \mathbb{F}_2 \).

    eliminate_linear_variables(maxlength=+Infinity, skip=None, return_reductors=False, use_polybori=False)

    Return a new system where linear leading variables are eliminated if the tail of the polynomial has length at most maxlength.

    INPUT:

    • `maxlength` - an optional upper bound on the number of monomials by which a variable is replaced. If `maxlength`==+Infinity then no condition is checked. (default: +Infinity).

    • `skip` - an optional callable to skip eliminations. It must accept two parameters and return either True or False. The two parameters are the leading term and the tail of a polynomial (default: None).

    • `return_reductors` - if True the list of polynomials with linear leading terms which were used for reduction is also returned (default: False).

    • `use_polybori` - if True then `polybori.ll.eliminate` is called. While this is typically faster what is implemented here, it is less flexible (skip is not supported) and may increase the degree (default: False).

    OUTPUT:

    When `return_reductors`==True, then a pair of sequences of boolean polynomials are returned, along with the promises that:

    1. The union of the two sequences spans the same boolean ideal as the argument of the method

    2. The second sequence only contains linear polynomials, and it forms a reduced gb (they all have pairwise distinct leading variables, and the leading variable of a polynomial does not occur anywhere in other polynomials).

    3. The leading variables of the second sequence do not occur anywhere in the first sequence (these variables have been eliminated).

    When `return_reductors`==False, only the first sequence is returned.

    EXAMPLES:

```
sage: B.<a,b,c,d> = BooleanPolynomialRing()
sage: F = Sequence([c + d + b + 1, a + c + d, a*b + c, b*c*d + c])
sage: F.eliminate_linear_variables()  # everything vanishes
[]
sage: F.eliminate_linear_variables(maxlength=2)
[b + c + d + 1, b*c + b*d + c, b*c*d + c]
sage: F.eliminate_linear_variables(skip=lambda lm, tail: str(lm)=='a')
[a + c + d, a*c + a*d + a + c, c*d + c]
```

The list of reductors can be requested by setting ‘return_reductors’ to True:
sage: B.<a,b,c,d> = BooleanPolynomialRing()
sage: F = Sequence([a + b + d, a + b + c])
sage: F,R = F.eliminate_linear_variables(return_reductors=True)
sage: F
[]
sage: R
[a + b + d, c + d]

If the input system is detected to be inconsistent then [1] is returned and the list of reductors is empty:

sage: R.<x,y,z> = BooleanPolynomialRing()
sage: S = Sequence([x*y*z+x*y+z*y+x*z, x+y+z+1, x+y+z])
sage: S.eliminate_linear_variables()
[1]

Note: This is called “massaging” in [BCJ2007].

reduced()

If this sequence is \((f_1, ..., f_n)\) this method returns \((g_1, ..., g_s)\) such that:

- \(< f_1, ..., f_n > = < g_1, ..., g_s >\)
- \(LT(g_i)! = LT(g_j)\) for all \(i! = j\)
- \(LT(g_i)\) does not divide \(m\) for all monomials \(m\) of \(g_1, ..., g_i-1, g_{i+1}, ..., g_s\)

EXAMPLES:

sage: sr = mq.SR(1, 1, 1, 4, gf2=True, polybori=True)
sage: while True:
    # workaround (see :trac:`31891`)
    ....:    try:
    ....:        F, s = sr.polynomial_system()
    ....:    except ZeroDivisionError:
    ....:        pass
    sage: g = F.reduced()
sage: len(g) == len(set(gi.lt() for gi in g))
True
sage: for i in range(len(g)):
    ....:      for j in range(len(g)):
    ....:          if i == j:
    ....:              continue
    ....:      for t in list(g[j]):
    ....:          assert g[i].lt() not in t.divisors()

solve(algorithm='polybori', n=1, eliminate_linear_variables=True, verbose=False, **kwds)

Find solutions of this boolean polynomial system.

This function provide a unified interface to several algorithms dedicated to solving systems of boolean equations. Depending on the particular nature of the system, some might be much faster than some others.
INPUT:

- **self** - a sequence of boolean polynomials

- **algorithm** - the method to use. Possible values are polybori, sat and exhaustive_search. (default: polybori, since it is always available)

- **n** - number of solutions to return. If $n == +\infty$ then all solutions are returned. If $n < \infty$ then $n$ solutions are returned if the equations have at least $n$ solutions. Otherwise, all the solutions are returned. (default: 1)

- **eliminate_linear_variables** - whether to eliminate variables that appear linearly. This reduces the number of variables (makes solving faster a priori), but is likely to make the equations denser (may make solving slower depending on the method).

- **verbose** - whether to display progress and (potentially) useful information while the computation runs. (default: False)

EXAMPLES:

Without argument, a single arbitrary solution is returned:

```
sage: from sage.doctest.fixtures import reproducible_repr
sage: R.<x,y,z> = BooleanPolynomialRing()
sage: S = Sequence([x*y+z, y*z+x, x+y+z+1])
sage: sol = S.solve()
sage: print(reproducible_repr(sol))
[{x: 0, y: 1, z: 0}]
```

We check that it is actually a solution:

```
sage: S.subs( sol[0] )
[0, 0, 0]
```

We obtain all solutions:

```
sage: sols = S.solve(n=Infinity)
sage: print(reproducible_repr(sols))
[{x: 0, y: 1, z: 0}, {x: 1, y: 1, z: 1}]
sage: [S.subs(x) for x in sols]
[[0, 0, 0], [0, 0, 0]]
```

We can force the use of exhaustive search if the optional package FES is present:

```
sage: sol = S.solve(algorithm='exhaustive_search') # optional - FES
sage: print(reproducible_repr(sol)) # optional - FES
[{x: 1, y: 1, z: 1}]
sage: S.subs( sol[0] )
[0, 0, 0]
```

And we may use SAT-solvers if they are available:

```
sage: sol = S.solve(algorithm='sat') # optional - pycryptosat
sage: print(reproducible_repr(sol)) # optional - pycryptosat
[{x: 0, y: 1, z: 0}]
sage: S.subs( sol[0] )
[0, 0, 0]
```
class sage.rings.polynomial.multi_polynomial_sequence.PolynomialSequence_gf2e(parts, ring, immutable=False, cr=False, cr_str=None)

Bases: PolynomialSequence_generic

PolynomialSequence over \( F_{2^e} \), i.e extensions over \( F_2 \).

weil_restriction()

Project this polynomial system to \( F_2 \).

That is, compute the Weil restriction of scalars for the variety corresponding to this polynomial system and express it as a polynomial system over \( F_2 \).

EXAMPLES:

sage: k.<a> = GF(2^2)

sage: P.<x,y> = PolynomialRing(k,2)

sage: a = P.base_ring().gen()

sage: F = Sequence([x*y + 1, a*x + 1], P)

sage: F2 = F.weil_restriction()

sage: F2

[x0*y0 + x1*y1 + 1, x1*y0 + x0*y1 + x1*y1, x1 + 1, x0 + x1, x0^2 + x0, x1^2 + x1, y0^2 + y0, y1^2 + y1]

Another bigger example for a small scale AES:

sage: sr = mq.SR(1,1,1,4,gf2=False)

sage: while True:
    ...:     try:
    ...:         F, s = sr.polynomial_system()
    ...:         break
    ...:     except ZeroDivisionError:
    ...:         pass

sage: F

Polynomial Sequence with 40 Polynomials in 20 Variables

sage: F2 = F.weil_restriction(); F2

Polynomial Sequence with 240 Polynomials in 80 Variables

sage.rings.polynomial.multi_polynomial_sequence.is_PolynomialSequence(F)

Return True if F is a PolynomialSequence.

INPUT:

• F - anything

EXAMPLES:

sage: P.<x,y> = PolynomialRing(QQ)

sage: I = [[x^2 + y^2], [x^2 - y^2]]

sage: F = Sequence(I, P); F

[x^2 + y^2, x^2 - y^2]

sage: from sage.rings.polynomial.multi_polynomial_sequence import is_PolynomialSequence

sage: is_PolynomialSequence(F)

True
3.1.8 Multivariate Polynomials via libSINGULAR

This module implements specialized and optimized implementations for multivariate polynomials over many coefficient rings, via a shared library interface to SINGULAR. In particular, the following coefficient rings are supported by this implementation:

- the rational numbers \( \mathbb{Q} \),
- the ring of integers \( \mathbb{Z} \),
- \( \mathbb{Z}/n\mathbb{Z} \) for any integer \( n \),
- finite fields \( \mathbb{F}_{p^n} \) for \( p \) prime and \( n > 0 \),
- and absolute number fields \( \mathbb{Q}(a) \).

EXAMPLES:

We show how to construct various multivariate polynomial rings:

```
sage: P.<x,y,z> = QQ[]
sage: P
Multivariate Polynomial Ring in x, y, z over Rational Field

sage: f = 27/113 * x^2 + y*z + 1/2; f
27/113*x^2 + y*z + 1/2

sage: P.term_order()
Degree reverse lexicographic term order

sage: P = PolynomialRing(GF(127),3,names='abc', order='lex')
sage: P
Multivariate Polynomial Ring in a, b, c over Finite Field of size 127

sage: a,b,c = P.gens()
sage: f = 57*a^2*b + 43*c + 1; f
57*a^2*b + 43*c + 1

sage: P.term_order()
Lexicographic term order

sage: z = QQ['z'].0
sage: K.<s> = NumberField(z^2 - 2)
sage: P.<x,y> = PolynomialRing(K, 2)
sage: 1/2*s*x^2 + 3/4*s
(1/2*s)*x^2 + (3/4*s)

sage: P.<x,y,z> = ZZ[]; P
Multivariate Polynomial Ring in x, y, z over Integer Ring

sage: P.<x,y,z> = Zmod(2^10)[]; P
Multivariate Polynomial Ring in x, y, z over Ring of integers modulo 1024

sage: P.<x,y,z> = Zmod(3^10)[]; P
Multivariate Polynomial Ring in x, y, z over Ring of integers modulo 59049

sage: P.<x,y,z> = Zmod(2^100)[]; P
```
We construct the Frobenius morphism on $F_5[x, y, z]$ over $F_5$:

```python
sage: R.<x,y,z> = PolynomialRing(GF(5), 3)
sage: frob = R.hom([x^5, y^5, z^5])
sage: frob(x^2 + 2*y - z^4)
  -z^20 + x^10 + 2*y^5
sage: frob((x + 2*y)^3)
  x^15 + x^10*y^5 + 2*x^5*y^10 - 2*y^15
sage: (x^5 + 2*y^5)^3
  x^15 + x^10*y^5 + 2*x^5*y^10 - 2*y^15
```

We make a polynomial ring in one variable over a polynomial ring in two variables:

```python
sage: R.<x, y> = PolynomialRing(QQ, 2)
sage: S.<t> = PowerSeriesRing(R)
sage: t*(x+y)
  (x + y)*t
```

**Todo:** Implement Real, Complex coefficient rings via libSINGULAR

**AUTHORS:**
- Martin Albrecht (2007-01): initial implementation
- Joel Mohler (2008-01): misc improvements, polishing
- Martin Albrecht (2008-08): added $\mathbb{Q}(a)$ and $\mathbb{Z}$ support
- Simon King (2009-04): improved coercion
- Martin Albrecht (2009-05): added $\mathbb{Z}/n\mathbb{Z}$ support, refactoring
- Martin Albrecht (2009-06): refactored the code to allow better re-use
- Simon King (2011-03): use a faster way of conversion from the base ring.
- Volker Braun (2011-06): major cleanup, refcount singular rings, bugfixes.

**class** `sage.rings.polynomial.multi_polynomial_libsingular.MPolynomialRing_libsingular`

Bases: `MPolynomialRing_base`

Construct a multivariate polynomial ring subject to the following conditions:
INPUT:

- **base_ring** - base ring (must be either GF(q), ZZ, ZZ/nZZ, QQ or absolute number field)
- **n** - number of variables (must be at least 1)
- **names** - names of ring variables, may be string of list/tuple
- **order** - term order (default: degrevlex)

EXAMPLES:

```sage
sage: P.<x,y,z> = QQ[]
sage: P
Multivariate Polynomial Ring in x, y, z over Rational Field
sage: f = 27/113 * x^2 + y*z + 1/2; f
27/113*x^2 + y*z + 1/2
sage: P.term_order()
Degree reverse lexicographic term order
sage: P = PolynomialRing(GF(127),3,names='abc', order='lex')
sage: P
Multivariate Polynomial Ring in a, b, c over Finite Field of size 127
sage: a,b,c = P.gens()
sage: f = 57 * a^2*b + 43 * c + 1; f
57*a^2*b + 43*c + 1
sage: P.term_order()
Lexicographic term order
sage: z = QQ['z'].0
sage: K.<s> = NumberField(z^2 - 2)
```

(continues on next page)
Polynomials, Release 10.0

(continued from previous page)

Example
alias of \texttt{MPolynomial_libsingular}

\begin{verbatim}
Element
  \textit{gen}(n=0)

  Returns the \textit{n}-th generator of this multivariate polynomial ring.

  INPUT:

  \begin{itemize}
  \item \textit{n} – an integer \textgreater= 0
  \end{itemize}

  EXAMPLES:

  \begin{verbatim}
sage: P.<x,y,z> = QQ[]
sage: P.gen(),P.gen(1)
(x, y)
sage: P = PolynomialRing(GF(127),1000,'x')
sage: P.gen(500)
x500
sage: P.<SAGE,SINGULAR> = QQ[]  # weird names
sage: P.gen(1)
SINGULAR
\end{verbatim}
\end{verbatim}

\begin{verbatim}
ideal(*gens, **kwds)

  Create an ideal in this polynomial ring.

  INPUT:

  \begin{itemize}
  \item \textit{gens} - list or tuple of generators (or several input arguments)
  \item \textit{coerce} - bool (default: True); this must be a keyword argument. Only set it to \texttt{False} if you are certain that each generator is already in the ring.
  \end{itemize}

  EXAMPLES:

  \begin{verbatim}
sage: P.<x,y,z> = QQ[]
sage: sage.rings.ideal.Katsura(P)
Ideal (x + 2*y + 2*z - 1, x^2 + 2*y^2 + 2*z^2 - x, 2*x*y + 2*y*z - y) of
  \begin{verbatim}
\texttt{Multivariate Polynomial Ring in x, y, z over Rational Field}
\end{verbatim}
sage: P.ideal([x + 2*y + 2*z-1, 2*x*y + 2*y*z-y, x^2 + 2*y^2 + 2*z^2-x])
\end{verbatim}
\end{verbatim}
\end{verbatim}

\end{verbatim}

3.1. Multivariate Polynomials and Polynomial Rings 425
Ideal (x + 2*y + 2*z - 1, 2*x*y + 2*y*z - y, x^2 + 2*y^2 + 2*z^2 - x) of
˓
Multivariate Polynomial Ring in x, y, z over Rational Field

monomial_all_divisors(t)

Return a list of all monomials that divide t.

Coefficients are ignored.

INPUT:
  • t - a monomial

OUTPUT:
  a list of monomials

EXAMPLES:

```sage
sage: P.<x,y,z> = QQ[]
```
```
sage: P.monomial_all_divisors(x^2*z^3)
[x, x^2, z, x*z, x^2*z, z^2, x*z^2, x^2*z^2, z^3, x*z^3, x^2*z^3]
```

ALGORITHM: addwithcarry idea by Toon Segers

monomial_divides(a, b)

Return False if a does not divide b and True otherwise.

Coefficients are ignored.

INPUT:
  • a – monomial
  • b – monomial

EXAMPLES:

```sage
sage: P.<x,y,z> = QQ[]
```
```
sage: P.monomial_divides(x*y*z, x^3*y^2*z^4)
True
```
```
sage: P.monomial_divides(x^3*y^2*z^4, x*y*z)
False
```

monomial_lcm(f, g)

LCM for monomials. Coefficients are ignored.

INPUT:
  • f - monomial
  • g - monomial

EXAMPLES:

```sage
sage: P.<x,y,z> = QQ[]
```
```
sage: P.monomial_lcm(3/2*x*y, x)
x*y
```
**monomial_pairwise_prime** *(g, h)*

Return True if h and g are pairwise prime. Both are treated as monomials.

Coefficients are ignored.

**INPUT:**
- h - monomial
- g - monomial

**EXAMPLES:**

```python
sage: P.<x,y,z> = QQ[]
sage: P.monomial_pairwise_prime(x^2*z^3, y^4)
True
sage: P.monomial_pairwise_prime(1/2*x^3*y^2, 3/4*y^3)
False
```

**monomial_quotient** *(f, g, coeff=False)*

Return f/g, where both f and g are treated as monomials.

Coefficients are ignored by default.

**INPUT:**
- f - monomial
- g - monomial
- coeff - divide coefficients as well (default: False)

**EXAMPLES:**

```python
sage: P.<x,y,z> = QQ[]
sage: P.monomial_quotient(3/2*x*y,x)
y
sage: P.monomial_quotient(3/2*x*y,x,coeff=True)
3/2*y
```

Note, that Z behaves different if coef=True:

```python
sage: P.monomial_quotient(2*x,3*x)
1
sage: P.<x,y> = PolynomialRing(ZZ)
sage: P.monomial_quotient(2*x,3*x,coeff=True)
Traceback (most recent call last):
...
ArithmeticError: Cannot divide these coefficients.
```

**Warning:** Assumes that the head term of f is a multiple of the head term of g and return the multiplicant m. If this rule is violated, funny things may happen.
monomial_reduce\((f, G)\)

Try to find a \(g\) in \(G\) where \(g.lm()\) divides \(f\). If found, \((\text{flt}, g)\) is returned, \((0, 0)\) otherwise, where \(\text{flt}\) is \(f/g.lm()\).

It is assumed that \(G\) is iterable and contains only elements in this polynomial ring.

Coefficients are ignored.

**INPUT:**

- \(f\) - monomial
- \(G\) - list/set of mpolynomials

**EXAMPLES:**

```
sage: P.<x,y,z> = QQ[

sage: f = x*y^2

sage: G = [ 3/2*x^3 + y^2 + 1/2, 1/4*x*y + 2/7, 1/2 ]

sage: P.monomial_reduce(f,G)
(y, 1/4*x*y + 2/7)
```

ngens()

Returns the number of variables in this multivariate polynomial ring.

**EXAMPLES:**

```
sage: P.<x,y> = QQ[

sage: P.ngens()
2

sage: k.<a> = GF(2^16)

sage: P = PolynomialRing(k,1000,'x')

sage: P.ngens()
1000
```

class \sage\.rings\.polynomial\.multi\_polynomial\_libsingular\.\MPolynomial\_libsingular

Bases: \MPolynomial\_libsingular

A multivariate polynomial implemented using libSINGULAR.

add_m_mul_q\((m, q)\)

Return \(self + m*q\), where \(m\) must be a monomial and \(q\) a polynomial.

**INPUT:**

- \(m\) - a monomial
- \(q\) - a polynomial

**EXAMPLES:**

```
sage: P.<x,y,z>=PolynomialRing(QQ,3)

sage: x.add_m_mul_q(y,z)
```

coefficient\((degrees)\)

Return the coefficient of the variables with the degrees specified in the python dictionary \(degrees\). Mathematically, this is the coefficient in the base ring adjoined by the variables of this ring not listed in \(degrees\). However, the result has the same parent as this polynomial.
This function contrasts with the function `monomial_coefficient` which returns the coefficient in the base ring of a monomial.

**INPUT:**

- **degrees** - Can be any of:
  - a dictionary of degree restrictions
  - a list of degree restrictions (with None in the unrestricted variables)
  - a monomial (very fast, but not as flexible)

**OUTPUT:**
element of the parent of this element.

**Note:** For coefficients of specific monomials, look at `monomial_coefficient()`.

**EXAMPLES:**

```sage
definitions:
R.<x,y> = QQ[]
f=x*y+y+5
definitions:
f.coefficient({x:0,y:1})
1
definitions:
f.coefficient({x:0})
y + 5
definitions:
f=(1+y+y^2)*(1+x+x^2)
definitions:
f.coefficient({x:0})
y^2 + y + 1
definitions:
f.coefficient([0,None])
y^2 + y + 1
definitions:
f.coefficient(x)
y^2 + y + 1
```

Note that exponents have all variables specified:

```sage
definitions:
x.coefficient(x.exponents()[0])
1
definitions:
f.coefficient([1,0])
1
definitions:
f.coefficient({x:1,y:0})
1
```

Be aware that this may not be what you think! The physical appearance of the variable x is deceiving – particularly if the exponent would be a variable.

```sage
definitions:
f.coefficient(x^0) # outputs the full polynomial
x^2*y^2 + x^2*y + x*y^2 + x^2 + x*y + y^2 + x + y + 1
definitions:
R.<x,y> = GF(389)[]
definitions:
f=x*y+5
definitions:
c=f.coefficient({x:0,y:0}); c
5
definitions:
parent(c)
Multivariate Polynomial Ring in x, y over Finite Field of size 389
```

**AUTHOR:**
coefficients()

Return the nonzero coefficients of this polynomial in a list. The returned list is decreasingly ordered by the term ordering of the parent.

EXAMPLES:

```
sage: R.<x,y,z> = PolynomialRing(QQ, order='degrevlex')
sage: f=23*x^6*y^7 + x^3*y+6*x^7*z
sage: f.coefficients()
[23, 6, 1]
sage: R.<x,y,z> = PolynomialRing(QQ, order='lex')
sage: f=23*x^6*y^7 + x^3*y+6*x^7*z
sage: f.coefficients()
[6, 23, 1]
```

AUTHOR:

- Didier Deshommes

constant_coefficient()

Return the constant coefficient of this multivariate polynomial.

EXAMPLES:

```
sage: P.<x, y> = QQ[]
sage: f = 3*x^2 - 2*y + 7*x^2*y^2 + 5
sage: f.constant_coefficient()
5
sage: f = 3*x^2
sage: f.constant_coefficient()
0
```

degree(x=None, std_grading=False)

Return the degree of this polynomial.

INPUT:

- x – (default: None) a generator of the parent ring

OUTPUT:

If x is not given, return the maximum degree of the monomials of the polynomial. Note that the degree of a monomial is affected by the gradings given to the generators of the parent ring. If x is given, it is (or coercible to) a generator of the parent ring and the output is the maximum degree in x. This is not affected by the gradings of the generators.

EXAMPLES:

```
sage: R.<x, y> = QQ[]
sage: f = y^2 - x^9 - x
sage: f.degree(x)
9
sage: f = 3^x^2
sage: f.constant_coefficient()
0
```
The term ordering of the parent ring determines the grading of the generators.

```
sage: T = TermOrder('wdegrevlex', (1,2,3,4))
sage: R = PolynomialRing(QQ, 'x', 12, order=T+T+T)
sage: [x.degree() for x in R.gens()]
[1, 2, 3, 4, 1, 2, 3, 4, 1, 2, 3, 4]
```

A matrix term ordering determines the grading of the generators by the first row of the matrix.

```
sage: m = matrix(3, [3,2,1,1,1,0,1,0,0])
sage: m
[3 2 1]
[1 1 0]
[1 0 0]
sage: R.<x,y,z> = PolynomialRing(QQ, order=TermOrder(m))
sage: x.degree(), y.degree(), z.degree()
(3, 2, 1)
sage: f = x^3*y + x*z^4
sage: f.degree()
11
```

If the first row contains zero, the grading becomes the standard one.

```
sage: m = matrix(3, [3,0,1,1,1,0,1,0,0])
sage: m
[3 0 1]
[1 1 0]
[1 0 0]
sage: R.<x,y,z> = PolynomialRing(QQ, order=TermOrder(m))
sage: x.degree(), y.degree(), z.degree()
(1, 1, 1)
sage: f = x^3*y + x*z^4
sage: f.degree()
5
```

To get the degree with the standard grading regardless of the term ordering of the parent ring, use `std_grading=True`.

```
sage: f.degree(std_grading=True)
5
```

`degrees()`

Returns a tuple with the maximal degree of each variable in this polynomial. The list of degrees is ordered by the order of the generators.

EXAMPLES:

```
sage: R.<y0,y1,y2> = PolynomialRing(QQ,3)
sage: q = 3*y0*y1*y1*y2; q
```
dict()

Return a dictionary representing self. This dictionary is in the same format as the generic MPolynomial: The dictionary consists of ETuple:coefficient pairs.

EXAMPLES:

```
sage: R.<x,y,z> = QQ[]
sage: f=2*x*y^3*z^2 + 1/7*x^2 + 2/3
sage: f.dict()
{(0, 0, 0): 2/3, (1, 3, 2): 2, (2, 0, 0): 1/7}
```

divides(other)

Return True if this polynomial divides other.

EXAMPLES:

```
sage: R.<x,y,z> = QQ[]
sage: p = 3*x*y + 2*y*z + x*z
sage: q = x + y + z + 1
sage: r = p * q
sage: p.divides(r)
True
sage: q.divides(p)
False
sage: r.divides(QQ[])
True
sage: R.zero().divides(r)
False
sage: R.zero().divides(QQ[])
True
```

exponents(as_ETuples=True)

Return the exponents of the monomials appearing in this polynomial.

INPUT:

- as_ETuples – (default: True) if True returns the result as an list of ETuples, otherwise returns a list of tuples

EXAMPLES:

```
sage: R.<a,b,c> = QQ[]
sage: f = a^3 + b + 2*b^2
sage: f.exponents()
[(3, 0, 0), (0, 2, 0), (0, 1, 0)]
sage: f.exponents(as_ETuples=False)
[[(3, 0, 0), (0, 2, 0), (0, 1, 0)]]
```
factor(proof=None)

Return the factorization of this polynomial.

INPUT:

• proof - ignored.

EXAMPLES:

```python
sage: R.<x, y> = QQ[]
sage: f = (x^4 + 2*y^4*x) * (x^2 + x + 1); f
x^5 + 2*x^3*y^4 + x^4 + 2*x^2*y^4 + x^3 + 2*x*y^4
sage: F = f.factor()
sage: F
x * (x^2 + x + 1) * (x^2 + 2*y^4)
```

Next we factor the same polynomial, but over the finite field of order 3:

```python
sage: R.<x, y> = GF(3)[]
sage: f = (x^4 + 2*a*y^4*x) * (x^2 + x + 1); f
x^5 - x^3*y^4 + x^4 - x^2*y^4 + x^3 - x*y^4
sage: F = f.factor()
sage: F
# order is somewhat random
(-1) * x * (-x + y) * (x + y) * (x - 1)^2
```

Next we factor a polynomial, but over a finite field of order 9:

```python
sage: K.<a> = GF(3^2)
sage: R.<x, y> = K[]
sage: factor(x^3 - 2*y^3)
(x + (-a)*y) * (x^2 + s*x*y + (s^2)*y^2)
```

Next we factor a polynomial over a number field:

```python
sage: p = var('p')
sage: K.<s> = NumberField(p^3-2)
sage: KXY.<x,y> = K[]
sage: factor(x^3 - 2*y^3)
(x + (-s)*y) * (x^2 + s*x*y + (s^2)*y^2)
```

This shows that issue github issue #2780 is fixed, i.e. that the unit part of the factorization is set correctly:

```python
sage: x = var('x')
sage: K.<a> = NumberField(x^2 + 1)
sage: R.<y, z> = PolynomialRing(K)
sage: f = 2*y^2 + 2*z^2
sage: F = f.factor(); F.unit()
2
```

3.1. Multivariate Polynomials and Polynomial Rings
Another example:

```sage
R.<x,y,z> = GF(32003)[]
sage: f = 9*(x-1)^2*(y+z)
sage: f.factor()
(9) * (y + z) * (x - 1)^2
sage: R.<x,w,v,u> = QQ['x','w','v','u']
sage: p = (4*v^4*w^2 - 16*v^2*w^4 + 16*w^6 - 4*v^4*w + 8*v^2*w^3 + w^4)
sage: p.factor()
(-2*v^2*w + 4*w^3 + v^2)^2
sage: R.<a,b,c,d> = QQ[]
sage: f = (-2) * (a - d) * (-a + b) * (b - d) * (a - c) * (b - c) * (c - d)
sage: F = f.factor(); F
(-2) * (c - d) * (-b + c) * (b - d) * (-a + c) * (-a + b) * (a - d)
sage: F[0][0]
c - d
sage: F.unit()
-2
```

Constant elements are factorized in the base rings.

```sage
P.<x,y> = ZZ[]
sage: P(2^3*7).factor()
2^3 * 7
sage: P.<x,y> = GF(2)[]
sage: P(1).factor()
1
```

Factorization for finite prime fields with characteristic $> 2^{29}$ is not supported.

```sage
q = 1073741789
sage: T.<aa, bb> = PolynomialRing(GF(q))
sage: f = aa^2 + 12124343*bb*aa + 32434598*bb^2
sage: f.factor()
Traceback (most recent call last):
  ... Not ImplementedError: Factorization of multivariate polynomials over prime
˓→fields with characteristic $> 2^{29}$ is not implemented.
```

Factorization over the integers is now supported, see github issue #17840:

```sage
P.<x,y> = PolynomialRing(ZZ)
sage: f = 12 * (3*x*y + 4) * (5*x - 2) * (2*y + 7)^2
sage: f.factor()
2^2 * 3 * (2*y + 7)^2 * (5*x - 2) * (3*x*y + 4)
sage: g = -12 * (x^2 - y^2)
sage: g.factor()
(-1) * 2^2 * 3 * (x - y) * (x + y)
sage: factor(-4*x*y - 2*x + 2*y + 1)
(-1) * (2*y + 1) * (2*x - 1)
```

Factorization over non-integral domains is not supported.
Polynomials, Release 10.0

```python
sage: R.<x,y> = PolynomialRing(Zmod(4))
sage: f = (2*x + 1) * (x^2 + x + 1)
sage: f.factor()
Traceback (most recent call last):
...  
NotImplementedError: Factorization of multivariate polynomials over Ring of integers modulo 4 is not implemented.
```

gcd(right, algorithm=None, **kwds)

Return the greatest common divisor of self and right.

INPUT:

- • right - polynomial
- • algorithm - ezgcd - EZGCD algorithm - modular - multi-modular algorithm (default)
- • **kwds - ignored

EXAMPLES:

```python
sage: P.<x,y,z> = QQ[]
sage: f = (x*y*z)^6 - 1
sage: g = (x*y*z)^4 - 1
sage: f.gcd(g)
x^2*y^2*z^2 - 1
sage: GCD([x^3 - 3*x + 2, x^4 - 1, x^6 -1])
x - 1
sage: R.<x,y> = QQ[]
sage: f = (x^3 + 2*y^2*x)^2
sage: g = x^2*y^2
sage: f.gcd(g)
x^2
We compute a gcd over a finite field:

```python
sage: F.<u> = GF(31^2)
sage: R.<x,y,z> = F[]
sage: p = x^3 + (1+u)*y^3 + z^3
sage: q = p^3 * (x - y + z*u)
sage: gcd(p,q)
x^3 + (u + 1)*y^3 + z^3  
```

We compute a gcd over a number field:

```python
sage: x = polygen(QQ)
sage: F.<u> = NumberField(x^3 - 2)
sage: R.<x,y,z> = F[]
sage: p = x^3 + (1+u)*y^3 + z^3
sage: q = p^3 * (x - y + z*u)
sage: gcd(p,q)
x^3 + (u + 1)*y^3 + z^3
```
global_height\( (\text{prec} = \text{None}) \)

Return the (projective) global height of the polynomial.

This returns the absolute logarithmic height of the coefficients thought of as a projective point.

**INPUT:**

- prec – desired floating point precision (default: default RealField precision).

**OUTPUT:**

- a real number.

**EXAMPLES:**

```
sage: R.<x,y> = PolynomialRing(QQ)
sage: f = 3*x^3 + 2*x*y^2
sage: exp(f.global_height())
3.00000000000000
```

```
sage: K.<k> = CyclotomicField(3)
sage: R.<x,y> = PolynomialRing(K, sparse=True)
sage: f = k*x*y + 1
sage: exp(f.global_height())
1.00000000000000
```

Scaling should not change the result:

```
sage: R.<x,y> = PolynomialRing(QQ)
sage: f = 1/25*x^3 + 25/3*x*y^2
sage: f.global_height()
6.43775164973640
sage: g = 100 * f
sage: g.global_height()
6.43775164973640
```

```
sage: R.<x> = PolynomialRing(QQ)
sage: K.<k> = NumberField(x^2 + 5)
sage: T.<t,w> = PolynomialRing(K)
sage: f = 1/1331 * t^2 + 5 * w + 7
sage: f.global_height()
9.13959596745043
```

```
sage: R.<x,y> = QQ[]
sage: f = 1/123*x*y + 12
sage: f.global_height(prec=2)
8.0
```

```
sage: R.<x,y> = QQ[]
sage: f = 0*x*y
sage: f.global_height()
0.000000000000000
```

gradient()

Return a list of partial derivatives of this polynomial, ordered by the variables of the parent.

**EXAMPLES:**
```
sage: P.<x,y,z> = PolynomialRing(QQ,3)
sage: f= x*y + 1
sage: f.gradient()
[y, x, 0]
```

**hamming_weight()**

Return the number of non-zero coefficients of this polynomial. This is also called weight, hamming_weight() or sparsity.

**EXAMPLES:**

```
sage: R.<x, y> = ZZ[]
sage: f = x^3 - y
sage: f.number_of_terms()
2
sage: R(0).number_of_terms()
0
sage: f = (x+y)^100
sage: f.number_of_terms()
101
```

The method **hamming_weight()** is an alias:

```
sage: f.hamming_weight()
101
```

**integral(var)**

Integrate this polynomial with respect to the provided variable. One requires that Q is contained in the ring.

**INPUT:**

- variable – the integral is taken with respect to variable

**EXAMPLES:**

```
sage: R.<x, y> = PolynomialRing(QQ, 2)
sage: f = 3*x^3*y^2 + 5*y^2 + 3*x + 2
sage: f.integral(x)
3/4*x^4*y^2 + 5*x*y^2 + 3*x^2 + 2*x
sage: f.integral(y)
x^3*y^3 + 5/3*y^3 + 3*x*y + 2*y
```

Check that **github issue #15896** is solved:

```
sage: s = x+y
sage: s.integral(x)+x
1/2*x^2 + x*y + x
sage: s.integral(x)*s
1/2*x^3 + 3/2*x^2*y + x*y^2
```

**inverse_of_unit()**

Return the inverse of this polynomial if it is a unit.

**EXAMPLES:**

3.1. Multivariate Polynomials and Polynomial Rings 437
is\_constant()  
Return True if this polynomial is constant.

EXAMPLES:

```python
sage: P.<x,y,z> = PolynomialRing(GF(127))
sage: x.is_constant()  
False  
sage: P(1).is_constant()  
True
```

is\_homogeneous()  
Return True if this polynomial is homogeneous.

EXAMPLES:

```python
sage: P.<x,y> = PolynomialRing(RationalField(), 2)
sage: (x+y).is_homogeneous()  
True  
sage: (x.parent()(0)).is_homogeneous()  
True  
sage: (x+y^2).is_homogeneous()  
False  
sage: (x^2 + y^2).is_homogeneous()  
True  
sage: (x^2 + y^2*x).is_homogeneous()  
False  
sage: (x^2*y + y^2*x).is_homogeneous()  
True
```

is\_monomial()  
Return True if this polynomial is a monomial. A monomial is defined to be a product of generators with coefficient 1.

EXAMPLES:

```python
sage: P.<x,y,z> = PolynomialRing(QQ)
sage: x.is_monomial()  
True  
sage: (2*x).is_monomial()  
False  
sage: (x*y).is_monomial()  
True  
sage: (x*y + x).is_monomial()  
False
```
Polynomials, Release 10.0

sage: P(2).is_monomial()
False
sage: P.zero().is_monomial()
False

is_squarefree()
Return True if this polynomial is square free.

EXAMPLES:

sage: P.<x,y,z> = PolynomialRing(QQ)
sage: f= x^2 + 2*x*y + 1/2*z
sage: f.is_squarefree()
True
sage: h = f^2
sage: h.is_squarefree()
False

is_term()
Return True if self is a term, which we define to be a product of generators times some coefficient, which need not be 1.
Use is_monomial() to require that the coefficient be 1.

EXAMPLES:

sage: P.<x,y,z> = PolynomialRing(QQ)
sage: x.is_term()
True
sage: (2*x).is_term()
True
sage: (x*y).is_term()
True
sage: (x*y + x).is_term()
False
sage: P(2).is_term()
True
sage: P.zero().is_term()
False

is_univariate()
Return True if self is a univariate polynomial, that is if self contains only one variable.

EXAMPLES:

sage: P.<x,y,z> = GF(2)[]
sage: f = x^2 + 1
sage: f.is_univariate()
True
sage: f = y*x^2 + 1
sage: f.is_univariate()
False
sage: f = P(0)

(continues on next page)
is_zero()

Return True if this polynomial is zero.

EXAMPLES:

```sage
sage: P.<x,y> = PolynomialRing(QQ)
sage: x.is_zero()
False
sage: (x-x).is_zero()
True
```

iterator_exp_coeff(as_ETuples=True)

Iterate over self as pairs of ((E)Tuple, coefficient).

INPUT:

- as_ETuples – (default: True) if True iterate over pairs whose first element is an ETuple, otherwise as a tuples

EXAMPLES:

```sage
sage: R.<a,b,c> = QQ[]
sage: f = a*c^3 + a^2*b + 2*b^4
sage: list(f.iterator_exp_coeff())
[((0, 4, 0), 2), ((1, 0, 3), 1), ((2, 1, 0), 1)]
sage: list(f.iterator_exp_coeff(as_ETuples=False))
[((0, 4, 0), 2), ((1, 0, 3), 1), ((2, 1, 0), 1)]
sage: R.<a,b,c> = PolynomialRing(QQ, 3, order='lex')
sage: f = a*c^3 + a^2*b + 2*b^4
sage: list(f.iterator_exp_coeff())
[((2, 1, 0), 1), ((1, 0, 3), 1), ((0, 4, 0), 2)]
```

lc()

Leading coefficient of this polynomial with respect to the term order of self.parent().

EXAMPLES:

```sage
sage: R.<x,y,z>=PolynomialRing(GF(7),3,order='lex')
sage: f = 3*x^1*y^2 + 2*y^3*z^4
sage: f.lc()
3
```

lcm(g)

Return the least common multiple of self and g.

EXAMPLES:
sage: P.<x,y,z> = QQ[]
sage: p = (x+y)*(y+z)
sage: q = (z^4+2)*(y+z)
sage: lcm(p,q)
x*y*z^4 + y^2*z^4 + x*z^5 + y*z^5 + 2*x*y + 2*y^2 + 2*x*z + 2*y*z

sage: P.<x,y,z> = ZZ[]
sage: p = 2*(x+y)*(y+z)
sage: q = 3*(z^4+2)*(y+z)
sage: lcm(p,q)
6*x*y*z^4 + 6*y^2*z^4 + 6*x*z^5 + 6*y*z^5 + 12*x*y^2 + 12*x*z + 12*y*z

sage: r.<x,y> = PolynomialRing(GF(2^8, 'a'), 2)
sage: a = r.base_ring().0
sage: f = (a^2+a)*x^2*y + (a^4+a^3+a)*y + a^5
sage: f.lcm(x^4)
(a^2 + a)*x^6*y + (a^4 + a^3 + a)*x^4*y + (a^5)*x^4

sage: w = var('w')
sage: r.<x,y> = PolynomialRing(NumberField(w^4 + 1, 'a'), 2)
sage: a = r.base_ring().0
sage: f = (a^2+a)*x^2*y + (a^4+a^3+a)*y + a^5
sage: f.lcm(x^4)
(a^2 + a)*x^6*y + (a^3 + a - 1)*x^4*y + (-a)*x^4

\textbf{lift(I)}

given an ideal \( I = (f_1, \ldots, f_r) \) and some \( g \ (== \text{self}) \) in \( I \), find \( s_1, \ldots, s_r \) such that \( g = s_1 f_1 + \ldots + s_r f_r \).

A \texttt{ValueError} exception is raised if \( g \ (== \text{self}) \) does not belong to \( I \).

\textbf{EXAMPLES:}

sage: A.<x,y> = PolynomialRing(QQ,2,order='degrevlex')
sage: I = A.ideal([x^10 + x^9*y^2, y^8 - x^2*y^7 ])
sage: f = x*y^13 + y^12
sage: M = f.lift(I)
sage: M
[y^7, x^7*y^2 + x^8 + x^5*y^3 + x^6*y + x^3*y^4 + x^4*y^2 + x*y^5 + x^2*y^3 + y^4]
sage: sum( map( mul , zip( M, I.gens() ) ) ) == f
True

Check that \href{https://github.com/sagemath/sage/commit/13671}{github issue #13671} is fixed:

sage: R.<x1,x2> = QQ[]
sage: I = R.ideal(x2**2 + x1 - 2, x1**2 - 1)
sage: f = I.gen(0) + x2*I.gen(1)
sage: f.lift(I)
[1, x2]
sage: (f+1).lift(I)
Traceback (most recent call last):
  ... ValueError: polynomial is not in the ideal

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\textbf{sage}: \texttt{f.lift(I)}
\begin{verbatim}
[1, x2]
\end{verbatim}

\textbf{lm()}

Returns the lead monomial of self with respect to the term order of \texttt{self.parent()}. In Sage a monomial is a product of variables in some power without a coefficient.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: R.<x,y,z>=PolynomialRing(GF(7),3,order='lex')
sage: f = x^1*y^2 + y^3*z^4
sage: f.lm()
x*y^2
sage: f = x^3*y^2*z^4 + x^3*y^2*z^1
sage: f.lm()
x^3*y^2*z^4
sage: R.<x,y,z>=PolynomialRing(QQ,3,order='deglex')
sage: f = x^1*y^2*z^3 + x^3*y^2*z^0
sage: f.lm()
x*y^2*z^3
sage: f = x^1*y^2*z^4 + x^1*y^1*z^5
sage: f.lm()
x*y^2*z^4
sage: R.<x,y,z>=PolynomialRing(GF(127),3,order='degrevlex')
sage: f = x^1*y^5*z^2 + x^4*y^1*z^3
sage: f.lm()
x*y^5*z^2
sage: f = x^4*y^7*z^1 + x^4*y^2*z^3
sage: f.lm()
x^4*y^7*z
\end{verbatim}

\textbf{local_height}(v, \texttt{prec=None})

Return the maximum of the local height of the coefficients of this polynomial.

\textbf{INPUT:}

\begin{itemize}
\item \texttt{v} – a prime or prime ideal of the base ring.
\item \texttt{prec} – desired floating point precision (default: default RealField precision).
\end{itemize}

\textbf{OUTPUT:}

\begin{itemize}
\item a real number.
\end{itemize}

\textbf{EXAMPLES:}

\begin{verbatim}
sage: R.<x,y> = PolynomialRing(QQ)
sage: f = 1/1331*x^2 + 1/4000*y^2
sage: f.local_height(1331)
7.19368581839511
sage: R.<x> = QQ[]
sage: K.<k> = NumberField(x^2 - 5)
\end{verbatim}

(continues on next page)
### local_height_arch \(i, prec=None\)

Return the maximum of the local height at the \(i\)-th infinite place of the coefficients of this polynomial.

**INPUT:**

- \(i\) – an integer.
- \(prec\) – desired floating point precision (default: default RealField precision).

**OUTPUT:**

- a real number.

**EXAMPLES:**

```python
sage: R.<x,y> = PolynomialRing(QQ)
sage: f = 210*x*y
sage: f.local_height_arch(0)
5.34710753071747

sage: R.<x> = QQ[]
sage: K.<k> = NumberField(x^2 - 5)
sage: T.<t,w> = K[]
sage: f = 1/2*t*w + 3
sage: f.local_height_arch(1, prec=52)
1.09861228866811

sage: R.<x,y> = QQ[]
sage: f = 1/2*x*y + 3
sage: f.local_height_arch(0, prec=2)
1.0
```

### lt()

Leading term of this polynomial. In Sage a term is a product of variables in some power and a coefficient.

**EXAMPLES:**

```python
sage: R.<x,y,z>=PolynomialRing(GF(7),3,order='lex')
sage: f = 3*x^1*y^2 + 2*y^3*z^4
sage: f.lt()
3*x*y^2

sage: f = 5*x^3*y^2*z^4 + 4*x^3*y^2*z^1
```

(continues on next page)
Polynomials, Release 10.0

\begin{verbatim}
sage: f.lt()
-2*x^3*y^2*z^4

\end{verbatim}

**monomial_coefficient** (\texttt{mon})

Return the coefficient in the base ring of the monomial \texttt{mon} in \texttt{self}, where \texttt{mon} must have the same parent as \texttt{self}.

This function contrasts with the function \texttt{coefficient} which returns the coefficient of a monomial viewing this polynomial in a polynomial ring over a base ring having fewer variables.

**INPUT:**

- \texttt{mon} - a monomial

**OUTPUT:**

coefficient in base ring

**See also:**

For coefficients in a base ring of fewer variables, look at \texttt{coefficient}.

**EXAMPLES:**

\begin{verbatim}
sage: P.<x,y> = QQ[]
The parent of the return is a member of the base ring.
sage: f = 2 * x * y
sage: c = f.monomial_coefficient(x*y); c
2
sage: c.parent()
Rational Field

sage: f = y^2 + y^2*x - x^9 - 7*x + 5*x*y
sage: f.monomial_coefficient(y^2)
1
sage: f.monomial_coefficient(x*y)
5
sage: f.monomial_coefficient(x^9)
-1
sage: f.monomial_coefficient(x^10)
0

\end{verbatim}

**monomials**

Return the list of monomials in \texttt{self}. The returned list is decreasingly ordered by the term ordering of \texttt{self.parent()}.

**EXAMPLES:**

\begin{verbatim}
sage: P.<x,y,z> = QQ[]
sage: f = x + 3/2*y*z^2 + 2/3
sage: f.monomials()
[y*z^2, x, 1]
sage: f = P(3/2)
sage: f.monomials()
[1]
\end{verbatim}
**number_of_terms()**

Return the number of non-zero coefficients of this polynomial.

This is also called weight, `hamming_weight()` or sparsity.

**EXAMPLES:**

```python
sage: R.<x, y> = ZZ[]
sage: f = x^3 - y
sage: f.number_of_terms()
2
sage: R(0).number_of_terms()
0
sage: f = (x+y)^100
sage: f.number_of_terms()
101
```

The method `hamming_weight()` is an alias:

```python
sage: f.hamming_weight()
101
```

**numerator()**

Return a numerator of self computed as self * self.denominator()

If the base_field of self is the Rational Field then the numerator is a polynomial whose base_ring is the Integer Ring, this is done for compatibility to the univariate case.

**Warning:** This is not the numerator of the rational function defined by self, which would always be self since self is a polynomial.

**EXAMPLES:**

First we compute the numerator of a polynomial with integer coefficients, which is of course self.

```python
sage: R.<x, y> = ZZ[]
sage: f = x^3 + 17*y + 1
sage: f.numerator()
x^3 + 17*y + 1
sage: f == f.numerator()
True
```

Next we compute the numerator of a polynomial with rational coefficients.

```python
sage: R.<x,y> = PolynomialRing(QQ)
sage: f = (1/17)*x^19 - (2/3)*y + 1/3; f
1/17*x^19 - 2/3*y + 1/3
sage: f.numerator()
x^19 + 34*y + 17
sage: f == f.numerator()
False
sage: f.numerator().base_ring()
Integer Ring
```

We check that the computation of numerator and denominator is valid.

3.1. Multivariate Polynomials and Polynomial Rings 445
Polynomials, Release 10.0

```python
sage: K=QQ['x,y']
sage: f=K.random_element()
sage: f.numerator() / f.denominator() == f
True
```

The following tests against a bug fixed in github issue #11780:

```python
sage: P.<foo,bar> = ZZ[]
sage: Q.<foo,bar> = QQ[]
sage: f = Q.random_element()
sage: f.numerator().parent() is P
True
```

**nvariables()**

Return the number variables in this polynomial.

EXAMPLES:

```python
sage: P.<x,y,z> = PolynomialRing(GF(127))
sage: f = x*y + z
sage: f.nvariables()
3
sage: f = x + y
sage: f.nvariables()
2
```

**quo_rem(right)**

Returns quotient and remainder of self and right.

EXAMPLES:

```python
sage: R.<x,y> = QQ[]
sage: f = y*x^2 + x + 1
sage: f.quo_rem(x)
(x*y + 1, 1)
sage: f.quo_rem(y)
(x^2, x + 1)
```

```python
sage: f = 2*y*x^2 + x + 1
sage: f.quo_rem(x)
(2*x*y + 1, 1)
sage: f.quo_rem(y)
(2*x^2, x + 1)
sage: f.quo_rem(3*x)
(0, 2*x^2*y + x + 1)
```

**reduce(I)**

Return a remainder of this polynomial modulo the polynomials in I.

INPUT:

- I - an ideal or a list/set/iterable of polynomials.

OUTPUT:

A polynomial r such that:
• self - r is in the ideal generated by I.

• No term in r is divisible by any of the leading monomials of I.

The result r is canonical if:

• I is an ideal, and Sage can compute a Groebner basis of it.

• I is a list/set/iterable that is a (strong) Groebner basis for the term order of self. (A strong Groebner basis is such that for every leading term t of the ideal generated by I, there exists an element g of I such that the leading term of g divides t.)

The result r is implementation-dependent (and possibly order-dependent) otherwise. If I is an ideal and no Groebner basis can be computed, its list of generators I.gens() is used for the reduction.

EXAMPLES:

\begin{verbatim}
sage: P.<x,y,z> = QQ[]
sage: f1 = -2 * x^2 + x^3
sage: f2 = -2 * y + x* y
sage: f3 = -x^2 + y^2
sage: F = Ideal([f1,f2,f3])
sage: g = x*y - 3*x*y^2
sage: g.reduce(F)
-6*y^2 + 2*y
sage: g.reduce(F.gens())
-6*y^2 + 2*y
\end{verbatim}

Z is also supported.

\begin{verbatim}
sage: P.<x,y,z> = ZZ[]
sage: f1 = -2 * x^2 + x^3
sage: f2 = -2 * y + x* y
sage: f3 = -x^2 + y^2
sage: F = Ideal([f1,f2,f3])
sage: g = x*y - 3*x*y^2
sage: g.reduce(F)
-6*y^2 + 2*y
sage: g.reduce(F.gens())
-6*y^2 + 2*y
\end{verbatim}

The reduction is not canonical when I is not a Groebner basis:

\begin{verbatim}
sage: A.<x,y> = QQ[]
sage: (x+y).reduce([x+y, x-y])
2*y
sage: (x+y).reduce([x-y, x+y])
0
\end{verbatim}

resultant(other, variable=None)

Compute the resultant of this polynomial and the first argument with respect to the variable given as the second argument.

If a second argument is not provided, the first variable of the parent is chosen.
INPUT:

- other - polynomial
- variable - optional variable (default: None)

EXAMPLES:

```
sage: P.<x,y> = PolynomialRing(QQ,2)
sage: a = x+y
sage: b = x^3-y^3
sage: c = a.resultant(b); c
-2*y^3
sage: d = a.resultant(b,y); d
2*x^3
```

The SINGULAR example:

```
sage: R.<x,y,z> = PolynomialRing(GF(32003),3)
sage: f = 3 *(x+2)^3 + y
sage: g = x+y+z
sage: f.resultant(g,x)
3*y^3 + 9*y^2*z + 9*y*z^2 + 3*z^3 - 18*y^2 - 36*y*z - 18*z^2 + 35*y + 36*z - 24
```

Resultants are also supported over the Integers:

```
sage: R.<x,y,a,b,u>=PolynomialRing(ZZ, 5, order='lex')
sage: r = (x^4*y^2+x^2*y-y).resultant(x*y-y*a-x*b+a*b+u,x)
sage: r
y^6*a^4 - 4*y^5*a^4*b - 4*y^5*a^3*u + y^5*a^2 - y^5 + 6*y^4*a^4*b^2 + 12*y^4*a^3*b - 3*b^3 - 12*y^3*a^3*b^2*u + 6*y^3*a^2*b^3 - 12*y^3*a^2*b*u^2 + 6*y^3*a*b^3 - 4*y^3*a^2*u^2 + 6*y^3*b^3 - 3*y^3*b^2*u^2 + 6*y^2*a^4*b^4 + 12*y^2*a^3*b^3*u - 6*y^2*a^2*b^3 + 6*y^2*a^2*b^2*u - 2*y^2*a*b^2*u^2 + 4*y^2*a*b*u^3 + 4*y^2*b^3 - 2*y^2*b^2*u^2 + y^2*b^2*u^3 + y^a^2*b^4 + 2*y^a*b^3*u - y^a*b^3*u^2 + y^a*b^2*u^3 + y^a*b^2*u^2
```

$sub_m_mul_q(m, q)$

Return $self - m*q$, where $m$ must be a monomial and $q$ a polynomial.

INPUT:

- $m$ - a monomial
- $q$ - a polynomial

EXAMPLES:

```
sage: P.<x,y,z>=PolynomialRing(QQ,3)
sage: x.sub_m_mul_q(y,z)
-y*z + x
```

$subs$ (fixed=None, **kw)

Fixes some given variables in a given multivariate polynomial and returns the changed multivariate polynomials. The polynomial itself is not affected. The variable,value pairs for fixing are to be provided as dictionary of the form \{variable:value\}.

This is a special case of evaluating the polynomial with some of the variables constants and the others the original variables, but should be much faster if only few variables are to be fixed.
INPUT:

- **fixed** - (optional) dict with variable:value pairs
- ****kw - names parameters

OUTPUT: a new multivariate polynomial

EXAMPLES:

```sage
sage: R.<x,y> = QQ[]
sage: f = x^2 + y + x^2*y^2 + 5
sage: f(5,y)
25*y^2 + y + 30
sage: f.subs({x:5})
25*y^2 + y + 30
sage: f.subs(x=5)
25*y^2 + y + 30
sage: P.<x,y,z> = PolynomialRing(GF(2),3)
sage: f = x + y + 1
sage: f.subs({x:y+1})
0
sage: f.subs(x=y)
1
sage: f.subs(x=x)
x + y + 1
sage: f.subs({x:y})
y + z + 1
sage: f.subs(x=z+1)
y + z
sage: f.subs(x=1/y)
(y^2 + y + 1)/y
sage: f.subs({x:1/y})
(y^2 + y + 1)/y
```

The parameters are substituted in order and without side effects:

```sage
sage: R.<x,y>=QQ[]
sage: g=x+y
sage: g.subs({x:x+1,y:x*y})
x*y + x + 1
sage: g.subs({x:x+1}).subs({y:x*y})
x*y + x + 1
sage: g.subs({y:x*y}).subs({x:x+1})
x*y + x + y + 1
```

```sage
sage: R.<x,y> = QQ[]
sage: f = x + 2*y
sage: f.subs(x=y,y=x)
2*x + y
```

**total_degree**(std_grading=False)

Return the total degree of `self`, which is the maximum degree of all monomials in `self`.

EXAMPLES:
sage: R.<x,y,z> = QQ[]
sage: f = 2*x*y^3*z^2
sage: f.total_degree()
6
sage: f = 4*x^2*y^2*z^3
sage: f.total_degree()
7
sage: f = 99*x^6*y^3*z^9
sage: f.total_degree()
18
sage: f = x*y^3*z^6+3*x^2
sage: f.total_degree()
10
sage: f = z^3+8*x^4*y^5*z
sage: f.total_degree()
10
sage: f = z^9+10*x^4+y^8*x^2
sage: f.total_degree()
10

A matrix term ordering changes the grading. To get the total degree using the standard grading, use std_grading=True:

sage: tord = TermOrder(matrix(3, 
[3,2,1],
[1,1,0],
[1,0,0]))
sage: tord
Matrix term order with matrix

[3 2 1]
[1 1 0]
[1 0 0]
sage: R.<x,y,z> = PolynomialRing(QQ, order=tord)
sage: f = x^2*y
sage: f.total_degree()
8
sage: f.total_degree(std_grading=True)
3

univariate_polynomial(R=None)

Returns a univariate polynomial associated to this multivariate polynomial.

INPUT:

• R - (default: None) PolynomialRing

If this polynomial is not in at most one variable, then a ValueError exception is raised. This is checked using the is_univariate() method. The new Polynomial is over the same base ring as the given MPolynomial and in the variable x if no ring R is provided.

EXAMPLES:

sage: R.<x, y> = QQ[]
sage: f = 3*x^2 - 2*y + 7*x^2*y^2 + 5
sage: f.univariate_polynomial()
Traceback (most recent call last):
...  
TypeError: polynomial must involve at most one variable
Here's an example with a constant multivariate polynomial:

```python
sage: g = R(1)
sage: h = g.univariate_polynomial(); h
1
sage: h.parent()
Univariate Polynomial Ring in x over Rational Field
```

### `variable(i=0)`

Return the i-th variable occurring in self. The index i is the index in `self.variables()`.

**EXAMPLES:**

```python
sage: P.<x,y,z> = GF(2)[]
sage: f = x*z^2 + z + 1
sage: f.variables()
(x, z)
sage: f.variable(1)
z
```

### `variables()`

Return a tuple of all variables occurring in self.

**EXAMPLES:**

```python
sage: P.<x,y,z> = GF(2)[]
sage: f = x*z^2 + z + 1
sage: f.variables()
(x, z)
```

sage.rings.polynomial.multi_polynomial_libsingular.unpickle_MPolynomialRing_libsingular

*inverse function for `MPolynomialRing_libsingular.__reduce__`*

**EXAMPLES:**

```python
sage: P.<x,y> = PolynomialRing(QQ)
sage: loads(dumps(P)) is P  # indirect doctest
True
```

sage.rings.polynomial.multi_polynomial_libsingular.unpickle_MPolynomial_libsingular

*Deserialize an `MPolynomial_libsingular` object*

**INPUT:**

- `R` - the base ring
- `d` - a Python dictionary as returned by `MPolynomial_libsingular.dict()`
3.1.9 Direct low-level access to SINGULAR’s Groebner basis engine via libSINGULAR

AUTHOR:
• Martin Albrecht (2007-08-08): initial version

EXAMPLES:

```python
sage: x, y, z = QQ['x, y, z'].gens()
sage: I = ideal(x^5 + y^4 + z^3 - 1, x^3 + y^3 + z^2 - 1)
sage: I.groebner_basis('libsingular:std')
[y^6 + x*y^4 + 2*y^3*z^2 + x*z^3 + z^4 - 2*y^3 - 2*z^2 - x + 1,
x^2*y^3 - y^4 + x^2*z^2 - z^3 - x^2 + 1, x^3 + y^3 + z^2 - 1]
```

We compute a Groebner basis for cyclic 6, which is a standard benchmark and test ideal:

```python
sage: R.<x,y,z,t,u,v> = QQ['x,y,z,t,u,v']
sage: I = R.ideal(Cyclic(R,6))
sage: B = I.groebner_basis('libsingular:std')
sage: len(B)
45
```

Two examples from the Mathematica documentation (done in Sage):

• We compute a Groebner basis:

```python
sage: R.<x,y> = PolynomialRing(QQ, order='lex')
sage: ideal(x^2 - 2*y^2, x*y - 3).groebner_basis('libsingular:slimgb')
[x - 2/3*y^3, y^4 - 9/2]
```

• We show that three polynomials have no common root:

```python
sage: R.<x,y> = QQ[]
sage: ideal(x+y, x^2 - 1, y^2 - 2*x).groebner_basis('libsingular:slimgb')
[1]
```

SINGULAR’s interred() command.

INPUT:
• I – a Sage ideal

EXAMPLES:

```python
sage: P.<x,y,z> = PolynomialRing(ZZ)
sage: I = ideal( x^2 - 3*y, y^3 - x*y, z^3 - x, x^4 - y^z + 1 )
sage: I.interreduced_basis()
[y^z^2 - 81*x*y - 9*y - z, z^3 - x, x^2 - 3*y, 9*y^2 - y*z + 1]
```

(continues on next page)
sage: P.<x,y,z> = PolynomialRing(QQ)
sage: I = ideal( x^2 - 3*y, y^3 - x*y, z^3 - x, x^4 - y*z + 1 )
sage: I.interreduced_basis()
[y*z^2 - 81*x*y - 9*y - z, z^3 - x, x^2 - 3*y, y^2 - 1/9*y*z + 1/9]

sage.rings.polynomial.multi_polynomial_ideal_libsingular.kbase_libsingular(I, degree=None)

SINGULAR’s kbase() algorithm.

INPUT:

• I – a groebner basis of an ideal

• degree – integer (default: None); if not None, return only the monomials of the given degree

OUTPUT:

Computes a vector space basis (consisting of monomials) of the quotient ring by the ideal, resp. of a free module by the module, in case it is finite dimensional and if the input is a standard basis with respect to the ring ordering. If the input is not a standard basis, the leading terms of the input are used and the result may have no meaning.

With two arguments: computes the part of a vector space basis of the respective quotient with degree of the monomials equal to the second argument. Here, the quotient does not need to be finite dimensional.

EXAMPLES:

sage: R.<x,y> = PolynomialRing(QQ, order='lex')
sage: I = R.ideal(x^2-2*y^2, x*y-3)
sage: I.normal_basis()  # indirect doctest
[y^3, y^2, y, 1]
sage: J = R.ideal(x^2-2*y^2)
sage: [J.normal_basis(d) for d in (0..4)]  # indirect doctest
[[1], [y, x], [y^2, x*y], [y^3, x*y^2], [y^4, x*y^3]]

sage.rings.polynomial.multi_polynomial_ideal_libsingular.slimb_libsingular(I)

SINGULAR’s slimgb() algorithm.

INPUT:

• I – a Sage ideal

sage.rings.polynomial.multi_polynomial_ideal_libsingular.std_libsingular(I)

SINGULAR’s std() algorithm.

INPUT:

• I – a Sage ideal
3.1.10 Solution of polynomial systems using msolve

msolve is a multivariate polynomial system solver based on Gröbner bases. This module provides implementations of some operations on polynomial ideals based on msolve. Note that the optional package msolve must be installed.

See also:

- sage.features.msolve
- sage.rings.polynomial.multi_polynomial_ideal

sage.rings.polynomial.msolve.groebner_basis_degrevlex(ideal)

Compute a degrevlex Gröbner basis using msolve

EXAMPLES:

```python
sage: from sage.rings.polynomial.msolve import groebner_basis_degrevlex

sage: R.<a,b,c> = PolynomialRing(GF(101), 3, order='lex')
sage: I = sage.rings.ideal.Katsura(R,3)
sage: gb = groebner_basis_degrevlex(I); gb
[0, 2*b + 2*c - 1, b*c - 19*c^2 + 10*b + 40*c, b^2 - 41*c^2 + 20*b - 20*c, c^3 + 28*c^2 - 37*b + 13*c]
sage: gb.universe() is R
False
sage: gb.universe().term_order()
Degree reverse lexicographic term order
sage: ideal(gb).transformed_basis(other_ring=R)
[c^4 + 38*c^3 - 6*c^2 - 6*c, 30*c^3 + 32*c^2 + b - 14*c, a + 2*b + 2*c - 1]
```

sage.rings.polynomial.msolve.variety(ideal, ring, proof)

Compute the variety of a zero-dimensional ideal using msolve.

Part of the initial implementation was loosely based on the example interfaces available as part of msolve, with the authors' permission.

EXAMPLES:

```python
sage: from sage.rings.polynomial.msolve import variety

sage: p = 536870909
sage: R.<x, y> = PolynomialRing(GF(p), 2, order='lex')
sage: I = Ideal([x*y - 1, (x-2)^2 + (y-1)^2 - 1])
sage: sorted(variety(I, GF(p^2), proof=False, key='str'))
[x: 1, y: 1],
{x: 254228855*z2 + 114981228, y: 232449571*z2 + 402714189},
{x: 267525699, y: 473946006},
{x: 282642054*z2 + 154363985, y: 304421338*z2 + 197081624]
3.1.11 Generic data structures for multivariate polynomials

This module provides an implementation of a generic data structure PolyDict and the underlying arithmetic for multivariate polynomial rings. It uses a sparse representation of polynomials encoded as a Python dictionary where keys are exponents and values coefficients.

\{(e_1,\ldots,e_r):c_1\} \leftrightarrow c_1x_1^{e_1}\ldots x_r^{e_r}+\ldots,

The exponent \((e_1,\ldots,e_r)\) in this representation is an instance of the class ETuple.

AUTHORS:

- William Stein
- David Joyner
- Martin Albrecht (ETuple)
- Joel B. Mohler (2008-03-17) – ETuple rewrite as sparse C array

class sage.rings.polynomial.polydict.ETuple

  Representation of the exponents of a polydict monomial. If \((0,0,3,0,5)\) is the exponent tuple of \(x_2^3x_4^5\) then this class only stores \(\{2:3, 4:5\}\) instead of the full tuple. This sparse information may be obtained by provided methods.

  The index/value data is all stored in the _data C int array member variable. For the example above, the C array would contain 2,3,4,5. The indices are interlaced with the values.

  This data structure is very nice to work with for some functions implemented in this class, but tricky for others. One reason that I really like the format is that it requires a single memory allocation for all of the values. A hashtable would require more allocations and presumably be slower. I didn’t benchmark this question (although, there is no question that this is much faster than the prior use of python dicts).

  combine_to_positives\(\)\(\text{other}\)

  Given a pair of ETuples \((\text{self, other})\), returns a triple of ETuples \((\text{a, b, c})\) so that \(\text{self} = \text{a} + \text{b}\), \(\text{other} = \text{a} + \text{c}\) and \(\text{b}\) and \(\text{c}\) have all positive entries.

  EXAMPLES:

  \[
  \begin{align*}
  \text{sage: from sage.rings.polynomial.polydict import ETuple} \\
  \text{sage: e} & = \text{ETuple([-2, 1, -5, 3, 1, 0])} \\
  \text{sage: f} & = \text{ETuple([1, -3, -3, 4, 0, 2])} \\
  \text{sage: e.combine_to_positives(f)} & = ((-2, -3, -5, 3, 0, 0), (0, 4, 0, 0, 1, 0), (3, 0, 2, 1, 0, 2))
  \end{align*}
  \]

  common_nonzero_positions\(\text{other, sort=False}\)

  Returns an optionally sorted list of non zero positions either in self or other, i.e. the only positions that need to be considered for any vector operation.

  EXAMPLES:

  \[
  \begin{align*}
  \text{sage: from sage.rings.polynomial.polydict import ETuple} \\
  \text{sage: e} & = \text{ETuple([1, 0, 2])} \\
  \text{sage: f} & = \text{ETuple([0, 0, 1])} \\
  \text{sage: e.common_nonzero_positions(f)} & = \{0, 2\} \\
  \text{sage: e.common_nonzero_positions(f, sort=True)} & = [0, 2]
  \end{align*}
  \]
divide_by_gcd(other)
    Return self / gcd(self, other).
    The entries of the result are the maximum of 0 and the difference of the corresponding entries of self and other.

divide_by_var(pos)
    Return division of self by the variable with index pos.
    If self[pos] == 0 then a ArithmeticError is raised. Otherwise, an ETuple is returned that is zero in position pos and coincides with self in the other positions.

EXAMPLES:

sage: from sage.rings.polynomial.polydict import ETuple
sage: e = ETuple([1, 2, 0, 1])
sage: e.divide_by_var(0)
(0, 2, 0, 1)
sage: e.divide_by_var(1)
(1, 1, 0, 1)
sage: e.divide_by_var(3)
(1, 2, 0, 0)
sage: e.divide_by_var(2)
Traceback (most recent call last):
... ArithmeticError: not divisible by this variable

divides(other)
    Return whether self divides other, i.e., no entry of self exceeds that of other.

EXAMPLES:

sage: from sage.rings.polynomial.polydict import ETuple
sage: ETuple([1, 1, 0, 1, 0]).divides(ETuple([2, 2, 2, 2, 2]))
True
sage: ETuple([0, 3, 0, 1, 0]).divides(ETuple([2, 2, 2, 2, 2]))
False
sage: ETuple([0, 3, 0, 1, 0]).divides(ETuple([0, 3, 2, 2, 2]))
True
sage: ETuple([0, 0, 0, 0, 0]).divides(ETuple([2, 2, 2, 2, 2]))
True
False
True

dotprod(other)
    Return the dot product of this tuple by other.

EXAMPLES:

sage: from sage.rings.polynomial.polydict import ETuple
sage: e = ETuple([1, 0, 2])
\texttt{sage: f = ETuple([0, 1, 1])}
\texttt{sage: e.dotprod(f)}
2
\texttt{sage: e = ETuple([1, 1, -1])}
\texttt{sage: f = ETuple([0, -2, 1])}
\texttt{sage: e.dotprod(f)}
-3

\texttt{eadd(others)}

Return the vector addition of self with other.

\textbf{EXAMPLES:}

\begin{verbatim}
\texttt{sage: from sage.rings.polynomial.polydict import ETuple}
\texttt{sage: e = ETuple([1, 0, 2])}
\texttt{sage: f = ETuple([0, 1, 1])}
\texttt{sage: e.eadd(f)}
(1, 1, 3)
\end{verbatim}

Verify that github issue \#6428 has been addressed:

\begin{verbatim}
\texttt{sage: R.<y, z> = Frac(QQ['x'])[]}
\texttt{sage: type(y)}
<class 'sage.rings.polynomial.multi_polynomial_libsingular.MPolynomial_libsingular'>
\texttt{sage: y^(2^32)}
Traceback (most recent call last):
... 
OverflowError: exponent overflow (...) # 64-bit
OverflowError: Python int too large to convert to C unsigned long # 32-bit
\end{verbatim}

\texttt{eadd_p(others, pos)}

Add other to self at position pos.

\textbf{EXAMPLES:}

\begin{verbatim}
\texttt{sage: from sage.rings.polynomial.polydict import ETuple}
\texttt{sage: e = ETuple([1, 0, 2])}
\texttt{sage: e.eadd_p(5, 1)}
(1, 5, 2)
\texttt{sage: e = ETuple([0]*7)}
\texttt{sage: e.eadd_p(5, 4)}
(0, 0, 0, 0, 5, 0, 0)
\texttt{ETuple([0,1]).eadd_p(1, 0) == ETuple([1,1])}
True
\texttt{sage: e = ETuple([0, 1, 0])}
\texttt{sage: e.eadd_p(0, 0).nonzero_positions()}
[1]
\texttt{sage: e.eadd_p(0, 1).nonzero_positions()}
[1]
\texttt{sage: e.eadd_p(0, 2).nonzero_positions()}
[1]
\end{verbatim}
**eadd_scaled**(other, scalar)

Vector addition of self with scalar * other.

**EXAMPLES:**

```python
sage: from sage.rings.polynomial.polydict import ETuple
sage: e = ETuple([1, 0, 2])
sage: f = ETuple([0, 1, 1])
sage: e.eadd_scaled(f, 3)
(1, 3, 5)
```

**emax**(other)

Vector of maximum of components of self and other.

**EXAMPLES:**

```python
sage: from sage.rings.polynomial.polydict import ETuple
sage: e = ETuple([1, 0, 2])
sage: f = ETuple([0, 1, 1])
sage: e.emax(f)
(1, 1, 2)
sage: e = ETuple([1, 2, 3, 4])
sage: f = ETuple([4, 0, 2, 1])
sage: f.emax(e)
(4, 2, 3, 4)
sage: e = ETuple([1, -2, -2, 4])
sage: f = ETuple([4, 0, 0, 0])
sage: f.emax(e)
(4, 0, 0, 4)
sage: f.emax(e).nonzero_positions()
[0, 3]
```

**emin**(other)

Vector of minimum of components of self and other.

**EXAMPLES:**

```python
sage: from sage.rings.polynomial.polydict import ETuple
sage: e = ETuple([1, 0, 2])
sage: f = ETuple([0, 1, 1])
sage: e.emin(f)
(0, 0, 1)
sage: e = ETuple([1, 0, -1])
sage: f = ETuple([0, -2, 1])
sage: e.emin(f)
(0, -2, -1)
```

**emul**(factor)

Scalar Vector multiplication of self.

**EXAMPLES:**

```python
sage: from sage.rings.polynomial.polydict import ETuple
sage: e = ETuple([1, 0, 2])
sage: e.emul(2)
(2, 0, 4)
```
**escalar_div**\((n)\)

Divide each exponent by \(n\).

**EXAMPLES:**

```
sage: from sage.rings.polynomial.polydict import ETuple
sage: ETuple([1, 0, 2]).escalar_div(2)
(0, 0, 1)
sage: ETuple([0, 3, 12]).escalar_div(3)
(0, 1, 4)
sage: ETuple([1, 5, 2]).escalar_div(0)
Traceback (most recent call last):
...
ZeroDivisionError```

**esub**\((other)\)

Vector subtraction of **self** with **other**.

**EXAMPLES:**

```
sage: from sage.rings.polynomial.polydict import ETuple
sage: e = ETuple([1, 0, 2])
sage: f = ETuple([0, 1, 1])
sage: e.esub(f)
(1, -1, 1)```

**is_constant**()

Return if all exponents are zero in the tuple.

**EXAMPLES:**

```
sage: from sage.rings.polynomial.polydict import ETuple
sage: e = ETuple([1, 0, 2])
sage: e.is_constant()
False
sage: e = ETuple([0, 0])
sage: e.is_constant()
True```

**is_multiple_of**\((n)\)

Test whether each entry is a multiple of \(n\).

**EXAMPLES:**

```
sage: from sage.rings.polynomial.polydict import ETuple
sage: ETuple([0, 0]).is_multiple_of(3)
True
sage: ETuple([0, 3, 12, 0, 6]).is_multiple_of(3)
True
sage: ETuple([0, 0, 2]).is_multiple_of(3)
False```

**nonzero_positions**\((sort=False)\)

Return the positions of non-zero exponents in the tuple.
INPUT:

- sort – (default: False) if True a sorted list is returned; if False an unsorted list is returned

EXAMPLES:

```
sage: from sage.rings.polynomial.polydict import ETuple
dsage: e = ETuple([1, 0, 2])
dsage: e.nonzero_positions()
[0, 2]
```

**nonzero_values** *(sort=True)*

Return the non-zero values of the tuple.

INPUT:

- sort – (default: True) if True the values are sorted by their indices; otherwise the values are returned unsorted

EXAMPLES:

```
sage: from sage.rings.polynomial.polydict import ETuple
dsage: e = ETuple([2, 0, 1])
dsage: e.nonzero_values()
[2, 1]
sage: f = ETuple([0, -1, 1])
dsage: f.nonzero_values(sort=True)
[-1, 1]
```

**reversed()**

Return the reversed ETuple of self.

EXAMPLES:

```
sage: from sage.rings.polynomial.polydict import ETuple
dsage: e = ETuple([1, 2, 3])
dsage: e.reversed()
(3, 2, 1)
```

**sparse_iter()**

Iterator over the elements of self where the elements are returned as (i, e) where i is the position of e in the tuple.

EXAMPLES:

```
sage: from sage.rings.polynomial.polydict import ETuple
dsage: e = ETuple([1, 0, 2, 0, 3])
dsage: list(e.sparse_iter())
[(0, 1), (2, 2), (4, 3)]
```

**unweighted_degree()**

Return the sum of entries.

EXAMPLES:

```
sage: from sage.rings.polynomial.polydict import ETuple
dsage: ETuple([1, 1, 0, 2, 0]).unweighted_degree()
```

(continues on next page)
unweighted_quotient_degree(other)
Return the degree of self divided by its gcd with other.
It amounts to counting the non-negative entries of self.esub(other).

weighted_degree(w)
Return the weighted sum of entries.

INPUT:
• w – tuple of non-negative integers

EXAMPLES:

```
sage: from sage.rings.polynomial.polydict import ETuple
sage: e = ETuple([1, 1, 0, 2, 0])
sage: e.weighted_degree((1, 2, 3, 4, 5))
11
sage: ETuple([-1, 1]).weighted_degree((1, 2))
1
sage: ETuple([1, 0]).weighted_degree((1, 2, 3))
Traceback (most recent call last):
  ... ValueError: w must be of the same length as the ETuple
```

weighted_quotient_degree(other, w)
Return the weighted degree of self divided by its gcd with other.

INPUT:
• other – an ETuple
• w – tuple of non-negative integers.

class sage.rings.polynomial.polydict.PolyDict
Bases: object

Data structure for multivariate polynomials.

A PolyDict holds a dictionary all of whose keys are ETuple and whose values are coefficients on which it is implicitly assumed that arithmetic operations can be performed.

No arithmetic operation on PolyDict clear zero coefficients as of now there is no reliable way of testing it in the most general setting, see github issue #35319. For removing zero coefficients from a PolyDict you can use the method remove_zeros() which can be parametrized by a zero test.

apply_map(f)
Apply the map f on the coefficients (inplace).

EXAMPLES:
sage: from sage.rings.polynomial.polydict import PolyDict
sage: f = PolyDict({(1, 0): 1, (1, 1): -2})

sage: f.apply_map(lambda x: x^2)

sage: f

PolyDict with representation {(1, 0): 1, (1, 1): 4}

coefficient(mon)

Return a polydict that defines a polynomial in 1 less number of variables that gives the coefficient of mon in this polynomial.

The coefficient is defined as follows. If f is this polynomial, then the coefficient is the sum T/mon where the sum is over terms T in f that are exactly divisible by mon.

coefficients()

Return the coefficients of self.

EXAMPLES:

sage: from sage.rings.polynomial.polydict import PolyDict
sage: f = PolyDict({(2, 3): 2, (1, 2): 3, (2, 1): 4})

sage: sorted(f.coefficients())
[2, 3, 4]

correct_coefficients(A)

Coerce the coefficients in the parent A

EXAMPLES:

sage: from sage.rings.polynomial.polydict import PolyDict
sage: f = PolyDict({(2, 3): 0})

sage: f
PolyDict with representation {(2, 3): 0}

sage: f.coerce_coefficients(QQ)

... DeprecationWarning: coerce_coefficients is deprecated; use apply_map instead
See https://github.com/sagemath/sage/issues/34000 for details.

sage: f
PolyDict with representation {(2, 3): 0}

degree(x=None)

Return the total degree or the maximum degree in the variable x.

EXAMPLES:

sage: from sage.rings.polynomial.polydict import PolyDict
sage: f = PolyDict({(2, 3): 2, (1, 2): 3, (2, 1): 4})

sage: f.degree()
5

sage: f.degree(PolyDict({(1, 0): 1}))
2

sage: f.degree(PolyDict({(0, 1): 1}))
3
**derivative**($x$)

Return the derivative of self with respect to $x$

EXAMPLES:

```python
sage: from sage.rings.polynomial.polydict import PolyDict
game: f = PolyDict({(2, 3): 2, (1, 2): 3, (2, 1): 4})
sage: f.derivative(PolyDict({(1, 0): 1}))
PolyDict with representation {(0, 2): 3, (1, 1): 8, (1, 3): 4}
sage: f.derivative(PolyDict({(0, 1): 1}))
PolyDict with representation {(1, 1): 6, (2, 0): 4, (2, 2): 6}
sage: PolyDict({(-1,): 1}).derivative(PolyDict({(1,): 1}))
PolyDict with representation {(-2,): -1}
sage: PolyDict({(-2,): 1}).derivative(PolyDict({(1,): 1}))
PolyDict with representation {(-3,): -2}
sage: PolyDict({}).derivative(PolyDict({(1, 1): 1}))
Traceback (most recent call last):
  ...  
ValueError: x must be a generator
```

**derivative_i**($i$)

Return the derivative of self with respect to the $i$-th variable.

EXAMPLES:

```python
sage: from sage.rings.polynomial.polydict import PolyDict
game: PolyDict({(1, 1): 1}).derivative_i(0)
PolyDict with representation {(0, 1): 1}
```

**dict()**

Return a copy of the dict that defines self.

EXAMPLES:

```python
sage: from sage.rings.polynomial.polydict import PolyDict
game: f = PolyDict({(2, 3): 2, (1, 2): 3, (2, 1): 4})
sgage: f.dict()
{(1, 2): 3, (2, 1): 4, (2, 3): 2}
```

**exponents()**

Return the exponents of self.

EXAMPLES:

```python
sage: from sage.rings.polynomial.polydict import PolyDict
game: f = PolyDict({(2, 3): 2, (1, 2): 3, (2, 1): 4})
game: sorted(f.exponents())
[(1, 2), (2, 1), (2, 3)]
```

**get**($e$, **default**=None)

Return the coefficient of the ETuple $e$ if present and default otherwise.

EXAMPLES:
Polynomials, Release 10.0

\[
sage: \text{from sage.rings.polynomial.polydict import PolyDict, ETuple}
\]
\[
sage: f = \text{PolyDict}(((2, 3): 2, (1, 2): 3, (2, 1): 4))
\]
\[
sage: f.get(ETuple([1,2]))
\]
\[
3
\]
\[
sage: f.get(ETuple([1,1]), 'hello')
\]
\[
'hello'
\]

**homogenize**(var)

Return the homogeneization of self by increasing the degree of the variable var.

EXAMPLES:

\[
sage: \text{from sage.rings.polynomial.polydict import PolyDict}
\]
\[
sage: f = \text{PolyDict}(((0, 0): 1, (2, 1): 3, (1, 1): 5))
\]
\[
sage: f.homogenize(0)
\]
\[
\text{PolyDict with representation } \{(2, 1): 8, (3, 0): 1\}
\]
\[
sage: f.homogenize(1)
\]
\[
\text{PolyDict with representation } \{(0, 3): 1, (1, 2): 5, (2, 1): 3\}
\]
\[
sage: \text{PolyDict}(((0, 1): 1, (1, 1): -1)).homogenize(0)
\]
\[
\text{PolyDict with representation } \{(1, 1): 0\}
\]

**integral**(x)

Return the integral of self with respect to x

EXAMPLES:

\[
sage: \text{from sage.rings.polynomial.polydict import PolyDict}
\]
\[
sage: f = \text{PolyDict}(((2, 3): 2, (1, 2): 3, (2, 1): 4))
\]
\[
sage: f.integral(PolyDict(((1, 0): 1)))
\]
\[
\]
\[
sage: f.integral(PolyDict(((0, 1): 1)))
\]
\[
\text{PolyDict with representation } \{(1, 3): 1, (2, 2): 2, (2, 4): 1/2\}
\]
\[
sage: PolyDict(((1,): 1)).integral(PolyDict(((1,): 1)))
\]
\[
\text{Traceback (most recent call last):}
\]
\[
\text{... ArithmeticError: integral of monomial with exponent -1}
\]
\[
sage: PolyDict(((2,-1): 1)).integral(PolyDict(((1,): 1)))
\]
\[
\text{PolyDict with representation } \{(-1,): -1\}
\]
\[
sage: PolyDict().integral(PolyDict(((1, 1): 1)))
\]
\[
\text{Traceback (most recent call last):}
\]
\[
\text{... ValueError: x must be a generator}
\]

**integral_i**(i)

Return the derivative of self with respect to the i-th variable.

EXAMPLES:

\[
sage: \text{from sage.rings.polynomial.polydict import PolyDict}
\]
\[
sage: PolyDict(((1, 1): 1)).integral_i(0)
\]
\[
\text{PolyDict with representation } \{(2, 1): 1/2\}
\]
is_constant()
Return whether this polynomial is constant.

EXAMPLES:

```sage
define f: from sage.rings.polynomial.polydict import PolyDict
sage: f = PolyDict({(2, 3): 2, (1, 2): 3, (2, 1): 4})
sage: f.is_constant()
False
sage: g = PolyDict({(0, 0): 2})
sage: g.is_constant()
True
sage: h = PolyDict({})
sage: h.is_constant()
True
```

is_homogeneous()
Return whether this polynomial is homogeneous.

EXAMPLES:

```sage
define f: from sage.rings.polynomial.polydict import PolyDict
sage: PolyDict({}).is_homogeneous()
True
sage: PolyDict({(1, 2): 1, (0, 3): -2}).is_homogeneous()
True
sage: PolyDict({(1, 0): 1, (1, 2): 3}).is_homogeneous()
False
```

latex(var, atomic_exponents=True, atomic_coefficients=True, sortkey=None)
Return a nice polynomial latex representation of this PolyDict, where the vars are substituted in.

INPUT:

• vars – list

• atomic_exponents – bool (default: True)

• atomic_coefficients – bool (default: True)

EXAMPLES:

```sage
define f: from sage.rings.polynomial.polydict import PolyDict
sage: f = PolyDict({(2, 3): 2, (1, 2): 3, (2, 1): 4})
sage: f.latex(['a', 'WW'])
'2 a^{2} WW^{3} + 4 a^{2} WW + 3 a WW^{2}'
```

lcmt(greater_etuple)
Provides functionality of lc, lm, and lt by calling the tuple compare function on the provided term order T.

INPUT:

• greater_etuple – a term order

list()
Return a list that defines self.

EXAMPLES:
```
sage: from sage.rings.polynomial.polydict import PolyDict
sage: f = PolyDict({(2, 3): 2, (1, 2): 3, (2, 1): 4})
sage: sorted(f.list())
[[2, [2, 3]], [3, [1, 2]], [4, [2, 1]]]
```

**max_exp()**

Returns an ETuple containing the maximum exponents appearing. If there are no terms at all in the PolyDict, it returns None.

The nvars parameter is necessary because a PolyDict doesn’t know it from the data it has (and an empty PolyDict offers no clues).

**EXAMPLES:**

```
sage: from sage.rings.polynomial.polydict import PolyDict
sage: f = PolyDict({(2, 3): 2, (1, 2): 3, (2, 1): 4})
sage: f.max_exp()
(2, 3)
sage: PolyDict({}).max_exp()  # returns None
```

**min_exp()**

Returns an ETuple containing the minimum exponents appearing. If there are no terms at all in the PolyDict, it returns None.

The nvars parameter is necessary because a PolyDict doesn’t know it from the data it has (and an empty PolyDict offers no clues).

**EXAMPLES:**

```
sage: from sage.rings.polynomial.polydict import PolyDict
sage: f = PolyDict({(2, 3): 2, (1, 2): 3, (2, 1): 4})
sage: f.min_exp()
(1, 1)
sage: PolyDict({}).min_exp()  # returns None
```

**monomial_coefficient** *(mon)*

Return the coefficient of the monomial *mon*.

**INPUT:**

- *mon* – a PolyDict with a single key

**EXAMPLES:**

```
sage: from sage.rings.polynomial.polydict import PolyDict
sage: f = PolyDict({(2, 3): 2, (1, 2): 3, (2, 1): 4})
sage: f.monomial_coefficient(PolyDict({(2, 1): 1}).dict())
doctest:warning
... DeprecationWarning: PolyDict.monomial_coefficient is deprecated; use PolyDict.
˓→get instead
See https://github.com/sagemath/sage/issues/34000 for details.
4
```

**poly_repr** *(vars, atomic_exponents=True, atomic_coefficients=True, sortkey=None)*

Return a nice polynomial string representation of this PolyDict, where the vars are substituted in.
INPUT:
• `vars` – list
• `atomic_exponents` – bool (default: True)
• `atomic_coefficients` – bool (default: True)

EXAMPLES:
```
sage: from sage.rings.polynomial.polydict import PolyDict
sage: f = PolyDict({(2,3):2, (1,2):3, (2,1):4})
sage: f.poly_repr(['a', 'WW'])
'2*a^2*WW^3 + 4*a^2*WW + 3*a*WW^2'
```

We check to make sure that when we are in characteristic two, we don’t put negative signs on the generators.
```
sage: Integers(2)['x, y'].gens()
(x, y)
```

We make sure that intervals are correctly represented.
```
sage: f = PolyDict({(2, 3): RIF(1/2,3/2), (1, 2): RIF(-1,1)})
sage: f.poly_repr(['x', 'y'])
'1.?*x^2*y^3 + 0.?*x*y^2'
```

`polynomial_coefficient(degrees)`

Return a polydict that defines the coefficient in the current polynomial viewed as a tower of polynomial extensions.

INPUT:
• `degrees` – a list of degree restrictions; list elements are None if the variable in that position should be unrestricted

EXAMPLES:
```
sage: from sage.rings.polynomial.polydict import PolyDict
sage: f = PolyDict({(2, 3): 2, (1, 2): 3, (2, 1): 4})
sage: f.polynomial_coefficient([2, None])
PolyDict with representation {(0, 1): 4, (0, 3): 2}
sage: f = PolyDict({(0, 3): 2, (0, 2): 3, (2, 1): 4})
sage: f.polynomial_coefficient([0, None])
PolyDict with representation {(0, 2): 3, (0, 3): 2}
```

`remove_zeros(zero_test=None)`

Remove the entries with zero coefficients.

INPUT:
• `zero_test` – optional function that performs test to zero of a coefficient

EXAMPLES:
```
sage: from sage.rings.polynomial.polydict import PolyDict
sage: f = PolyDict({(2, 3):0})
sage: f
PolyDict with representation {(2, 3): 0}
sage: f.remove_zeros()
```
(continues on next page)
The following example shows how to remove only exact zeros from a PolyDict containing univariate power series:

```
sage: R.<t> = PowerSeriesRing(QQ)
sage: f = PolyDict({(1, 1): 0(t), (1, 0): R.zero()})
sage: f.remove_zeros(lambda s: s.is_zero() and s.prec() is Infinity)
sage: f
PolyDict with representation {(1, 1): 0(t^1)}
```

**rich_compare**(other, op, sortkey=None)

Compare two PolyDict's using a specified term ordering 'sortkey'.

**EXAMPLES:**

```
sage: from sage.rings.polynomial.polydict import PolyDict
sage: from sage.structure.richcmp import op_EQ, op_NE, op_LT
sage: p1 = PolyDict({(0,): 1})
sage: p2 = PolyDict({(0,): 2})
sage: O = TermOrder()
sage: p1.rich_compare(PolyDict({(0,): 1}), op_EQ, O.sortkey)  # True
sage: p1.rich_compare(p2, op_EQ, O.sortkey)  # False
sage: p1.rich_compare(p2, op_NE, O.sortkey)  # True
sage: p1.rich_compare(p2, op_LT, O.sortkey)  # True
sage: p3 = PolyDict({(3, 2, 4): 1, (3, 2, 5): 2})
sage: p4 = PolyDict({(3, 2, 4): 1, (3, 2, 3): 2})
sage: p3.rich_compare(p4, op_LT, O.sortkey)  # False
```

**scalar_lmult**(s)

Return the left scalar multiplication of self by s.

**EXAMPLES:**

```
sage: from sage.rings.polynomial.polydict import PolyDict
sage: x, y = FreeMonoid(2, 'x, y').gens()  # a strange object to live in a polydict, but non-commutative!
sage: f = PolyDict({(2,3):x})
sage: f.scalar_lmult(y)
PolyDict with representation {(2, 3): y*x}
sage: f = PolyDict({(2,3):2, (1,2):3, (2,1):4})
sage: f.scalar_lmult(-2)
PolyDict with representation {(1, 2): -6, (2, 1): -8, (2, 3): -4}
sage: f.scalar_lmult(RIF(-1,1))
PolyDict with representation {(1, 2): 0.?e1, (2, 1): 0.?e1, (2, 3): 0.?e1}
```
scalar_rmult(s)

Return the right scalar multiplication of self by s.

EXAMPLES:

```
sage: from sage.rings.polynomial.polydict import PolyDict
sage: x, y = FreeMonoid(2, 'x, y').gens()  # a strange object to live in a
   →polydict, but non-commutative!
sage: f = PolyDict({(2, 3): x})
sage: f.scalar_rmult(y)
PolyDict with representation {(2, 3): x*y}
sage: f = PolyDict({(2,3):2, (1,2): 3, (2,1): 4})
sage: f.scalar_rmult(-2)
PolyDict with representation {(1, 2): -6, (2, 1): -8, (2, 3): -4}
sage: f.scalar_rmult(RIF(-1,1))
PolyDict with representation {(1, 2): 0.?e1, (2, 1): 0.?e1, (2, 3): 0.?e1}
```

term_lmult(exponent, s)

Return this element multiplied by s on the left and with exponents shifted by exponent.

INPUT:

- exponent – a ETuple
- s – a scalar

EXAMPLES:

```
sage: from sage.rings.polynomial.polydict import ETuple, PolyDict
sage: x, y = FreeMonoid(2, 'x, y').gens()  # a strange object to live in a
   →polydict, but non-commutative!
sage: f = PolyDict({(2, 3): x})
sage: f.term_lmult(ETuple((1, 2)), y)
PolyDict with representation {(3, 5): y*x}
sage: f = PolyDict({(2,3): 2, (1,2): 3, (2,1): 4})
sage: f.term_lmult(ETuple((1, 2)), -2)
PolyDict with representation {(2, 4): -6, (3, 3): -8, (3, 5): -4}
```

term_rmult(exponent, s)

Return this element multiplied by s on the right and with exponents shifted by exponent.

INPUT:

- exponent – a ETuple
- s – a scalar

EXAMPLES:

```
sage: from sage.rings.polynomial.polydict import ETuple, PolyDict
sage: x, y = FreeMonoid(2, 'x, y').gens()  # a strange object to live in a
   →polydict, but non-commutative!
sage: f = PolyDict({(2, 3): x})
sage: f.term_rmult(ETuple((1, 2)), y)
PolyDict with representation {(3, 5): x*y}
sage: f = PolyDict({(2,3): 2, (1,2): 3, (2,1): 4})
sage: f.term_rmult(ETuple((1, 2)), -2)
PolyDict with representation {(2, 4): -6, (3, 3): -8, (3, 5): -4}
```
(continues on next page)
sage: f.term_rmult(ETuple((1, 2)), -2)
PolyDict with representation {(2, 4): -6, (3, 3): -8, (3, 5): -4}

total_degree(w=None)
Return the total degree.

INPUT:
• w – (optional) a tuple of weights

EXAMPLES:

sage: from sage.rings.polynomial.polydict import PolyDict
sage: f = PolyDict({(2, 3): 2, (1, 2): 3, (2, 1): 4})
sage: f.total_degree()
5
sage: f.total_degree((3, 1))
9
sage: PolyDict({}).degree()
-1

sage.rings.polynomial.polydict.gen_index(x)
Return the index of the variable represented by x or -1 if x is not a monomial of degree one.

EXAMPLES:

sage: from sage.rings.polynomial.polydict import PolyDict, gen_index
sage: gen_index(PolyDict({(1, 0): 1}))
0
sage: gen_index(PolyDict({(0, 1): 1}))
1
sage: gen_index(PolyDict({}))
-1

sage.rings.polynomial.polydict.make_ETuple(data, length)
Ensure support for pickled data from older sage versions.

sage.rings.polynomial.polydict.make_PolyDict(data)
Ensure support for pickled data from older sage versions.

sage.rings.polynomial.polydict.monomial_exponent(p)
Return the unique exponent of p if it is a monomial or raise a ValueError.

EXAMPLES:

sage: from sage.rings.polynomial.polydict import PolyDict, monomial_exponent
sage: monomial_exponent(PolyDict({(2, 3): 1}))
(2, 3)
sage: monomial_exponent(PolyDict({(2, 3): 3}))
Traceback (most recent call last):
... ValueError: not a monomial
sage: monomial_exponent(PolyDict({(1, 0): 1, (0, 1): 1}))
Traceback (most recent call last):
3.1.12 Compute Hilbert series of monomial ideals

This implementation was provided at github issue #26243 and is supposed to be a way out when Singular fails with an int overflow, which will regularly be the case in any example with more than 34 variables.

```python
class sage.rings.polynomial.hilbert.Node

Bases: object

A node of a binary tree

It has slots for data that allow to recursively compute the first Hilbert series of a monomial ideal.

sage.rings.polynomial.hilbert.first_hilbert_series(I, grading=None, return_grading=False)

Return the first Hilbert series of the given monomial ideal.

INPUT:

- I – a monomial ideal (possibly defined in singular)
- grading – (optional) a list or tuple of integers used as degree weights
- return_grading – (default: False) whether to return the grading

OUTPUT:

A univariate polynomial, namely the first Hilbert function of I, and if return_grading==True also the grading used to compute the series.

EXAMPLES:

```
The following example is taken from github issue #20145:

```python
t^9 + t^8 + t^7 + t^6 + t^5 + t^4 + t^3 + t^2 + t + 1
```

This example exceeded the capabilities of Singular before version 4.2.1p2. In Singular 4.3.1, it works correctly on 64-bit, but on 32-bit, it prints overflow warnings and omits some terms.

```python
120*t^3 + 135*t^2 + 30*t + 1
```

This example exceeded the capabilities of Singular before version 4.2.1p2. In Singular 4.3.1, it works correctly on 64-bit, but on 32-bit, it prints overflow warnings and omits some terms.

```python
(t - 1)^14
```

---

### 3.1.13 Class to flatten polynomial rings over polynomial ring

For example `QQ['a','b'],['x','y']` flattens to `QQ['a','b','x','y']`.

**EXAMPLES:**

```python
sage: R = QQ['x']['y']['s','t']['X']
sage: phi = FlattenMorphism(R); phi
Flattening morphism:
  From: Univariate Polynomial Ring in X over Multivariate Polynomial Ring in s, t over
  Univariate Polynomial Ring in y over Univariate Polynomial Ring in x over Rational
  Field
  To:   Multivariate Polynomial Ring in x, y, s, t, X over Rational Field
```

**Authors:**

Vincent Delecroix, Ben Hutz (July 2016): initial implementation
sage: R = QQ['a','b'] ['x','y','z'] ['t1','t2']
sage: from sage.rings.polynomial.flatten import FlatteningMorphism
sage: f = FlatteningMorphism(R)
sage: f.codomain()
Multivariate Polynomial Ring in a, b, x, y, z, t1, t2 over Rational Field
sage: p = R((a+b)*x + (a^2-b)*t2*(z+y))
sage: f(p)
a^2*y*t2 + a^2*z*t2 - b*y*t2 - b*z*t2 + a*x + b*x

Also works when univariate polynomial ring are involved:

sage: R = QQ['x'] ['y'] ['s','t'] ['X']
sage: from sage.rings.polynomial.flatten import FlatteningMorphism
sage: f = FlatteningMorphism(R)
sage: f.codomain()
Multivariate Polynomial Ring in x, y, s, t, X over Rational Field
sage: p = R((x^2 + 1) + (x+2)*y + x*y^3)*(s+t) + x*y*X
sage: f(p)
x*y*X + (x*y^3 + (x + 2)*y + x^2 + 1)*s + (x*y^3 + (x + 2)*y + x^2 + 1)*t

inverse()
Return the inverse of this flattening morphism.
This is the same as calling section().

EXAMPLES:

sage: f = QQ['x,y'] ['u,v'].flattening_morphism()
sage: f.inverse()
Unflattening morphism:
  From: Multivariate Polynomial Ring in x, y, u, v over Rational Field
  To: Multivariate Polynomial Ring in x, y over Multivariate
  Ring in u, v over Rational Field

section()
Inverse of this flattening morphism.

EXAMPLES:

sage: R = QQ['a','b','c'] ['x','y','z']
sage: from sage.rings.polynomial.flatten import FlatteningMorphism
sage: h = FlatteningMorphism(R)
sage: h.section()
Unflattening morphism:
  From: Multivariate Polynomial Ring in a, b, c, x, y, z over Rational Field
  To: Multivariate Polynomial Ring in a, b, c over Multivariate Polynomial
 Ring in x, y, z over Rational Field
class sage.rings.polynomial.flatten.FractionSpecializationMorphism(domain, D)

Bases: Morphism

A specialization morphism for fraction fields over (stacked) polynomial rings

class sage.rings.polynomial.flatten.SpecializationMorphism(domain, D)

Bases: Morphism

Morphisms to specialize parameters in (stacked) polynomial rings

EXAMPLES:

```python
sage: R.<c> = PolynomialRing(QQ)
sage: S.<x,y,z> = PolynomialRing(R)
sage: D = dict({c:1})
sage: from sage.rings.polynomial.flatten import SpecializationMorphism
sage: f = SpecializationMorphism(S, D)
sage: f(x^2 + c*y^2 - z^2); g
x^2 + y^2 - z^2
sage: g.parent()
Multivariate Polynomial Ring in x, y, z over Rational Field
```

```python
sage: R.<c> = PolynomialRing(QQ)
sage: S.<z> = PolynomialRing(R)
sage: from sage.rings.polynomial.flatten import SpecializationMorphism
sage: xi = SpecializationMorphism(S, {c:0}); xi
Specialization morphism:
  From: Univariate Polynomial Ring in z over Univariate Polynomial Ring in c
  → over Rational Field
  To:    Univariate Polynomial Ring in z over Rational Field
sage: xi(z^2+c)
z^2
```

```python
sage: R1.<u,v> = PolynomialRing(QQ)
sage: R2.<a,b,c> = PolynomialRing(R1)
sage: S.<x,y,z> = PolynomialRing(R2)
sage: D = dict({a:1, b:2, x:0, u:1})
sage: from sage.rings.polynomial.flatten import SpecializationMorphism
sage: xi = SpecializationMorphism(S, D); xi
Specialization morphism:
  From: Multivariate Polynomial Ring in x, y, z over Multivariate Polynomial Ring in a, b, c over Multivariate Polynomial Ring in u, v over Rational Field
  → over Univariate Polynomial Ring in x, y, z over Rational Field
  To:    Multivariate Polynomial Ring in y, z over Univariate Polynomial Ring in c, v over Rational Field
sage: xi(a*(x*z+y^2)*u+b*v*u*(x*z+y^2)*y^2*c+c*y^2*z^2)
2*v*c*y^4 + c*y^2*z^2 + y^2
```

class sage.rings.polynomial.flatten.UnflatteningMorphism(domain, codomain)

Bases: Morphism

Inverses for UnflatteningMorphism

EXAMPLES:

```
sage: R = QQ['c','x','y','z']
sage: S = QQ['c']['x','y','z']
sage: from sage.rings.polynomial.flatten import UnflatteningMorphism
sage: f = UnflatteningMorphism(R, S)
sage: f(R(x^2 + c*y^2 - z^2));g
x^2 + c*y^2 - z^2
sage: g.parent()
Multivariate Polynomial Ring in x, y, z over Univariate Polynomial Ring in c over Rational Field
```

```
sage: R = QQ['a','b', 'x','y']
sage: S = QQ['a','b']['x','y']
sage: from sage.rings.polynomial.flatten import UnflatteningMorphism
sage: UnflatteningMorphism(R, S)
Unflattening morphism:
    From: Multivariate Polynomial Ring in a, b, x, y over Rational Field
    To:    Multivariate Polynomial Ring in x, y over Multivariate Polynomial Ring in a, b over Rational Field
```

### 3.1.14 Monomials

sage.rings.monomials.monomials(v, n)

Given two lists `v` and `n`, of exactly the same length, return all monomials in the elements of `v`, where variable `i` (i.e., `v[i]`) in the monomial appears to degree strictly less than `n[i]`.

**INPUT:**

- `v` – list of ring elements
- `n` – list of integers

**EXAMPLES:**

```
sage: monomials([x], [3])
[1, x, x^2]
sage: R.<x,y,z> = QQ[]
sage: monomials([x,y,z], [5,5])
[1, y^2, y^3, y^4, x, x*y, x*y^2, x*y^3, x^2, x^2*y, x^2*y^2, x^2*y^3, x^2*y^4, x^3, x^3*y, x^3*y^2, x^3*y^3, x^3*y^4, x^4, x^4*y, x^4*y^2, x^4*y^3, x^4*y^4]
sage: monomials([x,y,z], [2,3,2])
[1, z, y*z, y^2*z, x, x*z, x*y, x*y*z, x*y^2, x*y^2*z]
```
3.2 Classical Invariant Theory

3.2.1 Classical Invariant Theory

This module lists classical invariants and covariants of homogeneous polynomials (also called algebraic forms) under the action of the special linear group. That is, we are dealing with polynomials of degree $d$ in $n$ variables. The special linear group $SL(n, C)$ acts on the variables $(x_1, \ldots, x_n)$ linearly,

$$(x_1, \ldots, x_n)^t \to A(x_1, \ldots, x_n)^t, \quad A \in SL(n, C)$$

The linear action on the variables transforms a polynomial $p$ generally into a different polynomial $g \cdot p$. We can think of it as an action on the space of coefficients in $p$. An invariant is a polynomial in the coefficients that is invariant under this action. A covariant is a polynomial in the coefficients and the variables $(x_1, \ldots, x_n)$ that is invariant under the combined action.

For example, the binary quadratic $p(x, y) = ax^2 + bxy + cy^2$ has as its invariant the discriminant $disc(p) = b^2 - 4ac$. This means that for any $SL(2, C)$ coordinate change

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \alpha & \beta \\ \gamma & \delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}, \quad \alpha \delta - \beta \gamma = 1$$

the discriminant is invariant, $disc\left(p(x', y')\right) = disc\left(p(x, y)\right)$.

To use this module, you should use the factory object $\text{invariant\_theory}$. For example, take the quartic:

```sage
sage: R.<x,y> = QQ[]
sage: q = x^4 + y^4
sage: quartic = invariant\_theory.binary\_quartic(q); quartic
Binary quartic with coefficients (1, 0, 0, 0, 1)
```

One invariant of a quartic is known as the Eisenstein D-invariant. Since it is an invariant, it is a polynomial in the coefficients (which are integers in this example):

```sage
sage: quartic.EisensteinD()
1
```

One example of a covariant of a quartic is the so-called g-covariant (actually, the Hessian). As with all covariants, it is a polynomial in $x, y$ and the coefficients:

```sage
sage: quartic.g\_covariant()
-x^2*y^2
```

As usual, use tab completion and the online help to discover the implemented invariants and covariants.

In general, the variables of the defining polynomial cannot be guessed. For example, the zero polynomial can be thought of as a homogeneous polynomial of any degree. Also, since we also want to allow polynomial coefficients we cannot just take all variables of the polynomial ring as the variables of the form. This is why you will have to specify the variables explicitly if there is any potential ambiguity. For example:

```sage
sage: invariant\_theory.binary\_quartic(R.zero(), [x,y])
Binary quartic with coefficients (0, 0, 0, 0, 0)
sage: invariant\_theory.binary\_quartic(x^4, [x,y])
Binary quartic with coefficients (0, 0, 0, 0, 1)
```

(continues on next page)
Finally, it is often convenient to use inhomogeneous polynomials where it is understood that one wants to homogenize them. This is also supported, just define the form with an inhomogeneous polynomial and specify one less variable:

```
sage: R.<x,t> = QQ[]
sage: invariant_theory.binary_quartic(x^4 + 1 + t*x^2, [x])
Binary quartic with coefficients (1, 0, t, 0, 1)
```

REFERENCES:

- Wikipedia article *Glossary of invariant theory*

AUTHORS:

- Volker Braun (2013-01-24): initial version
- Jesper Noordsij (2018-05-18): support for binary quintics added

```python
class sage.rings.invariants.invariant_theory.AlgebraicForm(n, d, polynomial, *args, **kwds)
    Bases: FormsBase
    The base class of algebraic forms (i.e. homogeneous polynomials).
    You should only instantiate the derived classes of this base class.
    Derived classes must implement `coeffs()` and `scaled_coeffs()`
    INPUT:
    • n – The number of variables.
    • d – The degree of the polynomial.
    • polynomial – The polynomial.
    • *args – The variables, as a single list/tuple, multiple arguments, or None to use all variables of the polynomial.
    Derived classes must implement the same arguments for the constructor.
    EXAMPLES:
```
```
AlgebraicForm(2, 2, p, [x, y]).variables()
(x, y)
sage: AlgebraicForm(2, 2, p, x, y).variables()
(x, y)
sage: AlgebraicForm(3, 2, p, [x, y, None]).variables()
(x, y, None)
sage: AlgebraicForm(3, 2, p, x, y, None).variables()
(x, y, None)

Traceback (most recent call last):
...
ValueError: polynomial is of the wrong degree

AlgebraicForm(2, 2, x^2 + y, [x, y]).variables()
Traceback (most recent call last):
...
ValueError: polynomial is not homogeneous

coefficients()

Alias for coeffs().

See the documentation for coeffs() for details.

EXAMPLES:

R.<a,b,c,d,e,f,g, x,y,z> = QQ[]
p = a*x^2 + b*y^2 + c*z^2 + d*x*y + e*x*z + f*y*z
q = invariant_theory.quadratic_form(p, x,y,z)
q.coefficients()
(a, b, c, d, e, f)

form()

Return the defining polynomial.

OUTPUT:

The polynomial used to define the algebraic form.

EXAMPLES:

R.<x,y> = QQ[]
quartic = invariant_theory.binary_quartic(x^4+y^4)
quartic.form()
x^4 + y^4

homogenized(var='h')

Return form as defined by a homogeneous polynomial.

INPUT:
• var – either a variable name, variable index or a variable (default: 'h').

OUTPUT:
The same algebraic form, but defined by a homogeneous polynomial.

EXAMPLES:

```sage
sage: T.<t> = QQ[]
sage: quadratic = invariant_theory.binary_quadratic(t^2 + 2*t + 3)
sage: quadratic
Binary quadratic with coefficients (1, 3, 2)
sage: quadratic.homogenized()
Binary quadratic with coefficients (1, 3, 2)
sage: quadratic == quadratic.homogenized()
True
sage: quadratic.form()
t^2 + 2*t + 3
sage: quadratic.homogenized().form()
t^2 + 2*t*h + 3*h^2
```

`polynomial()`

Return the defining polynomial.

OUTPUT:
The polynomial used to define the algebraic form.

EXAMPLES:

```sage
sage: R.<x,y> = QQ[]
sage: quartic = invariant_theory.binary_quartic(x^4+y^4)
sage: quartic.form()
x^4 + y^4
sage: quartic.polynomial()
x^4 + y^4
```

`transformed(g)`

Return the image under a linear transformation of the variables.

INPUT:

• g – a $GL(n, C)$ matrix or a dictionary with the
  variables as keys. A matrix is used to define the linear transformation of homogeneous variables,
  a dictionary acts by substitution of the variables.

OUTPUT:
A new instance of a subclass of `AlgebraicForm` obtained by replacing the variables of the homogeneous polynomial by their image under $g$.

**EXAMPLES:**

```python
sage: R.<x,y,z> = QQ[]
sage: cubic = invariant_theory.ternary_cubic(x^3 + 2*y^3 + 3*z^3 + 4*x*y*z)
sage: cubic.transformed({x:y, y:z, z:x}).form()
3*x^3 + y^3 + 4*x*y*z + 2*z^3
sage: cyc = matrix([[0,1,0],[0,0,1],[1,0,0]])
sage: cubic.transformed(cyc) == cubic.transformed({x:y, y:z, z:x})
True
sage: g = matrix(QQ, [[1, 0, 0], [-1, 1, -3], [-5, -5, 16]])
sage: cubic.transformed(g)
Ternary cubic with coefficients (-356, -373, 12234, -1119, 3578, -1151, 3582, -11766, -11466, 7360)
sage: cubic.transformed(g).transformed(g.inverse()) == cubic
True
```

**class** `sage.rings.invariants.invariant_theory.BinaryQuartic(n, d, polynomial, *args)`

Bases: `AlgebraicForm`

Invariant theory of a binary quartic.

You should use the `invariant_theory` factory object to construct instances of this class. See `binary_quartic()` for details.

**EisensteinD()**

One of the Eisenstein invariants of a binary quartic.

**OUTPUT:**

The Eisenstein D-invariant of the quartic.

\[
f(x) = a_0 x_1^4 + 4 a_1 x_0 x_1^3 + 6 a_2 x_0^2 x_1^2 + 4 a_3 x_0^3 x_1 + a_4 x_0^4
\]

\[\Rightarrow D(f) = a_0 a_4 + 3 a_2^2 - 4 a_1 a_3\]

**EXAMPLES:**

```python
sage: R.<a0, a1, a2, a3, a4, x0, x1> = QQ[]
sage: f = a0*x1^4 + 4*a1*x0*x1^3 + 6*a2*x0^2*x1^2 + 4*a3*x0^3*x1 + a4*x0^4
sage: inv = invariant_theory.binary_quartic(f, x0, x1)
sage: inv.EisensteinD()
3*a2^2 - 4*a1*a3 + a0*a4
```

**EisensteinE()**

One of the Eisenstein invariants of a binary quartic.

**OUTPUT:**

The Eisenstein E-invariant of the quartic.

\[
f(x) = a_0 x_1^4 + 4 a_1 x_0 x_1^3 + 6 a_2 x_0^2 x_1^2 + 4 a_3 x_0^3 x_1 + a_4 x_0^4
\]

\[\Rightarrow E(f) = a_0 a_3^2 + a_1^2 a_4 - a_0 a_2 a_4 - 2 a_1 a_2 a_3 + a_2^3\]

**EXAMPLES:**
```python
sage: R.<a0, a1, a2, a3, a4, x0, x1> = QQ[]
sage: f = a0*x1^4+4*a1*x0*x1^3+6*a2*x0^2*x1^2+4*a3*x0^3*x1+a4*x0^4
sage: inv = invariant_theory.binary_quartic(f, x0, x1)
sage: inv.EisensteinE()
a2^3 - 2*a1*a2*a3 + a0*a3^2 + a1^2*a4 - a0*a2*a4
```

`coeffs()`

The coefficients of a binary quartic.

Given

\[ f(x) = a_0 x_1^4 + a_1 x_0 x_1^3 + a_2 x_0^2 x_1^2 + a_3 x_0^3 x_1 + a_4 x_0^4 \]

this function returns \( a = (a_0, a_1, a_2, a_3, a_4) \)

**EXAMPLES:**

```python
sage: R.<a0, a1, a2, a3, a4, x, y> = QQ[]
sage: p = a0*x^4+4*a1*x^3*y+6*a2*x^2*y^2+4*a3*x*y^3+a4*y^4
sage: inv = invariant_theory.binary_quartic(p, x, y)
sage: g = inv.g_covariant(); g
a1^2*x^4 - a0*a2*x^4 + 2*a1*a2*x^3*y - 2*a0*a3*x^3*y + 3*a2^2*x^2*y^2 - 2*a1*a3*x^2*y^2 - a0*a4*x^2*y^2 + 2*a2*a3*x*y^3 - 2*a1*a4*x*y^3 + a3^2*y^4 - a2*a4*y^4

sage: inv_inhomogeneous = invariant_theory.binary_quartic(p.subs(y=1), x)
sage: inv_inhomogeneous.g_covariant()
a1^2*x^4 - a0*a2*x^4 + 2*a1*a2*x^3*y - 2*a0*a3*x^3*y + 3*a2^2*x^2*y^2 - 2*a1*a3*x^2*y^2 - a0*a4*x^2*y^2 + 2*a2*a3*x*y^3 - 2*a1*a4*x*y^3 + a3^2*x^2 - a2*a4*x^2

sage: g == 1/144 * (p.derivative(x,y)^2 - p.derivative(x,x)*p.derivative(y,y))
True
```

3.2. Classical Invariant Theory
**h_covariant()**  
The h-covariant of a binary quartic.  

**OUTPUT:**  
The h-covariant of the quartic.

\[
f(x) = a_0 x_1^4 + 4a_1 x_0 x_1^3 + 6a_2 x_0^2 x_1^2 + 4a_3 x_0^3 x_1 + a_4 x_0^4
\]

\[
\Rightarrow D(f) = \frac{1}{144} \left( \frac{\partial^2 f}{\partial x \partial x} \right)
\]

**EXAMPLES:**

```python
sage: R.<a0, a1, a2, a3, a4, x, y> = QQ[]
sage: p = a0*x^4+4*a1*x^3*y+6*a2*x^2*y^2+4*a3*x*y^3+a4*y^4
sage: inv = invariant_theory.binary_quartic(p, x, y)
sage: h = inv.h_covariant(); h
-2*a1^3*x^6 + 3*a0*a1*a2*x^6 - 6*a1^2*a2*x^5*y + 9*a0*a2^2*x^5*y
- 2*a0^2*a1*a3*x^5*y - a0^2*a4*x^5*y - 10*a1^2*a3*x^4*y^2 + 15*a0*a2*a3*x^4*y^2
- 5*a0*a1*a4*x^4*y^2 + 10*a0*a3^2*x^3*y^3 - 10*a1*a2*a4*x^3*y^3
+ 10*a1*a3^2*x^2*y^4 - 15*a1*a2*a4*x^2*y^4 + 5*a0*a3*a4*x^2*y^4
+ 6*a2*a3^2*x*y^5 - 9*a2^2*a4*x*y^5 + 2*a1*a3*a4*x*y^5 + a0*a4^2*x*y^5
+ 2*a3^3*y^6 - 3*a2*a3*a4*y^6 + a1*a4^2*y^6
```

```python
sage: inv_inhomogeneous = invariant_theory.binary_quartic(p.subs(y=1), x)
sage: inv_inhomogeneous.h_covariant()
-2*a1^3*x^6 + 3*a0*a1*a2*x^6 - 6*a1^2*a2*x^5 + 9*a0*a2^2*x^5
- 2*a0^2*a1*a3*x^5 - a0^2*a4*x^5 - 10*a1^2*a3*x^4 + 10*a1*a2*a3*x^4
- 5*a0*a1*a4*x^4 + 10*a0*a3^2*x^3 - 10*a1*a2*a4*x^3 + 10*a1*a3^2*x^2
- 15*a1*a2*a4*x^2 + 5*a0*a3*a4*x^2 + 6*a2*a3^2*x - 9*a2^2*a4*x
+ 2*a1*a3*a4*x + a0*a4^2*x + 2*a3^3 - 3*a2*a3*a4 + a1*a4^2
```

```python
sage: g = inv.g_covariant()
sage: h == 1/8 * (p.derivative(x)*g.derivative(y)-p.derivative(y)*g.derivative(x))
True
```

**monomials()**  
List the basis monomials in the form.

**OUTPUT:**

A tuple of monomials. They are in the same order as `coeffs()`.

**EXAMPLES:**

```python
sage: R.<x,y> = QQ[]
sage: quartic = invariant_theory.binary_quartic(x^4+y^4)
sage: quartic.monomials()
(y^4, x*y^3, x^2*y^2, x^3*y, x^4)
```

**scaled_coeffs()**  
The coefficients of a binary quartic.

Given

\[
f(x) = a_0 x_1^4 + 4a_1 x_0 x_1^3 + 6a_2 x_0^2 x_1^2 + 4a_3 x_0^3 x_1 + a_4 x_0^4
\]
this function returns \( a = (a_0, a_1, a_2, a_3, a_4) \)

EXAMPLES:

```python
sage: R.<a0, a1, a2, a3, a4, x0, x1> = QQ[]
sage: quartic = a0*x1^4 + 4*a1*x1^3*x0 + 6*a2*x1^2*x0^2 + 4*a3*x1*x0^3 + a4*x0^4
sage: inv = invariant_theory.binary_quartic(quartic, x0, x1)
sage: inv.scaled_coeffs()
(a0, a1, a2, a3, a4)
```

```python
sage: R.<a0, a1, a2, a3, a4, x> = QQ[]
sage: quartic = a0 + 4*a1*x + 6*a2*x^2 + 4*a3*x^3 + a4*x^4
sage: inv = invariant_theory.binary_quartic(quartic, x)
sage: inv.scaled_coeffs()
(a0, a1, a2, a3, a4)
```

class sage.rings.invariants.invariant_theory.BinaryQuintic(n, d, polynomial, *args)

Bases: AlgebraicForm

Invariant theory of a binary quintic form.

You should use the `invariant_theory` factory object to construct instances of this class. See `binary_quintic()` for details.

REFERENCES:

For a description of all invariants and covariants of a binary quintic, see section 73 of [Cle1872].

A_invariant()

Return the invariant \( A \) of a binary quintic.

OUTPUT:

The \( A \)-invariant of the binary quintic.

EXAMPLES:

```python
sage: R.<a0, a1, a2, a3, a4, a5, x0, x1> = QQ[]
sage: p = a0*x1^5 + a1*x1^4*x0 + a2*x1^3*x0^2 + a3*x1^2*x0^3 + a4*x1*x0^4 + a5*x0^5
sage: quintic = invariant_theory.binary_quintic(p, x0, x1)
sage: quintic.A_invariant()
4/625*a2^2*a3^2 - 12/625*a1*a3^3 - 12/625*a2^3*a4 + 38/625*a1*a2*a3*a4 + 6/125*a0*a3^2*a4 - 16/125*a1*a2*a4^2 - 2/25*a0*a3*a4^2 - 4/5*a0*a1*a4*a5 - 2*a0^2*a5^2
```

B_invariant()

Return the invariant \( B \) of a binary quintic.

OUTPUT:

The \( B \)-invariant of the binary quintic.

EXAMPLES:

```python
sage: R.<a0, a1, a2, a3, a4, a5, x0, x1> = QQ[]
sage: p = a0*x1^5 + a1*x1^4*x0 + a2*x1^3*x0^2 + a3*x1^2*x0^3 + a4*x1*x0^4 + a5*x0^5
sage: quintic = invariant_theory.binary_quintic(p, x0, x1)
sage: quintic.B_invariant()
```
```
sage: quintic = invariant_theory.binary_quintic(p, x0, x1)
sage: quintic.B_invariant()
1/1562500*a2^4*a3^4 - 3/781250*a1*a2^2*a3^5 + 9/1562500*a1^2*a3^6
- 3/781250*a2^5*a3^2*a4 + 37/1562500*a1*a2^3*a3^3*a4
- 57/1562500*a1^2*a2^2*a3^4*a4 + 3/312500*a0*a2^2*a3^4*a4
...
+ 8/625*a0^2*a1^2*a4^2*a5^2 - 4/125*a0^3*a2^2*a4^2*a5^2 - 16/3125*a1^5*a5^3
+ 4/125*a0^3*a1^3*a2^2*a5^3 - 6/125*a0^2*a1^2*a2*a5^3
- 4/125*a0^2*a1^2*a3*a5^3 + 2/25*a0^3*a2*a3*a5^3
```

C_invariant()

Return the invariant $C$ of a binary quintic.

OUTPUT:

The $C$-invariant of the binary quintic.

EXAMPLES:

```
sage: R.<a0, a1, a2, a3, a4, a5, x0, x1> = QQ[]
sage: p = a0*x1^5 + a1*x1^4*x0 + a2*x1^3*x0^2 + a3*x1^2*x0^3 + a4*x1*x0^4 +
˓→ a5*x0^5
sage: quintic = invariant_theory.binary_quintic(p, x0, x1)
sage: quintic.C_invariant()
-3/1953125000*a2^6*a3^6 + 27/1953125000*a1*a2^4*a3^7
- 249/7812500000*a1^2*a2^2*a3^8 - 3/7812500000*a0*a2^3*a3^8
+ 3/9765625000*a1^3*a3^9 + 27/1562500000*a0*a1*a2*a3^9
...
+ 192/15625*a0^2*a1^3*a2^2*a3*a5^4 - 36/3125*a0^3*a1^2*a2^3*a3*a5^4
+ 24/15625*a0^2*a1^4*a3^2*a5^4 - 24/3125*a0^3*a1^2*a2*a3^2*a5^4
+ 6/625*a0^4*a2^2*a3^2*a5^4
```

H_covariant(as_form=False)

Return the covariant $H$ of a binary quintic.

INPUT:

- `as_form` – if `as_form` is `False`, the result will be returned as polynomial (default). If it is `True` the result is returned as an object of the class `AlgebraicForm`.

OUTPUT:

The $H$-covariant of the binary quintic as polynomial or as binary form.

EXAMPLES:

```
sage: R.<a0, a1, a2, a3, a4, a5, x0, x1> = QQ[]
sage: p = a0*x1^5 + a1*x1^4*x0 + a2*x1^3*x0^2 + a3*x1^2*x0^3 + a4*x1*x0^4 +
˓→ a5*x0^5
sage: quintic = invariant_theory.binary_quintic(p, x0, x1)
sage: quintic.H_covariant()
-2/25*a4^2*x0^6 + 1/5*a3*a5*x0^6 - 3/25*a3*a4*x0^5*x1
+ 3/5*a2*a5*x0^5*x1 - 3/25*a3^2*x0^4*x1^2 + 3/25*a2*a4*x0^4*x1^2
+ 6/5*a1*a5*x0^4*x1^2 - 4/25*a2*a3*x0^3*x1^3 + 14/25*a1*a4*x0^3*x1^3
+ 2*a0*a5*x0^3*x1^3 - 3/25*a2*a2*x0^2*x1^4 + 3/25*a1*a3*x0^2*x1^4
+ 6/5*a0*a4*x0^2*x1^4 - 3/25*a1^2*x0^1*x1^5 + 3/5*a0*a3*x0^1*x1^5
```
- \(2/25\cdot a_1^2\cdot x_1^6 + 1/5\cdot a_0\cdot a_2\cdot x_1^6\)

```sage```
quintic.H_covariant(as_form=True)
Binary sextic given by ...
```

**R\_invariant()**

Return the invariant \(R\) of a binary quintic.

**OUTPUT:**

The \(R\)-invariant of the binary quintic.

**EXAMPLES:**

```sage```
R.<a0, a1, a2, a3, a4, a5, x0, x1> = QQ[
```
```sage```
p = a0\cdot x1^5 + a1\cdot x1^4\cdot x0 + a2\cdot x1^3\cdot x0^2 + a3\cdot x1^2\cdot x0^3 + a4\cdot x1\cdot x0^4 + ... + a5\cdot x0^5
```
```sage```
quintic = invariant_theory.binary_quintic(p, x0, x1)
```sage```
quintic.R_invariant()
```

\[
\frac{3}{390625}\cdot a_1^2\cdot a_2^5\cdot a_3^{11} - \frac{3}{9765625}\cdot a_0\cdot a_2^6\cdot a_3^{11} - \frac{51}{781250}\cdot a_1^3\cdot a_2^3\cdot a_3^{12} + \frac{27}{9765625}\cdot a_0\cdot a_1^2\cdot a_4^4\cdot a_3^{12} + ... + \frac{384}{9765625}\cdot a_0^2\cdot a_2^6\cdot a_5^7 - \frac{192}{390625}\cdot a_1^2\cdot a_4^2\cdot a_5^7 - \frac{96}{15625}\cdot a_0^3\cdot a_2^2\cdot a_3^6\cdot a_5^7 + \frac{24}{3125}\cdot a_0^4\cdot a_2^2\cdot a_3^6\cdot a_5^7 - \frac{12}{3125}\cdot a_0^5\cdot a_2^2\cdot a_3^6\cdot a_5^7
\]

**T\_covariant(as\_form=False)**

Return the covariant \(T\) of a binary quintic.

**INPUT:**

- as_form – if as_form is False, the result will be returned as polynomial (default). If it is True the result is returned as an object of the class *AlgebraicForm*.

**OUTPUT:**

The \(T\)-covariant of the binary quintic as polynomial or as binary form.

**EXAMPLES:**

```sage```
R.<a0, a1, a2, a3, a4, a5, x0, x1> = QQ[
```
```sage```
p = a0\cdot x1^5 + a1\cdot x1^4\cdot x0 + a2\cdot x1^3\cdot x0^2 + a3\cdot x1^2\cdot x0^3 + a4\cdot x1\cdot x0^4 + ... + a5\cdot x0^5
```
```sage```
quintic = invariant_theory.binary_quintic(p, x0, x1)
```sage```
quintic.T_covariant()
```
```
```sage```
quintic.T_covariant(as_form=True)
```

\[
\frac{2}{125}\cdot a_4^3\cdot x_0^9 - \frac{3}{50}\cdot a_3\cdot a_4\cdot a_5\cdot x_0^9 + \frac{1}{10}\cdot a_2\cdot a_5^2\cdot x_0^9 + ... + \frac{11}{25}\cdot a_0\cdot a_4\cdot x_0^9 - \frac{a_0^2\cdot a_5}{2}\cdot x_0^9 - \frac{9}{250}\cdot a_1^2\cdot a_4\cdot x_0^9 + \frac{3}{25}\cdot a_0\cdot a_1\cdot a_3^2\cdot x_0^9 - \frac{2}{5}\cdot a_0^2\cdot a_4\cdot x_0^9 + \frac{1}{50}\cdot a_0^3\cdot a_2\cdot x_0^9 + \frac{2}{5}\cdot a_0^2\cdot a_3^2\cdot x_0^9 + ... + \frac{11}{25}\cdot a_0\cdot a_1^2\cdot a_2\cdot x_0^9 + \frac{3}{50}\cdot a_0\cdot a_1\cdot a_2^2\cdot x_0^9 - \frac{1}{10}\cdot a_0^2\cdot a_3\cdot x_1^9
\]

3.2. Classical Invariant Theory
**alpha_covariant**(as\_form=False)

Return the covariant $\alpha$ of a binary quintic.

**INPUT:**

- **as\_form** – if *as\_form* is False, the result will be returned as polynomial (default). If it is True the result is returned as an object of the class `AlgebraicForm`.

**OUTPUT:**

The $\alpha$-covariant of the binary quintic as polynomial or as binary form.

**EXAMPLES:**

```python
sage: R.<a0, a1, a2, a3, a4, a5, x0, x1> = QQ[]
sage: p = a0*x1^5 + a1*x1^4*x0 + a2*x1^3*x0^2 + a3*x1^2*x0^3 + a4*x1*x0^4 + a5*x0^5
sage: quintic = invariant_theory.binary_quintic(p, x0, x1)
sage: quintic.alpha_covariant()
1/2500*a2^2*a3^3*x0 - 3/2500*a1*a3^4*x0 - 1/625*a2^3*a3*a4*x0 + 3/625*a1*a2*a3^2*a4*x0 + 3/625*a0*a3^3*a4*x0 + 2/625*a1*a2^2*a4^2*x0 - 6/625*a1^2*a3*a4^2*x0 - 12/625*a0*a2*a3*a4^2*x0 + 24/625*a1*a4^3*x0 - 12/625*a1^2*a2*a3*a5*x1 - 1/125*a0*a2^2*a3*a5*x1 + 8/125*a0*a1*a3^2*a5*x1 - 4/25*a0^2*a4*a5*x1 + 2/5*a0^2*a5^2*x1
```

```python
sage: quintic.alpha_covariant(as\_form=True)
Binary monic given by ...
```

**arithmetic\_invariants()**

Return a set of generating arithmetic invariants of a binary quintic.

An arithmetic invariants is an invariant whose coefficients are integers for a general binary quintic. They are linear combinations of the Clebsch invariants, such that they still generate the ring of invariants.

**OUTPUT:**

The arithmetic invariants of the binary quintic. They are given by

\[
\begin{align*}
I_4 &= 2^{-1} \cdot 5^4 \cdot A \\
I_8 &= 5^5 \cdot (2^{-1} \cdot 47 \cdot A^2 - 2^2 \cdot B) \\
I_{12} &= 5^{10} \cdot (2^{-1} \cdot 3 \cdot A^3 - 2^5 \cdot 3^{-1} \cdot C) \\
I_{18} &= 2^8 \cdot 3^{-1} \cdot 5^{15} \cdot R
\end{align*}
\]

where $A$, $B$, $C$ and $R$ are the `BinaryQuintic.clebsch\_invariants()`.

**EXAMPLES:**

```python
sage: R.<x0, x1> = QQ[]
sage: p = 2*x1^5 + 4*x1^4*x0 + 5*x1^3*x0^2 + 7*x1^2*x0^3 - 11*x1*x0^4 + x0^5
sage: quintic = invariant_theory.binary_quintic(p, x0, x1)
sage: quintic.arithmetic\_invariants()
{'I12': -1156502613073152, 'I18': -12712872348048797642752, 'I4': -138016, 'I8': 14164936192}
```
We can check that the coefficients of the invariants have no common divisor for a general quintic form:

```
sage: R.<a0,a1,a2,a3,a4,a5,x0,x1> = QQ[]
sage: p = a0*x1^5 + a1*x1^4*x0 + a2*x1^3*x0^2 + a3*x1^2*x0^3 + a4*x1*x0^4 +
    a5*x0^5
sage: quintic = invariant_theory.binary_quintic(p, x0, x1)
sage: invs = quintic.arithmetic_invariants()
sage: [invs[x].content() for x in invs]
[1, 1, 1, 1]
```

`beta_covariant(as_form=False)`

Return the covariant $\beta$ of a binary quintic.

**INPUT:**

- `as_form` – If `as_form` is `False`, the result will be returned as polynomial (default). If it is `True` the result is returned as an object of the class `AlgebraicForm`.

**OUTPUT:**

The $\beta$-covariant of the binary quintic as polynomial or as binary form.

**EXAMPLES:**

```
sage: R.<a0, a1, a2, a3, a4, a5, x0, x1> = QQ[]
sage: p = a0*x1^5 + a1*x1^4*x0 + a2*x1^3*x0^2 + a3*x1^2*x0^3 + a4*x1*x0^4 +
    a5*x0^5
sage: quintic = invariant_theory.binary_quintic(p, x0, x1)
sage: quintic.beta_covariant()
-1/62500*a2^3*a3^4*x0 + 9/125000*a1*a2*a3^5*x0 - 27/125000*a0*a3^6*x0 +
  13/125000*a2^4*a3^2*a4*x0 - 31/62500*a1*a2^2*a3^3*a4*x0 -
  3/62500*a1^2*a3^4*a4*x0 + 27/15625*a0*a2*a3^4*a4*x0 +
  ... + 6/125*a0^2*a1*a3^2*a5^2*x1 - 28/625*a0^3*a1^2*a4*a5^2*x1 +
  8/25*a0^3*a3^2*a4*a5^2*x1 + 4/25*a0^2*a1^2*a5^3*x1 - 2/5*a0^3*a2*a5^3*x1
sage: quintic.beta_covariant(as_form=True)
Binary monic given by ... 
```

`canonical_form(reduce_gcd=False)`

Return a canonical representative of the quintic.

Given a binary quintic $f$ with coefficients in a field $K$, returns a canonical representative of the $GL(2, \bar{K})$-orbit of the quintic, where $\bar{K}$ is an algebraic closure of $K$. This means that two binary quintics $f$ and $g$ are $GL(2, \bar{K})$-equivalent if and only if their canonical forms are the same.

**INPUT:**

- `reduce_gcd` – If set to `True`, then a variant of this canonical form is computed where the coefficients are coprime integers. The obtained form is then unique up to multiplication by a unit. See also `binary_quintic_from_invariants()`.

**OUTPUT:**

A canonical $GL(2, \bar{K})$-equivalent binary quintic.

**EXAMPLES:**
sage: R.<x0, x1> = QQ[]  
sage: p = 2*x1^5 + 4*x1^4*x0 + 5*x1^3*x0^2 + 7*x1^2*x0^3 - 11*x1*x0^4 + x0^5  
sage: f = invariant_theory.binary_quintic(p, x0, x1)  
sage: g = matrix(QQ, [[11, 5], [7, 2]])  
sage: gf = f.transformed(g)  
sage: f.canonical_form() == gf.canonical_form()  
True  
sage: h = f.canonical_form(reduce_gcd=True)  
sage: gcd(h.coeffs())  
1

clebsch_invariants(as_tuple=False)

Return the invariants of a binary quintic as described by Clebsch.

The following invariants are returned: $A$, $B$, $C$ and $R$.

OUTPUT:

The Clebsch invariants of the binary quintic.

EXAMPLES:

sage: R.<x0, x1> = QQ[]  
sage: p = 2*x1^5 + 4*x1^4*x0 + 5*x1^3*x0^2 + 7*x1^2*x0^3 - 11*x1*x0^4 + x0^5  
sage: quintic = invariant_theory.binary_quintic(p, x0, x1)  
sage: quintic.clebsch_invariants()  
{'A': -276032/625,  
'B': 4983526016/390625,  
'C': -247056495846408/244140625,  
'R': -148978972828696847376/30517578125}

sage: quintic.clebsch_invariants(as_tuple=True)  
(-276032/625,  
4983526016/390625,  
-247056495846408/244140625,  
-148978972828696847376/30517578125)

coeffs()

The coefficients of a binary quintic.

Given

\[ f(x) = a_0 x_1^5 + a_1 x_0 x_1^4 + a_2 x_0^2 x_1^3 + a_3 x_0^3 x_1^2 + a_4 x_0^4 x_1 + a_5 x_1^5 \]

this function returns $a = (a_0, a_1, a_2, a_3, a_4, a_5)$

EXAMPLES:

sage: R.<a0, a1, a2, a3, a4, a5, x0, x1> = QQ[]  
sage: p = a0*x1^5 + a1*x1^4*x0 + a2*x1^3*x0^2 + a3*x1^2*x0^3 + a4*x1*x0^4 + a5*x0^5  
sage: quintic = invariant_theory.binary_quintic(p, x0, x1)  
sage: quintic.coeffs()  
(a0, a1, a2, a3, a4, a5)  

sage: R.<a0, a1, a2, a3, a4, a5, x> = QQ[]  
(continues on next page)
delta_covariant(as_form=False)

Return the covariant $\delta$ of a binary quintic.

INPUT:

- as_form – if as_form is False, the result will be returned as polynomial (default). If it is True the result is returned as an object of the class AlgebraicForm.

OUTPUT:

The $\delta$-covariant of the binary quintic as polynomial or as binary form.

EXAMPLES:

```python
sage: R.<a0, a1, a2, a3, a4, a5, x0, x1> = QQ[]
```
```
sage: p = a0*x1^5 + a1*x1^4*x0 + a2*x1^3*x0^2 + a3*x1^2*x0^3 + a4*x1*x0^4 + a5*x0^5
sage: quintic = invariant_theory.binary_quintic(p, x0, x1)
```
```
sage: quintic.delta_covariant(as_form=True)
Binary monic given by ...
```
```
\texttt{gamma\_covariant}(\texttt{as\_form=False})

Return the covariant $\gamma$ of a binary quintic.

**INPUT:**

- \texttt{as\_form} – if \texttt{as\_form} is False, the result will be returned as polynomial (default). If it is True the result is returned as an object of the class \texttt{AlgebraicForm}.

**OUTPUT:**

The $\gamma$-covariant of the binary quintic as polynomial or as binary form.

**EXAMPLES:**

\begin{verbatim}
sage: R.<a0, a1, a2, a3, a4, a5, x0, x1> = QQ[]
sage: p = a0*x1^5 + a1*x1^4*x0 + a2*x1^3*x0^2 + a3*x1^2*x0^3 + a4*x1*x0^4 + a5*x0^5
sage: quintic = invariant_theory.binary_quintic(p, x0, x1)
sage: quintic.gamma_covariant() 1/156250000*a2^5*a3^6*x0 - 3/62500000*a1*a2^3*a3^7*x0 + 27/312500000*a1^2*a2*a3^8*x0 + 27/312500000*a0*a2^2*a3^8*x0 - 81/312500000*a0*a1*a3^9*x0 - 19/312500000*a2^6*a3^4*a4*x0 ... - 32/3125*a0^2*a1^3*a2^2*a5^4*x1 + 6/625*a0^3*a1*a2*a3*a5^4*x1 - 8/3125*a0^2*a1^4*a3*a5^4*x1 + 8/625*a0*a2^3*a5^4*x1 - 2/125*a0^4*a2^2*a3*a5^4*x1
sage: quintic.gamma_covariant(as_form=True)
Binary monic given by ...
\end{verbatim}

\texttt{i\_covariant}(\texttt{as\_form=False})

Return the covariant $i$ of a binary quintic.

**INPUT:**

- \texttt{as\_form} – if \texttt{as\_form} is False, the result will be returned as polynomial (default). If it is True the result is returned as an object of the class \texttt{AlgebraicForm}.

**OUTPUT:**

The $i$-covariant of the binary quintic as polynomial or as binary form.

**EXAMPLES:**

\begin{verbatim}
sage: R.<a0, a1, a2, a3, a4, a5, x0, x1> = QQ[]
sage: p = a0*x1^5 + a1*x1^4*x0 + a2*x1^3*x0^2 + a3*x1^2*x0^3 + a4*x1*x0^4 + a5*x0^5
sage: quintic = invariant_theory.binary_quintic(p, x0, x1)
sage: quintic.i_covariant() 3/50*a3^2*x0^2 - 4/25*a2*a4*x0^2 + 2/5*a1*a5*x0^2 + 1/25*a2^2*a3^3*x0 - 6/25*a1*a4*x0*x1 + 2*a0*a5*x0*x1 + 3/50*a2^2*x1^2 - 4/25*a1*a3*x1^2 + 2/5*a0*a4*x1^2
sage: quintic.i_covariant(as_form=True)
Binary quadratic given by ...
\end{verbatim}

\texttt{invariants}(\texttt{type='clebsch'})

Return a tuple of invariants of a binary quintic.
INPUT:

• type – The type of invariants to return. The default choice is to return the Clebsch invariants.

OUTPUT:

The invariants of the binary quintic.

EXAMPLES:

```sage
R.<x0, x1> = QQ[]
p = 2*x1^5 + 4*x1^4*x0 + 5*x1^3*x0^2 + 7*x1^2*x0^3 - 11*x1*x0^4 + x0^5
quintic = invariant_theory.binary_quintic(p, x0, x1)
quintic.invariants()
(-276032/625, 4983526016/390625, -247056495846408/244140625,
 -148978972828696847376/30517578125)
quintic.invariants('unknown')
Traceback (most recent call last):
  ... IOError: unknown type of invariants unknown for a binary quintic
```

**jcovariant(as_form=False)**

Return the covariant $j$ of a binary quintic.

INPUT:

• as_form – if as_form is False, the result will be returned as polynomial (default). If it is True the result is returned as an object of the class `AlgebraicForm`.

OUTPUT:

The $j$-covariant of the binary quintic as polynomial or as binary form.

EXAMPLES:

```sage
R.<a0, a1, a2, a3, a4, a5, x0, x1> = QQ[]
p = a0*x1^5 + a1*x1^4*x0 + a2*x1^3*x0^2 + a3*x1^2*x0^3 + a4*x1*x0^4 + a5*x0^5
quintic = invariant_theory.binary_quintic(p, x0, x1)
quintic.j_covariant()      
-3/500*a3^3*x0^3 + 3/125*a2*a3*a4*x0^3 - 6/125*a1*a4^2*x0^3
- 3/50*a2^2*a5*x0^3 + 3/25*a1*a3*a5*x0^3 - 3/500*a2*a3^2*x0^2*x1
+ 3/250*a2*a4^2*x0^2*x1 + 3/125*a1*a3*a4*x0^2*x1 - 6/25*a0*a4^2*x0^2*x1
- 3/25*a1*a2*a5*x0^2*x1 + 3/5*a0*a3*a5*x0^2*x1 - 3/500*a2*a3^2*x0*x1^2
+ 3/250*a1*a3^2*x0*x1^2 + 3/125*a1*a2*a4*x0*x1^2 - 3/25*a0*a3*a4*x0*x1^2
- 6/25*a1*a2*a5*x0*x1^2 + 3/5*a0*a2*a5*x0*x1^2 - 3/500*a2*a3^2*x1^3
+ 3/125*a1*a2*a3*x1^3 - 3/50*a0*a3^2*x1^3 - 6/125*a1*a2*a4*x1^3
+ 3/25*a0*a2*a4*x1^3
quintic.j_covariant(as_form=True)
Binary cubic given by ...
```

**monomials()**

List the basis monomials of the form.

This function lists a basis of monomials of the space of binary quintics of which this form is an element.
OUTPUT:
A tuple of monomials. They are in the same order as `coeffs()`

EXAMPLES:

```python
sage: R.<x,y> = QQ[]
sage: quintic = invariant_theory.binary_quintic(x^5+y^5)
sage: quintic.monomials()
(y^5, x*y^4, x^2*y^3, x^3*y^2, x^4*y, x^5)
```

`scaled_coeffs()`
The coefficients of a binary quintic.

Given

\[ f(x) = a_0 x_1^5 + a_1 x_0^4 x_1 + a_2 x_0^3 x_1^2 + a_3 x_0^2 x_1^3 + a_4 x_0 x_1^4 + a_5 x_1^5 \]

this function returns \( a = (a_0, a_1, a_2, a_3, a_4, a_5) \)

EXAMPLES:

```python
sage: R.<a0, a1, a2, a3, a4, a5, x0, x1> = QQ[]
sage: p = a0*x1^5 + a1*x0^4*x1 + a2*x0^3*x1^2 + a3*x0^2*x1^3 + a4*x0*x1^4 + a5*x1^5
sage: quintic = invariant_theory.binary_quintic(p, x0, x1)
sage: quintic.scaled_coeffs()
(a0, a1, a2, a3, a4, a5)
```

`tau_covariant(as_form=False)`
Return the covariant \( \tau \) of a binary quintic.

**INPUT:**

- `as_form` – if `as_form` is `False`, the result will be returned as polynomial (default). If it is `True` the result is returned as an object of the class `AlgebraicForm`.

**OUTPUT:**
The \( \tau \)-covariant of the binary quintic as polynomial or as binary form.

**EXAMPLES:**

```python
sage: R.<a0, a1, a2, a3, a4, a5, x> = QQ[]
sage: p = a0 + 5*a1*x + 10*a2*x^2 + 10*a3*x^3 + 5*a4*x^4 + a5*x^5
sage: quintic = invariant_theory.binary_quintic(p, x)
sage: quintic.tau_covariant(as_form=True)
1/62500*a2^2*a3^4*x0^2 - 3/62500*a1*a3^5*x0 - 1/15625*a2^3*a3^2*a4*x0^2 + 3/62500*a0*a3^4*a4*x0^2 - 1/31250*a2*a4^2*x0^2
```
- 2/125*a0*a1*a2^2*a4*a5*x1^2 - 4/125*a0*a1^2*a3*a4*a5*x1^2
+ 2/25*a0^2*a2*a3*a4*a5*x1^2 - 8/625*a1^4*a5^2*x1^2
+ 8/125*a0*a1^2*a2*a5^2*x1^2 - 2/25*a0^2*a2^2*a5^2*x1^2

\textbf{sage:} quintic.tau_covariant(as_form=True)
Binary quadratic given by ...

\textbf{theta_covariant} \textbf{(as_form=False)}

Return the covariant $\theta$ of a binary quintic.

\textbf{INPUT:}

\begin{itemize}
  \item \textbf{as\_form} – if \textbf{as\_form} is \textbf{False}, the result will be returned as polynomial (default). If it is \textbf{True} the result is returned as an object of the class \textit{AlgebraicForm}.
\end{itemize}

\textbf{OUTPUT:}

The $\theta$-covariant of the binary quintic as polynomial or as binary form.

\textbf{EXAMPLES:}

\begin{verbatim}
\textbf{sage:} \textit{R.<a0, a1, a2, a3, a4, a5, x0, x1> = QQ[]}
\textbf{sage:} \textit{p = a0*x1^5 + a1*x1^4*x0 + a2*x1^3*x0^2 + a3*x1^2*x0^3 + a4*x1*x0^4 + a5*x0^5}
\textbf{sage:} \textit{quintic = invariant_theory.binary_quintic(p, x0, x1)}
\textbf{sage:} \textit{quintic.theta_covariant()}
-1/625000*a2^3*a3^5*x0^2 + 9/1250000*a1*a2*a3^6*x0^2
- 27/1250000*a0*a3^7*x0^2 + 3/250000*a2^4*a3^3*a4*x0^2
- 7/1250000*a1*a2^2*a3^4*a4*x0^2 - 3/3125000*a1^2*a3^5*a4*x0^2
... + 6/625*a0^2*a1^2*a2^2*a4*a5^2*x1^2 + 24/625*a0^2*a1^2*a3*a4*a5^2*x1^2
- 12/125*a0^3*a2*a3*a4*a5^2*x1^2 + 8/625*a0*a1^4*a5^3*x1^2
- 8/125*a0^2*a1^2*a2*a5^3*x1^2 + 2/25*a0^3*a2^2*a5^3*x1^2
\textbf{sage:} \textit{quintic.theta_covariant(as_form=True)}
\end{verbatim}
Binary quadratic given by ...

\textbf{class} \textbf{sage.rings.invariants.invariant_theory.FormsBase(n, homogeneous, ring, variables)}

\textbf{Bases:} \textit{SageObject}

The common base class of \textit{AlgebraicForm} and \textit{SeveralAlgebraicForms}.

This is an abstract base class to provide common methods. It does not make much sense to instantiate it.

\textbf{is\_homogeneous()} \hfill

Return whether the forms were defined by homogeneous polynomials.

\textbf{OUTPUT:}

Boolean. Whether the user originally defined the form via homogeneous variables.

\textbf{EXAMPLES:}

\begin{verbatim}
\textbf{sage:} \textit{R.<x,y,t> = QQ[]}
\textbf{sage:} \textit{quartic = invariant_theory.binary_quartic(x^4+y^4+t*x^2*y^2, [x,y])}
\textbf{sage:} \textit{quartic.is_homogeneous()}
True
\end{verbatim}
sage: quartic.form()
x^2*y^2*t + x^4 + y^4

sage: R.<x,y,t> = QQ[]
sage: quartic = invariant_theory.binary_quartic(x^4+1+t*x^2, [x])
sage: quartic.is_homogeneous()
False
sage: quartic.form()
x^4 + x^2*t + 1

ring()
Return the polynomial ring.

OUTPUT:
A polynomial ring. This is where the defining polynomial(s) live. Note that the polynomials may be homogeneous or inhomogeneous, depending on how the user constructed the object.

EXAMPLES:

sage: R.<x,y,t> = QQ[]
sage: quartic = invariant_theory.binary_quartic(x^4+y^4+t*x^2*y^2, [x,y])
sage: quartic.ring()
Multivariate Polynomial Ring in x, y, t over Rational Field

sage: R.<x,y,t> = QQ[]
sage: quartic = invariant_theory.binary_quartic(x^4+1+t*x^2, [x])
sage: quartic.ring()
Multivariate Polynomial Ring in x, y, t over Rational Field

variables()
Return the variables of the form.

OUTPUT:
A tuple of variables. If inhomogeneous notation is used for the defining polynomial then the last entry will be None.

EXAMPLES:

sage: R.<x,y,t> = QQ[]
sage: quartic = invariant_theory.binary_quartic(x^4+y^4+t*x^2*y^2, [x,y])
sage: quartic.variables()
(x, y)

sage: R.<x,y,t> = QQ[]
sage: quartic = invariant_theory.binary_quartic(x^4+1+t*x^2, [x])
sage: quartic.variables()
(x, None)

class sage.rings.invariants.invariant_theory.InvariantTheoryFactory

Bases: object

Factory object for invariants of multilinear forms.

Use the invariant_theory object to construct algebraic forms. These can then be queried for invariant and covariants.
EXAMPLES:

```python
sage: R.<x,y,z> = QQ[]
sage: invariant_theory.ternary_cubic(x^3+y^3+z^3)
Ternary cubic with coefficients (1, 1, 1, 0, 0, 0, 0, 0, 0)
sage: invariant_theory.ternary_cubic(x^3+y^3+z^3).J_covariant()
x^6*y^3 - x^3*y^6 - x^6*z^3 + y^6*z^3 + x^3*z^6 - y^3*z^6
```

`binary_form_from_invariants(degree, invariants, variables=None, as_form=True, *args, **kwargs)`

Reconstruct a binary form from the values of its invariants.

INPUT:

- `degree` – The degree of the binary form.
- `invariants` – A list or tuple of values of the invariants of the binary form.
- `variables` – A list or tuple of two variables that are used for the resulting form (only if `as_form` is True). If no variables are provided, two abstract variables `x` and `z` will be used.
- `as_form` – boolean. If False, the function will return a tuple of coefficients of a binary form.

OUTPUT:

A binary form or a tuple of its coefficients, whose invariants are equal to the given `invariants` up to a scaling.

EXAMS:

In the case of binary quadratics and cubics, the form is reconstructed based on the value of the discriminant. See also `binary_quadratic_coefficients_from_invariants()` and `binary_cubic_coefficients_from_invariants()`. These methods will always return the same result if the discriminant is non-zero:

```python
sage: discriminant = 1
sage: invariant_theory.binary_form_from_invariants(2, [discriminant])
Binary quadratic with coefficients (1, -1/4, 0)
sage: invariant_theory.binary_form_from_invariants(3, [discriminant], as_form=False)
(0, 1, -1, 0)
```

For binary cubics, there is no class implemented yet, so `as_form=True` will yield a `NotImplementedError`:

```python
sage: invariant_theory.binary_form_from_invariants(3, [discriminant])
Traceback (most recent call last):
... Not Implemented: no class for binary cubics implemented
```

For binary quintics, the three Clebsch invariants of the form should be provided to reconstruct the form. For more details about these invariants, see `clebsch_invariants()`:

```python
sage: invariants = [1, 0, 0]
sage: invariant_theory.binary_form_from_invariants(5, invariants)
Binary quintic with coefficients (1, 0, 0, 0, 0, 1)
```

An optional scaling argument may be provided in order to scale the resulting quintic. For more details, see `binary_quintic_coefficients_from_invariants()`:

---

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sage: invariants = [3, 4, 7]
sage: invariant_theory.binary_form_from_invariants(5, invariants)
Binary quintic with coefficients (-37725479487783/1048576, 565882192316745/8388608, 0, 1033866765362693115/67108864, 1284948694936328715/268435456, -23129076493685391687/2147483648)
sage: invariant_theory.binary_form_from_invariants(5, invariants, scaling='normalized')
Binary quintic with coefficients (24389/892616806656, 4205/11019960576, 0, 1015/209952, -145/1296, -3/16)
sage: invariant_theory.binary_form_from_invariants(5, invariants, scaling='coprime')
Binary quintic with coefficients (-2048, 3840, 0, 876960, 2724840, -613089)

The invariants can also be computed using the invariants of a given binary quintic. The resulting form has the same invariants up to scaling, is $GL(2, \mathbb{Q})$-equivalent to the provided form and hence has the same canonical form (see `canonical_form()`):

sage: R.<x0, x1> = QQ[]
sage: p = 3*x1^5 + 6*x1^4*x0 + 3*x1^3*x0^2 + 4*x1^2*x0^3 - 5*x1*x0^4 + 4*x0^5
sage: quintic = invariant_theory.binary_quintic(p, x0, x1)
sage: invariants = quintic.clebsch_invariants(as_tuple=True)
sage: newquintic = invariant_theory.binary_form_from_invariants(5, invariants, variables=quintic.variables())
sage: newquintic
Binary quintic with coefficients (9592267437341790539005557/244140625000000, 21492969282076255632300464707/610351562500000, 11149651890347700974453304786783/76293945312500000, 12265077518194638395648891202734239/476837158203125000000, 3239968630945706528474286334593218447/11920928955078125000, 150450650364660839584163253858481466127/14901161193847656250000)
sage: quintic.canonical_form() == newquintic.canonical_form()
True

For binary forms of other degrees, no reconstruction has been implemented yet. For forms of degree 6, see github issue #26462:

sage: invariant_theory.binary_form_from_invariants(6, invariants)
Traceback (most recent call last):
  ...
NotImplementedError: no reconstruction for binary forms of degree 6 implemented

binary_quadratic(quadratic, *args)
Invariant theory of a quadratic in two variables.

**INPUT:**
- quadratic – a quadratic form.
- x, y – the homogeneous variables. If y is None, the quadratic is assumed to be inhomogeneous.

**REFERENCES:**
- Wikipedia article Invariant_of_a_binary_form

**EXAMPLES:**
binary_quartic(quartic, *args, **kwds)

Invariant theory of a quartic in two variables.

The algebra of invariants of a quartic form is generated by invariants $i, j$ of degrees 2, 3. This ring is naturally isomorphic to the ring of modular forms of level 1, with the two generators corresponding to the Eisenstein series $E_4$ (see `EisensteinD()`) and $E_6$ (see `EisensteinE()`). The algebra of covariants is generated by these two invariants together with the form $f$ of degree 1 and order 4, the Hessian $g$ (see `g_covariant()`) of degree 2 and order 4, and a covariant $h$ (see `h_covariant()`) of degree 3 and order 6. They are related by a syzygy

$$jf^3 - gf^2 i + 4g^3 + h^2 = 0$$

of degree 6 and order 12.

INPUT:

- quartic – a quartic.
- x, y – the homogeneous variables. If y is `None`, the quartic is assumed to be inhomogeneous.

REFERENCES:

- Wikipedia article Invariant_of_a_binary_form

EXAMPLES:

```python
sage: R.<x,y> = QQ[]
sage: quartic = invariant_theory.binary_quartic(x^4+y^4)
sage: quartic
Binary quartic with coefficients (1, 0, 0, 0, 1)
sage: type(quartic)
<class 'sage.rings.invariants.invariant_theory.BinaryQuartic'>
```

binary_quintic(quintic, *args, **kwds)

Create a binary quintic for computing invariants.

A binary quintic is a homogeneous polynomial of degree 5 in two variables. The algebra of invariants of a binary quintic is generated by the invariants $A, B$ and $C$ of respective degrees 4, 8 and 12 (see `A_invariant()`, `B_invariant()` and `C_invariant()`).

INPUT:

- quintic – a homogeneous polynomial of degree five in two variables or a (possibly inhomogeneous) polynomial of degree at most five in one variable.
- *args – the two homogeneous variables. If only one variable is given, the polynomial quintic is assumed to be univariate. If no variables are given, they are guessed.

REFERENCES:

- Wikipedia article Invariant_of_a_binary_form
**EXAMPLES:**

If no variables are provided, they will be guessed:

```python
sage: R.<x,y> = QQ[]
sage: quintic = invariant_theory.binary_quintic(x^5+y^5)
sage: quintic
Binary quintic with coefficients (1, 0, 0, 0, 1)
```

If only one variable is given, the quintic is the homogenisation of the provided polynomial:

```python
sage: quintic = invariant_theory.binary_quintic(x^5+y^5, x)
sage: quintic
Binary quintic with coefficients (y^5, 0, 0, 0, 1)
sage: quintic.is_homogeneous()
False
```

If the polynomial has three or more variables, the variables should be specified:

```python
sage: R.<x,y,z> = QQ[]
sage: quintic = invariant_theory.binary_quintic(x^5+z*y^5)
Traceback (most recent call last):
  ... ValueError: need 2 or 1 variables, got (x, y, z)
sage: quintic = invariant_theory.binary_quintic(x^5+z*y^5, x, y)
sage: quintic
Binary quintic with coefficients (z, 0, 0, 0, 1)
sage: type(quintic)
<class 'sage.rings.invariants.invariant_theory.BinaryQuintic'>
```

**inhomogeneous_quadratic_form**(*polynomial, *args*)

Invariants of an inhomogeneous quadratic form.

**INPUT:**

- *polynomial* – an inhomogeneous quadratic form.
- *args* – the variables as multiple arguments, or as a single list/tuple.

**EXAMPLES:**

```python
sage: R.<x,y,z> = QQ[]
sage: quadratic = x^2+2*y^2+3*x*y+4*x+5*y+6
sage: inv3 = invariant_theory.inhomogeneous_quadratic_form(quadratic)
sage: type(inv3)
<class 'sage.rings.invariants.invariant_theory.TernaryQuadratic'>
sage: inv4 = invariant_theory.inhomogeneous_quadratic_form(x^2+y^2+z^2)
sage: type(inv4)
<class 'sage.rings.invariants.invariant_theory.QuadraticForm'>
```

**quadratic_form**(*polynomial, *args*)

Invariants of a homogeneous quadratic form.

**INPUT:**
• **polynomial** – a homogeneous or inhomogeneous quadratic form.

• *args – the variables as multiple arguments, or as a single list/tuple. If the last argument is None, the cubic is assumed to be inhomogeneous.

**EXAMPLES:**

```python
sage: R.<x,y,z> = QQ[]
sage: quadratic = x^2+y^2+z^2
sage: inv = invariant_theory.quadratic_form(quadratic)
sage: type(inv)
<class 'sage.rings.invariants.invariant_theory.TernaryQuadratic'>
```

If some of the ring variables are to be treated as coefficients you need to specify the polynomial variables:

```python
sage: R.<x,y,z, a,b> = QQ[]
sage: quadratic = a*x^2+b*y^2+z^2+2*y*z
sage: invariant_theory.quadratic_form(quadratic, x,y,z)  # alternate syntax
Ternary quadratic with coefficients (a, b, 1, 0, 0, 2)
sage: invariant_theory.quadratic_form(quadratic, [x,y,z])
Ternary quadratic with coefficients (a, b, 1, 0, 0, 2)
```

Inhomogeneous quadratic forms (see also `inhomogeneous_quadratic_form()`) can be specified by passing None as the last variable:

```python
sage: inhom = quadratic.subs(z=1)
sage: invariant_theory.quadratic_form(inhom, x,y, None)
Ternary quadratic with coefficients (a, b, 1, 0, 0, 2)
```

**quaternary_biquadratic**(quadratic1, quadratic2, *args, **kwds)

Invariants of two quadratics in four variables.

**INPUT:**

• quadratic1, quadratic2 – two polynomials. Either homogeneous quadratic in 4 homogeneous variables, or inhomogeneous quadratic in 3 variables.

• w, x, y, z – the variables. If z is None, the quadratics are assumed to be inhomogeneous.

**EXAMPLES:**

```python
sage: R.<w,x,y,z> = QQ[]
sage: q1 = w^2+x^2+y^2+z^2
sage: q2 = w*x + y*z
sage: inv = invariant_theory.quaternary_biquadratic(q1, q2)
sage: type(inv)
<class 'sage.rings.invariants.invariant_theory.TwoQuaternaryQuadratics'>
```

Distance between two spheres [Sal1958], [Sal1965]

```python
sage: R.<x,y,z, a,b,c, r1,r2> = QQ[]
sage: S1 = -r1^2 + x^2 + y^2 + z^2
sage: S2 = -r2^2 + (x-a)^2 + (y-b)^2 + (z-c)^2
sage: inv = invariant_theory.quaternary_biquadratic(S1, S2, [x, y, z])
sage: inv.Delta_invariant()
-r1^2
sage: inv.Delta_prime_invariant()
```

(continues on next page)
Polynomials, Release 10.0

-quaternary_quadratic\(\text{(quadratic, *args)}\)

Invariant theory of a quadratic in four variables.

INPUT:

- quadratic – a quadratic form.
- w, x, y, z – the homogeneous variables. If z is None, the quadratic is assumed to be inhomogeneous.

REFERENCES:

- Wikipedia article Invariant_of_a_binary_form

EXAMPLES:

\[
\begin{align*}
\text{sage: } & \quad \text{R.<w,x,y,z> = QQ[]}
\text{sage: } & \quad \text{invariant_theory.quaternary_quadratic(w^2+x^2+y^2+z^2)}
\text{Quaternary quadratic with coefficients (1, 1, 1, 1, 0, 0, 0, 0, 0, 0)}
\text{sage: } & \quad \text{R.<x,y,z> = QQ[]}
\text{sage: } & \quad \text{invariant_theory.quaternary_quadratic(1+x^2+y^2+z^2)}
\text{Quaternary quadratic with coefficients (1, 1, 1, 1, 0, 0, 0, 0, 0, 0)}
\end{align*}
\]

- ternary_biquadratic\(\text{(quadratic1, quadratic2, *args, **kwds)}\)

Invariants of two quadratics in three variables.

INPUT:

- quadratic1, quadratic2 – two polynomials. Either homogeneous quadratic in 3 homogeneous variables, or inhomogeneous quadratic in 2 variables.
- x, y, z – the variables. If z is None, the quadratics are assumed to be inhomogeneous.

EXAMPLES:

\[
\begin{align*}
\text{sage: } & \quad \text{R.<x,y,z> = QQ[]}
\text{sage: } & \quad \text{q1 = x^2+y^2+z^2}
\text{sage: } & \quad \text{q2 = x*y + y*z + x*z}
\text{sage: } & \quad \text{inv = invariant_theory.ternary_biquadratic(q1, q2)}
\text{sage: } & \quad \text{type(inv)}
\text{<class 'sage.rings.invariants.invariant_theory.TwoTernaryQuadratics'>}
\end{align*}
\]

Distance between two circles:

\[
\begin{align*}
\text{sage: } & \quad \text{R.<x,y, a,b, r1,r2> = QQ[]}
\text{sage: } & \quad \text{S1 = -r1^2 + x^2 + y^2}
\text{sage: } & \quad \text{S2 = -r2^2 + (x-a)^2 + (y-b)^2}
\end{align*}
\]
sage: inv = invariant_theory.ternary_biquadratic(S1, S2, [x, y])
sage: inv.Delta_invariant()
-r1^2
sage: inv.Delta_prime_invariant()
-r2^2
sage: inv.Theta_invariant()
a^2 + b^2 - 2*r1^2 - r2^2
sage: inv.Theta_prime_invariant()
a^2 + b^2 - r1^2 - 2*r2^2
sage: inv.F_covariant()
2*x^2*a^2 + y^2*a^2 - 2*x*a^3 + a^4 + 2*x*y*a*b - 2*y^2*a^2*b + x^2*b^2 +
2*y^2*b^2 - 2*x*a*b^2 - 2*a^2*b^2 - 2*y^2*b^3 + b^4 - 2*x^2*r1^2 - 2*y^2*r1^2 +
2*x*a*r1^2 - 2*a^2*r1^2 + 2*x*b*r1^2 - 2*b^2*r1^2 + r1^4 - 2*x^2*r2^2 -
2*y^2*r2^2 + 2*x*a*r2^2 - 2*a^2*r2^2 + 2*y*b*r2^2 - 2*b^2*r2^2 + 2*r1^2*r2^2 +
r2^4
sage: inv.J_covariant()
-8*x^2*y*a^3 + 8*x^3*y*a^4 + 8*x^3*a^3*b - 16*x*y^2*a^2*b - 8*x^2*a^2*b^3 +
8*y^2*a^3*b - 16*x^2*y*a^2*b^2 - 8*x^3*y^2*b^2 - 8*x^2*y^2*b^3 + 8*x^2*a*b^3 +
8*y^2*a*b^3 - 8*x*y*b^4 + 8*x*y*a^2*r1^2 - 8*y^2*a^3*r1^2 - 8*x^2*a*b*r1^2 +
8*y^2*a*b*r1^2 + 8*x*a^2*b*r1^2 - 8*x^2*y^2*b*r1^2 - 8*x*y^2*b^2*r1^2 - 8*y^2*a*b^2*r1^2 + 8*x*b^3*r1^2 -
2 - 8*x*y*a^2*r2^2 + 8*x^2*a^2*b*r2^2 - 8*y^2*a^2*b^2*r2^2 + 8*x*y*b^2*r2^2

**ternary_cubic**(*cubic, *args, **kwds*)

Invariants of a cubic in three variables.

The algebra of invariants of a ternary cubic under $SL_3(\mathbb{C})$ is a polynomial algebra generated by two invariants $S$ (see `S_invariant()`) and $T$ (see `T_invariant()`) of degrees 4 and 6, called Aronhold invariants.

The ring of covariants is given as follows. The identity covariant $U$ of a ternary cubic has degree 1 and order 3. The Hessian $H$ (see `Hessian()`) is a covariant of ternary cubics of degree 3 and order 3. There is a covariant $\Theta$ (see `Theta_covariant()`) of ternary cubics of degree 8 and order 6 that vanishes on points $x$ lying on the Salmon conic of the polar of $x$ with respect to the curve and its Hessian curve. The Brioschi covariant $J$ (see `J_covariant()`) is the Jacobian of $U$, $\Theta$, and $H$ of degree 12, order 9. The algebra of covariants of a ternary cubic is generated over the ring of invariants by $U$, $\Theta$, $H$, and $J$, with a relation

$$J^2 = 4\Theta^3 + TU^2\Theta^2 + \Theta(-4STUH + 2STU^3H - 72S^2U^2H^2 - 18TUH^3 + 108SH^4) + 16S^4U^5H - 115STU^4H^2 - 4T^2U^3H^3 + 54STU^2H^4 - 432S^2UH^5 - 27TH^6$$

REFERENCES:

- Wikipedia article Ternary_cubic

INPUT:

- cubic – a homogeneous cubic in 3 homogeneous variables, or an inhomogeneous cubic in 2 variables.
- `x, y, z` – the variables. If `z` is `None`, the cubic is assumed to be inhomogeneous.

EXAMPLES:

```python
sage: R.<x,y,z> = QQ[]
sage: cubic = invariant_theory.ternary_cubic(x^3+y^3+z^3)
sage: type(cubic)
<class 'sage.rings.invariants.invariant_theory.TernaryCubic'>
```
\textbf{ternary\_quadratic}(\textit{quadratic}, *\textit{args}, **\textit{kwds})

Invariants of a quadratic in three variables.

\textbf{INPUT:}

\begin{itemize}
  \item \textit{quadratic} – a homogeneous quadratic in 3 homogeneous variables, or an inhomogeneous quadratic in 2 variables.
  \item \textit{x}, \textit{y}, \textit{z} – the variables. If \textit{z} is \texttt{None}, the quadratic is assumed to be inhomogeneous.
\end{itemize}

\textbf{REFERENCES:}

\begin{itemize}
  \item Wikipedia article Invariant\_of\_a\_binary\_form
\end{itemize}

\textbf{EXAMPLES:}

\begin{verbatim}
sage: R.<x,y,z> = QQ[]
sage: invariant_theory.ternary_quadratic(x^2+y^2+z^2)
Ternary quadratic with coefficients (1, 1, 1, 0, 0, 0)
sage: T.<u, v> = QQ[]
sage: invariant_theory.ternary_quadratic(1+u^2+v^2)
Ternary quadratic with coefficients (1, 1, 1, 0, 0, 0)
sage: quadratic = x^2+y^2+z^2
sage: inv = invariant_theory.ternary_quadratic(quadratic)
sage: type(inv)
<class 'sage.rings.invariants.invariant_theory.TernaryQuadratic'>
\end{verbatim}

\textbf{class} \textit{QuadraticForm}(n, d, \textit{polynomial}, *\textit{args})

\textbf{Bases:} \textit{AlgebraicForm}

Invariant theory of a multivariate quadratic form.

You should use the \textit{invariant\_theory} factory object to construct instances of this class. See \textit{quadratic\_form()} for details.

\textbf{as\_QuadraticForm()}\n
Convert into a \textit{QuadraticForm}.

\textbf{OUTPUT:}

Sage has a special quadratic forms subsystem. This method converts \textit{self} into this \textit{QuadraticForm} representation.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: R.<x,y,z> = QQ[]
sage: p = x^2+y^2+z^2+2*x*y+3*x*z
sage: quadratic = invariant_theory.ternary_quadratic(p)
sage: matrix(quadratic)
\begin{bmatrix}
 1 & 1 & 3/2 \\
 1 & 1 & 0 \\
3/2 & 0 & 1
\end{bmatrix}
sage: quadratic.as_QuadraticForm()
Quadratic form in 3 variables over Multivariate Polynomial Ring in x, y, z over Rational Field with coefficients:
\begin{bmatrix}
 1 & 2 & 3 \\
 * & 1 & 0
\end{bmatrix}
\end{verbatim}
coffs()

The coefficients of a quadratic form.

Given

\[ f(x) = \sum_{0 \leq i < n} a_i x_i^2 + \sum_{0 \leq j < k < n} a_{jk} x_j x_k \]

this function returns \( a = (a_0, \ldots, a_n, a_{00}, a_{01}, \ldots, a_{n-1,n}) \)

EXAMPLES:

```python
sage: R.<a,b,c,d,e,f,g,x,y,z> = QQ[]
sage: p = a*x^2 + b*y^2 + c*z^2 + d*x*y + e*x*z + f*y*z
sage: inv = invariant_theory.quadratic_form(p, x,y,z); inv
Ternary quadratic with coefficients (a, b, c, d, e, f)
sage: inv.coeffs()
(a, b, c, d, e, f)
sage: inv.scaled_coeffs()
(a, b, c, 1/2*d, 1/2*e, 1/2*f)
```

discriminant()

Return the discriminant of the quadratic form.

Up to an overall constant factor, this is just the determinant of the defining matrix, see matrix(). For a quadratic form in \( n \) variables, the overall constant is \( 2^{n-1} \) if \( n \) is odd and \((-1)^{n/2}2^n\) if \( n \) is even.

EXAMPLES:

```python
sage: R.<a,b,c,x,y> = QQ[]
sage: p = a*x^2 + b*y^2 + c*y^2
sage: quadratic = invariant_theory.quadratic_form(p, x,y)
sage: quadratic.discriminant()
b^2 - 4*a*c
sage: R.<a,b,c,d,e,f,g,x,y,z> = QQ[]
sage: p = a*x^2 + b*y^2 + c*z^2 + d*x*y + e*x*z + f*y*z
sage: quadratic = invariant_theory.quadratic_form(p, x,y,z)
sage: quadratic.discriminant()
4*a*b*c - c*d^2 - b*e^2 + d*e*f - a*f^2
```
dual()

Return the dual quadratic form.

OUTPUT:

A new quadratic form (with the same number of variables) defined by the adjoint matrix.

EXAMPLES:

```python
sage: R.<a,b,c,x,y,z> = QQ[]
sage: cubic = x^2+y^2+z^2
```

(continues on next page)
sage: quadratic = invariant_theory.ternary_quadratic(a*x^2+b*y^2+c*z^2, [x,y,z])
sage: quadratic.form()
a*x^2 + b*y^2 + c*z^2
sage: quadratic.dual().form()
b*c*x^2 + a*c*y^2 + a*b*z^2

sage: R.<x,y,z, t> = QQ[

sage: cubic = x^2+y^2+z^2 
sage: quadratic = invariant_theory.ternary_quadratic(x^2+y^2+z^2 + t*x*y, [x,y, z])

sage: quadratic.dual()
Ternary quadratic with coefficients (1, 1, -1/4*t^2 + 1, -t, 0, 0)

sage: R.<x,y, t> = QQ[

sage: quadratic = invariant_theory.ternary_quadratic(x^2+y^2+1 + t*x*y, [x,y])

sage: quadratic.dual()
Ternary quadratic with coefficients (1, 1, -1/4*t^2 + 1, -t, 0, 0)

\textbf{classmethod from\_invariants}(\textit{discriminant, x, z, }\ast\textit{args, }\ast\ast\textit{kwargs})

Construct a binary quadratic from its discriminant.

This function constructs a binary quadratic whose discriminant equal the one provided as argument up to scaling.

\textbf{INPUT:}

\begin{itemize}
  \item discriminant – Value of the discriminant used to reconstruct the binary quadratic.
\end{itemize}

\textbf{OUTPUT:}

A QuadraticForm with 2 variables.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: R.<x,y> = QQ[
sage: from sage.rings.invariants.invariant_theory import QuadraticForm
sage: QuadraticForm.from_invariants(1, x, y)
Binary quadratic with coefficients (1, -1/4, 0)
\end{verbatim}

\textbf{invariants}\textbf{\((type='discriminant')\)}

Return a tuple of invariants of a binary quadratic.

\textbf{INPUT:}

\begin{itemize}
  \item type – The type of invariants to return. The default choice is to return the discriminant.
\end{itemize}

\textbf{OUTPUT:}

The invariants of the binary quadratic.

\textbf{EXAMPLES:}

\begin{verbatim}
sage: R.<x0, x1> = QQ[
sage: p = 2*x1^2 + 5*x0^2*x1 + 3*x0^2 
sage: quadratic = invariant_theory.binary_quadratic(p, x0, x1)
sage: quadratic.invariants()
(1,)
\end{verbatim}
sage: quadratic.invariants('unknown')
Traceback (most recent call last):
...
ValueError: unknown type of invariants unknown for a binary quadratic matrix

matrix()
Return the quadratic form as a symmetric matrix
OUTPUT:
This method returns a symmetric matrix $A$ such that the quadratic $Q$ equals
$$Q(x, y, z, \ldots) = (x, y, \ldots)A(x, y, \ldots)^t$$

EXAMPLES:

```
sage: R.<x,y,z> = QQ[]
sage: quadratic = invariant_theory.ternary_quadratic(x^2+y^2+z^2+x*y)
sage: matrix(quadratic)
[ 1 1/2 0]
[1/2 1 0]
[ 0 0 1]
sage: quadratic._matrix_() == matrix(quadratic)
True
```

monomials()
List the basis monomials in the form.
OUTPUT:
A tuple of monomials. They are in the same order as `coeffs()`.

EXAMPLES:

```
sage: R.<x,y> = QQ[]
sage: quadratic = invariant_theory.quadratic_form(x^2+y^2)
sage: quadratic.monomials()
(x^2, y^2, x*y)
sage: quadratic = invariant_theory.inhomogeneous_quadratic_form(x^2+y^2)
sage: quadratic.monomials()
(x^2, y^2, 1, x*y, x, y)
```

scaled_coeffs()
The scaled coefficients of a quadratic form.

Given
$$f(x) = \sum_{0 \leq i < n} a_i x_i^2 + \sum_{0 \leq j < k < n} 2a_{jk} x_j x_k$$
this function returns $a = (a_0, \cdots, a_n, a_{00}, a_{01}, \ldots, a_{n-1,n})$

EXAMPLES:
```python
sage: R.<a,b,c,d,e,f,g, x,y,z> = QQ[]
sage: p = a*x^2 + b*y^2 + c*z^2 + d*x*y + e*x*z + f*y*z
sage: inv = invariant_theory.quadratic_form(p, x,y,z); inv
Ternary quadratic with coefficients (a, b, c, d, e, f)
sage: inv.coeffs()
(a, b, c, d, e, f)
sage: inv.scaled_coeffs()
(a, b, c, 1/2*d, 1/2*e, 1/2*f)
```

```python
class sage.rings.invariants.invariant_theory.SeveralAlgebraicForms(forms)
    Bases: FormsBase
    The base class of multiple algebraic forms (i.e. homogeneous polynomials).
    You should only instantiate the derived classes of this base class.
    See AlgebraicForm for the base class of a single algebraic form.
    INPUT:
    • forms – a list/tuple/iterable of at least one AlgebraicForm object, all with the same number of variables.
    Interpreted as multiple homogeneous polynomials in a common polynomial ring.
    EXAMPLES:
```
```python
sage: from sage.rings.invariants.invariant_theory import AlgebraicForm,
         SeveralAlgebraicForms
sage: R.<x,y> = QQ[]
sage: p = AlgebraicForm(2, 2, x^2, (x,y))
sage: q = AlgebraicForm(2, 2, y^2, (x,y))
sage: pq = SeveralAlgebraicForms([p, q])
```
```
get_form(i)
    Return the i-th form.
    EXAMPLES:
```
```python
sage: R.<x,y> = QQ[]
sage: q1 = invariant_theory.quadratic_form(x^2 + y^2)
sage: q2 = invariant_theory.quadratic_form(x*y)
sage: from sage.rings.invariants.invariant_theory import SeveralAlgebraicForms
sage: q12 = SeveralAlgebraicForms([q1, q2])
sage: q12.get_form(0) is q1
True
sage: q12.get_form(1) is q2
True
sage: q12[0] is q12.get_form(0)  # syntactic sugar
True
sage: q12[1] is q12.get_form(1)  # syntactic sugar
True
```
```
homogenized(var='h')
    Return form as defined by a homogeneous polynomial.
    INPUT:
    • var – either a variable name, variable index or a variable (default: 'h').
```
```
OUTPUT:
The same algebraic form, but defined by a homogeneous polynomial.

EXAMPLES:

```python
sage: R.<x,y,z> = QQ[]
sage: q = invariant_theory.quaternary_biquadratic(x^2+1, y^2+1, [x,y,z])
sage: q
Joint quaternary quadratic with coefficients (1, 0, 0, 1, 0, 0, 0, 0, 0, 0)
and quaternary quadratic with coefficients (0, 1, 0, 1, 0, 0, 0, 0, 0, 0)
sage: q.homogenized()
Joint quaternary quadratic with coefficients (1, 0, 0, 1, 0, 0, 0, 0, 0, 0)
and quaternary quadratic with coefficients (0, 1, 0, 1, 0, 0, 0, 0, 0, 0)
sage: type(q) is type(q.homogenized())
True
```

`n_forms()`

Return the number of forms.

EXAMPLES:

```python
sage: R.<x,y> = QQ[]
sage: q1 = invariant_theory.quadratic_form(x^2 + y^2)
sage: q2 = invariant_theory.quadratic_form(x*y)
sage: from sage.rings.invariants.invariant_theory import SeveralAlgebraicForms
sage: q12 = SeveralAlgebraicForms([q1, q2])
sage: q12.n_forms()
2
sage: len(q12) == q12.n_forms()  # syntactic sugar
True
```

class `sage.rings.invariants.invariant_theory.TernaryCubic(n, d, polynomial, *args)`

Invariant theory of a ternary cubic.

You should use the `invariant_theory` factory object to construct instances of this class. See `ternary_cubic()` for details.

`Hessian()`

Return the Hessian covariant.

OUTPUT:
The Hessian matrix multiplied with the conventional normalization factor 1/216.

EXAMPLES:

```python
sage: R.<x,y,z> = QQ[]
sage: cubic = invariant_theory.ternary_cubic(x^3+y^3+z^3)
sage: cubic.Hessian()
x^3y^3z
sage: R.<x,y> = QQ[]
sage: cubic = invariant_theory.ternary_cubic(x^3+y^3+1)
sage: cubic.Hessian()
x^3y
```
J\_covariant()

Return the J-covariant of the ternary cubic.

EXAMPLES:

```
sage: R.<x,y,z> = QQ[]
sage: cubic = invariant_theory.ternary_cubic(x^3+y^3+z^3)
sage: cubic.J\_covariant()
x^6*y^3 - x^3*y^6 - x^6*z^3 + y^6*z^3 + x^3*z^6 - y^3*z^6

sage: R.<x,y> = QQ[]
sage: cubic = invariant_theory.ternary_cubic(x^3+y^3+1)
sage: cubic.J\_covariant()
x^6*y^3 - x^3*y^6 - x^6 + y^6 + x^3 - y^3
```

S\_invariant()

Return the S-invariant.

EXAMPLES:

```
sage: R.<x,y,z> = QQ[]
sage: cubic = invariant_theory.ternary_cubic(x^2*y+y^3+z^3+x*y*z)
sage: cubic.S\_invariant()
-1/1296
```

T\_invariant()

Return the T-invariant.

EXAMPLES:

```
sage: R.<x,y,z> = QQ[]
sage: cubic = invariant_theory.ternary_cubic(x^3+y^3+z^3)
sage: cubic.T\_invariant()
1

sage: R.<x,y,z,t> = GF(7)[]
sage: cubic = invariant_theory.ternary_cubic(x^3+y^3+z^3+t*x*y*z, [x,y,z])
sage: cubic.T\_invariant()
-t^6 - t^3 + 1
```

Theta\_covariant()

Return the Θ covariant.

EXAMPLES:

```
sage: R.<x,y,z> = QQ[]
sage: cubic = invariant_theory.ternary_cubic(x^3+y^3+z^3)
sage: cubic.Theta\_covariant()
-x^3*y^3 - x^3*z^3 - y^3*z^3

sage: R.<x,y> = QQ[]
sage: cubic = invariant_theory.ternary_cubic(x^3+y^3+1)
sage: cubic.Theta\_covariant()
-x^3*y^3 - x^3 - y^3
```
coefs()  
Return the coefficients of a cubic.

Given
\[ p(x, y) = a_{30}x^3 + a_{21}x^2y + a_{12}xy^2 + a_{03}y^3 + a_{20}x^2z + \ldots + a_{11}xyz + a_{02}y^2z + a_{10}xz^2 + a_{01}yz^2 + a_{00}z^3 \]

this function returns \( a = (a_{30}, a_{03}, a_{00}, a_{21}, a_{20}, a_{12}, a_{02}, a_{10}, a_{01}, a_{11}) \)

EXAMPLES:

```
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 + \ldots + a11*x*y*z + a02*y^2*z + a10*x*z^2 + a01*y*z^2 + a00*z^3 )
sage: cubic = invariant_theory.ternary_cubic(p, x,y,z)
sage: len(list(cubic.Theta_covariant()))
6952
```

monomials()  
List the basis monomials of the form.

OUTPUT:  
A tuple of monomials. They are in the same order as coefs().

EXAMPLES:

```
sage: R.<x,y,z,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 + \ldots + a11*x*y*z + a02*y^2*z + a10*x*z^2 + a01*y*z^2 + a00*z^3 )
sage: cubic = invariant_theory.ternary_cubic(p, x,y,z)
sage: cubic.monomials()
(x^3, y^3, z^3, x^2*y, x^2*z, x*y^2, y^2*z, x^2*z^2, y^2*z^2, x*y*z)
```

polar_conic()  
Return the polar conic of the cubic.

OUTPUT:  
Given the ternary cubic \( f(X, Y, Z) \), this method returns the symmetric matrix \( A(x, y, z) \) defined by
\[
x f_X + y f_Y + z f_Z = (X, Y, Z) \cdot A(x, y, z) \cdot (X, Y, Z)^t
\]

EXAMPLES:

```
sage: R.<x,y,z,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 + \ldots + a11*x*y*z + a02*y^2*z + a10*x*z^2 + a01*y*z^2 + a00*z^3 )
sage: cubic = invariant_theory.ternary_cubic(p, x,y,z)
```

(continues on next page)
sage: cubic.polar_conic()
[x^3*a30 + y*a21 + z*a20 x*a21 + y*a12 + 1/2*z*a11 x*a20 + 1/2*y*a12 + z*a10]
[x^3*a21 + y*a12 + 1/2*z*a11 x*a12 + 3*y*a03 + z*a02 2/3*x*a12 + y*a03 + z*a01]
[x^3*a20 + 1/2*y*a12 + z*a10 1/2*x*a12 + 3*y*a02 + z*a01 x*a10 + y*a01 + 3*z*a00]

sage: polar_eqn = X*p.derivative(x) + Y*p.derivative(y) + Z*p.derivative(z)
sage: polar = invariant_theory.ternary_quadratic(polar_eqn, [x,y,z])
sage: polar.matrix().subs(X=x,Y=y,Z=z) == cubic.polar_conic()
True

scaled_coeffs()

Return the coefficients of a cubic.

Compared to coeffs(), this method returns rescaled coefficients that are often used in invariant theory.

Given
\[ p(x, y) = a_{30}x^3 + a_{21}x^2y + a_{12}xy^2 + a_{03}y^3 + a_{20}x^2 + \]
\[ a_{11}xy + a_{02}y^2 + a_{10}x + a_{01}y + a_{00} \]

this function returns \( a = (a_{30}, a_{03}, a_{00}, 1/3*a_{21}, 1/3*a_{20}, 1/3*a_{12}, 1/3*a_{02}, 1/3*a_{10}, 1/3*a_{01}, 1/6*a_{11}) \)

EXAMPLES:

sage: R.<x,y,z,a30,a21,a12,a03,a20,a10,a02,a01,a00> = QQ[
 sage: p = ( a30*x^3 + a21*x^2*y + a12*x*y^2 + a03*y^3 + a20*x^2 + \]
 ....:     a11*x*y + a02*y^2 + a10*x + a01*y + a00 )
 sage: cubic = invariant_theory.ternary_cubic(p, x,y,z).scaled_coeffs()
(a30, a03, a00, 1/3*a21, 1/3*a20, 1/3*a12, 1/3*a02, 1/3*a10, 1/3*a01, 1/6*a11)

syzygy(U, S, T, H, Theta, J)

Return the syzygy of the cubic evaluated on the invariants and covariants.

INPUT:

• U, S, T, H, Theta, J – polynomials from the same polynomial ring.

OUTPUT:

0 if evaluated for the form, the S invariant, the T invariant, the Hessian, the \( \Theta \) covariant and the J-covariant of a ternary cubic.

EXAMPLES:

sage: R.<x,y,z> = QQ[
 sage: monomials = (x^3, y^3, z^3, x^2*y, x^2*z, x*y^2, \]
 ....:     y^2*z, x*z^2, y*z^2, x*y*z)
 sage: random_poly = sum([ randint(0,10000) * m for m in monomials ])
 sage: cubic = invariant_theory.ternary_cubic(random_poly)
 sage: U = cubic.form()
 sage: S = cubic.S_invariant()
 sage: T = cubic.T_invariant()
 sage: H = cubic.Hessian()
 sage: Theta = cubic.Theta_covariant()
 sage: J = cubic.J_covariant()
 sage: cubic.syzygy(U, S, T, H, Theta, J)
0
class sage.rings.invariants.invariant_theory.TernaryQuadratic(n, d, polynomial, *args)

Bases: QuadraticForm

Invariant theory of a ternary quadratic.

You should use the invariant_theory factory object to construct instances of this class. See ternary_quadratic() for details.

coeffs()

Return the coefficients of a quadratic.

Given

\[ p(x, y) = a_{20}x^2 + a_{11}xy + a_{02}y^2 + a_{10}x + a_{01}y + a_{00} \]

this function returns \( a = (a_{20}, a_{02}, a_{00}, a_{11}, a_{10}, a_{01}) \)

EXAMPLES:

```
sage: R.<x,y,z,a20,a11,a02,a10,a01,a00> = QQ[]
sage: p = ( a20*x^2 + a11*x*y + a02*y^2 +
      ...:     a10*x*z + a01*y*z + a00*z^2 )
sage: invariant_theory.ternary_quadratic(p, x,y,z).coeffs()
(a20, a02, a00, a11, a10, a01)
sage: invariant_theory.ternary_quadratic(p.subs(z=1), x, y).coeffs()
(a20, a02, a00, a11, a10, a01)
```

covariant_conic(other)

Return the ternary quadratic covariant to self and other.

INPUT:

• other – Another ternary quadratic.

OUTPUT:

The so-called covariant conic, a ternary quadratic. It is symmetric under exchange of self and other.

EXAMPLES:

```
sage: ring.<x,y,z> = QQ[]
sage: Q = invariant_theory.ternary_quadratic(x^2+y^2+z^2)
sage: R = invariant_theory.ternary_quadratic(x*y+x*z+y*z)
sage: Q.covariant_conic(R)
-x*y - x*z - y*z
sage: R.covariant_conic(Q)
-x*y - x*z - y*z
```

monomials()

List the basis monomials of the form.

OUTPUT:

A tuple of monomials. They are in the same order as coeffs().

EXAMPLES:

```
sage: R.<x,y,z> = QQ[]
sage: quadratic = invariant_theory.ternary_quadratic(x^2+y*z)
sage: quadratic.monomials()
(x^2, y^2, z^2, x*y, x*z, y*z)
```
scaled_coeffs()
Return the scaled coefficients of a quadratic.
Given
\[ p(x, y) = a_{20}x^2 + a_{11}xy + a_{02}y^2 + a_{10}x + a_{01}y + a_{00} \]
this function returns \( a = (a_{20}, a_{02}, a_{00}, a_{11}/2, a_{10}/2, a_{01}/2, ) \)

EXAMPLES:

```
sage: R.<x,y,z,a20,a11,a02,a10,a01,a00> = QQ[]
sage: p = ( a20*x^2 + a11*x*y + a02*y^2 +
      ....:   a10*x*z + a01*y*z + a00*z^2 )
sage: invariant_theory.ternary_quadratic(p, x,y,z).scaled_coeffs()
(a20, a02, a00, 1/2*a11, 1/2*a10, 1/2*a01)
sage: invariant_theory.ternary_quadratic(p.subs(z=1), x, y).scaled_coeffs()
(a20, a02, a00, 1/2*a11, 1/2*a10, 1/2*a01)
```

class sage.rings.invariants.invariant_theory.TwoAlgebraicForms(forms)
Bases: SeveralAlgebraicForms

first()
Return the first of the two forms.
OUTPUT:
The first algebraic form used in the definition.
EXAMPLES:

```
sage: R.<x,y> = QQ[]
sage: q0 = invariant_theory.quadratic_form(x^2 + y^2)
sage: q1 = invariant_theory.quadratic_form(x*y)
sage: from sage.rings.invariants.invariant_theory import TwoAlgebraicForms
sage: q = TwoAlgebraicForms([q0, q1])
sage: q.first() is q0
True
sage: q.get_form(0) is q0
True
sage: q.first().polynomial()
x^2 + y^2
```

second()
Return the second of the two forms.
OUTPUT:
The second form used in the definition.
EXAMPLES:

```
sage: R.<x,y> = QQ[]
sage: q0 = invariant_theory.quadratic_form(x^2 + y^2)
sage: q1 = invariant_theory.quadratic_form(x*y)
sage: from sage.rings.invariants.invariant_theory import TwoAlgebraicForms
sage: q = TwoAlgebraicForms([q0, q1])
sage: q.second() is q1
```

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```python
True
sage: q.get_form(1) is q1
True
sage: q.second().polynomial()
x*y
```

class sage.rings.invariants.invariant_theory.TwoQuaternaryQuadratics(forms)

Bases: TwoAlgebraicForms

Invariant theory of two quaternary quadratics.

You should use the invariant_theory factory object to construct instances of this class. See quaternary_biquadratics() for details.

REFERENCES:

- section on “Invariants and Covariants of Systems of Quadrics” in [Sal1958], [Sal1965]

**Delta_invariant()**

Return the $\Delta$ invariant.

EXAMPLES:

```python
sage: R.<x,y,z,t,a0,a1,a2,a3,b0,b1,b2,b3,b4,b5,A0,A1,A2,A3,B0,B1,B2,B3,B4,B5> = QQ[]
sage: p1 = a0*x^2 + a1*y^2 + a2*z^2 + a3
sage: p1 += b0*x*y + b1*x*z + b2*x + b3*y*z + b4*y + b5*z
sage: p2 = A0*x^2 + A1*y^2 + A2*z^2 + A3
sage: p2 += B0*x*y + B1*x*z + B2*x + B3*y*z + B4*y + B5*z
sage: q = invariant_theory.quaternary_biquadratic(p1, p2, [x, y, z])
sage: coeffs = det(t * q[0].matrix() + q[1].matrix()).polynomial(t).
    coefficients(sparse=False)
True
```

**Delta_prime_invariant()**

Return the $\Delta'$ invariant.

EXAMPLES:

```python
sage: R.<x,y,z,t,a0,a1,a2,a3,b0,b1,b2,b3,b4,b5,A0,A1,A2,A3,B0,B1,B2,B3,B4,B5> = QQ[]
sage: p1 = a0*x^2 + a1*y^2 + a2*z^2 + a3
sage: p1 += b0*x*y + b1*x*z + b2*x + b3*y*z + b4*y + b5*z
sage: p2 = A0*x^2 + A1*y^2 + A2*z^2 + A3
sage: p2 += B0*x*y + B1*x*z + B2*x + B3*y*z + B4*y + B5*z
sage: q = invariant_theory.quaternary_biquadratic(p1, p2, [x, y, z])
sage: coeffs = det(t * q[0].matrix() + q[1].matrix()).polynomial(t).
    coefficients(sparse=False)
sage: q.Delta_prime_invariant() == coeffs[0]
True
```

**J_covariant()**

The $J$-covariant.

```python
sage: invariant_theory.quaternary_biquadratic(p1, p2, [x, y, z])
sage: coeffs = det(t * q[0].matrix() + q[1].matrix()).polynomial(t).
    coefficients(sparse=False)
sage: q.J_covariant() == coeffs[0]
True
```

3.2. Classical Invariant Theory
This is the Jacobian determinant of the two biquadratics, the $T$-covariant, and the $T'$-covariant with respect to the four homogeneous variables.

EXAMPLES:

```
sage: R.<w,x,y,z,a0,a1,a2,a3,A0,A1,A2,A3> = QQ[]
sage: p1 = a0*w^2 + a1*x^2 + a2*y^2 + a3*z^2
sage: p2 = A0*w^2 + A1*x^2 + A2*y^2 + A3*z^2
sage: q = invariant_theory.quaternary_biquadratic(p1, p2, [w, x, y, z])
sage: q.J_covariant().factor()
z * y * x * w * (a3*A2 - a2*A3) * (a3*A1 - a1*A3) * (-a2*A1 + a1*A2) * (a3*A0 - a0*A3) * (-a2*A0 + a0*A2) * (-a1*A0 + a0*A1)
```

`Phi_invariant()`

Return the $\Phi'$ invariant.

EXAMPLES:

```
sage: R.<x,y,z,t,a0,a1,a2,a3,b0,b1,b2,b3,b4,b5,A0,A1,A2,A3,B0,B1,B2,B3,B4,B5> = QQ[]
sage: p1 = a0*x^2 + a1*y^2 + a2*z^2 + a3
sage: p1 += b0*x*y + b1*x*z + b2*x + b3*y*z + b4*y + b5*z
sage: p2 = A0*x^2 + A1*y^2 + A2*z^2 + A3
sage: p2 += B0*x*y + B1*x*z + B2*x + B3*y*z + B4*y + B5*z
sage: q = invariant_theory.quaternary_biquadratic(p1, p2, [x, y, z])
sage: coeffs = det(t * q[0].matrix() + q[1].matrix()).polynomial(t).coefficients(sparse=False)
sage: q.Phi_invariant() == coeffs[2]
True
```

`T_covariant()`

The $T$-covariant.

EXAMPLES:

```
sage: R.<x,y,z,t,a0,a1,a2,a3,b0,b1,b2,b3,b4,b5,A0,A1,A2,A3,B0,B1,B2,B3,B4,B5> = QQ[]
sage: p1 = a0*x^2 + a1*y^2 + a2*z^2 + a3
sage: p1 += b0*x*y + b1*x*z + b2*x + b3*y*z + b4*y + b5*z
sage: p2 = A0*x^2 + A1*y^2 + A2*z^2 + A3
sage: p2 += B0*x*y + B1*x*z + B2*x + B3*y*z + B4*y + B5*z
sage: q = invariant_theory.quaternary_biquadratic(p1, p2, [x, y, z])
sage: T = invariant_theory.quaternary_quadratic(q.T_covariant(), [x,y,z]).matrix()
sage: M = q[0].matrix().adjugate() + t*q[1].matrix().adjugate()
sage: M = M.adjugate().apply_map(lambda m: m.coefficient(t)) # long time (4s on my thinkpad)
....: lambda m: m.coefficient(t)) # long time
sage: M == q.Delta_invariant()*T
True
```

`T_prime_covariant()`

The $T'$-covariant.

EXAMPLES:

```
sage: R.<x,y,z,t,a0,a1,a2,a3,b0,b1,b2,b3,b4,b5,A0,A1,A2,A3,B0,B1,B2,B3,B4,B5> = QQ[]
sage: p1 = a0*x^2 + a1*y^2 + a2*z^2 + a3
sage: p1 += b0*x*y + b1*x*z + b2*x + b3*y*z + b4*y + b5*z
sage: p2 = A0*x^2 + A1*y^2 + A2*z^2 + A3
sage: p2 += B0*x*y + B1*x*z + B2*x + B3*y*z + B4*y + B5*z
sage: q = invariant_theory.quaternary_biquadratic(p1, p2, [x, y, z])
sage: M = q[0].matrix().adjugate() + t*q[1].matrix().adjugate()
sage: M = M.adjugate().apply_map(lambda m: m.coefficient(t)) # long time (4s on my thinkpad)
....: lambda m: m.coefficient(t))
sage: M == q.Delta_invariant()*T
True
```

Chapter 3. Multivariate Polynomials
sage: R.<x,y,z,t,a0,a1,a2,a3,b0,b1,b2,b3,b4,b5,A0,A1,A2,A3,B0,B1,B2,B3,B4,B5> = QQ[]
sage: p1 = a0*x^2 + a1*y^2 + a2*z^2 + a3
sage: p1 += b0*x*y + b1*x*z + b2*x + b3*y*z + b4*y + b5*z
sage: p2 = A0*x^2 + A1*y^2 + A2*z^2 + A3
sage: p2 += B0*x*y + B1*x*z + B2*x + B3*y*z + B4*y + B5*z
sage: q = invariant_theory.quaternary_biquadratic(p1, p2, [x, y, z])
sage: Tprime = invariant_theory.quaternary_quadratic(q.T_prime_covariant(), [x,y,z]).matrix()
sage: M = q[0].matrix().adjugate() + t*q[1].matrix().adjugate()
sage: M = M.adjugate().apply_map(lambda m: m.coefficient(t^2))
# long time (4s on my thinkpad, ~W530)
sage: M == q.Delta_prime_invariant() * Tprime
# long time
True

Theta_invariant()

Return the Θ invariant.

EXAMPLES:

sage: R.<x,y,z,t,a0,a1,a2,a3,b0,b1,b2,b3,b4,b5,A0,A1,A2,A3,B0,B1,B2,B3,B4,B5> = QQ[]
sage: p1 = a0*x^2 + a1*y^2 + a2*z^2 + a3
sage: p1 += b0*x*y + b1*x*z + b2*x + b3*y*z + b4*y + b5*z
sage: p2 = A0*x^2 + A1*y^2 + A2*z^2 + A3
sage: p2 += B0*x*y + B1*x*z + B2*x + B3*y*z + B4*y + B5*z
sage: q = invariant_theory.quaternary_biquadratic(p1, p2, [x, y, z])
sage: coeffs = det(t * q[0].matrix() + q[1].matrix()).polynomial(t).
-->coefficients(sparse=False)
sage: q.Theta_invariant() == coeffs[3]
True

Theta_prime_invariant()

Return the Θ’ invariant.

EXAMPLES:

sage: R.<x,y,z,t,a0,a1,a2,a3,b0,b1,b2,b3,b4,b5,A0,A1,A2,A3,B0,B1,B2,B3,B4,B5> = QQ[]
sage: p1 = a0*x^2 + a1*y^2 + a2*z^2 + a3
sage: p1 += b0*x*y + b1*x*z + b2*x + b3*y*z + b4*y + b5*z
sage: p2 = A0*x^2 + A1*y^2 + A2*z^2 + A3
sage: p2 += B0*x*y + B1*x*z + B2*x + B3*y*z + B4*y + B5*z
sage: q = invariant_theory.quaternary_biquadratic(p1, p2, [x, y, z])
sage: coeffs = det(t * q[0].matrix() + q[1].matrix()).polynomial(t).
-->coefficients(sparse=False)
sage: q.Theta_prime_invariant() == coeffs[1]
True

syzygy(Delta, Theta, Phi, Theta_prime, Delta_prime, U, V, T, T_prime, J)

Return the syzygy evaluated on the invariants and covariants.

INPUT:

3.2. Classical Invariant Theory
• Delta, Theta, Phi, Theta_prime, Delta_prime, U, V, T, T_prime, J – polynomials from the same polynomial ring.

OUTPUT:
Zero if the U is the first polynomial, V the second polynomial, and the remaining input are the invariants and covariants of a quaternary biquadratic.

EXAMPLES:

```python
sage: R.<w,x,y,z> = QQ[]
sage: monomials = [x^2, x*y, y^2, x*z, y*z, z^2, x*w, y*w, z*w, w^2]
sage: def q_rnd():
    return sum(randint(-1000,1000)*m for m in monomials)
sage: biquadratic = invariant_theory.quaternary_biquadratic(q_rnd(), q_rnd())
sage: Delta = biquadratic.Delta_invariant()
sage: Theta = biquadratic.Theta_invariant()
sage: Phi = biquadratic.Phi_invariant()
sage: Theta_prime = biquadratic.Theta_prime_invariant()
sage: Delta_prime = biquadratic.Delta_prime_invariant()
sage: U = biquadratic.first().polynomial()
sage: V = biquadratic.second().polynomial()
sage: T = biquadratic.T_covariant()
sage: T_prime = biquadratic.T_prime_covariant()
sage: J = biquadratic.J_covariant()
sage: biquadratic.syzygy(Delta, Theta, Phi, Theta_prime, Delta_prime, U, V, T, T_prime, J)
0
```

If the arguments are not the invariants and covariants then the output is some (generically non-zero) polynomial:

```python
sage: biquadratic.syzygy(1, 1, 1, 1, 1, 1, 1, 1, 1, x)
-x^2 + 1
```

class sage.rings.invariants.invariant_theory.TwoTernaryQuadratics(forms)

Bases: TwoAlgebraicForms

Invariant theory of two ternary quadratics.

You should use the invariant_theory factory object to construct instances of this class. See ternary_biquadratics() for details.

REFERENCES:
• Section on “Invariants and Covariants of Systems of Conics”, Art. 388 (a) in [Sal1954]

Delta_invariant()

Return the Δ invariant.

EXAMPLES:

```python
sage: R.<a00, a01, a11, a02, a12, a22, b00, b01, b11, b02, b12, b22, y0, y1, y2, t> = QQ[]
sage: p1 = a00*y0^2 + 2*a01*y0*y1 + a11*y1^2 + 2*a02*y0*y2 + 2*a12*y1*y2 + a22*y2^2
sage: p2 = b00*y0^2 + 2*b01*y0*y1 + b11*y1^2 + 2*b02*y0*y2 + 2*b12*y1*y2 + b22*y2^2
sage: q = invariant_theory.ternary_biquadratic(p1, p2, [y0, y1, y2])
```
sage: coeffs = det(t * q[0].matrix() + q[1].matrix()).polynomial(t).
   →coefficients(sparse=False)
sage: q.Delta_invariant() == coeffs[3]
True

Delta_prime_invariant()

Return the \( \Delta' \) invariant.

EXAMPLES:

sage: R.<a00, a01, a11, a02, a12, b00, b01, b11, b02, b12, b22, y0, y1, y2, →t> = QQ[]
sage: p1 = a00*y0^2 + 2*a01*y0*y1 + a11*y1^2 + 2*a02*y0*y2 + 2*a12*y1*y2 + a22*y2^2
sage: p2 = b00*y0^2 + 2*b01*y0*y1 + b11*y1^2 + 2*b02*y0*y2 + 2*b12*y1*y2 + b22*y2^2
sage: q = invariant_theory.ternary_biquadratic(p1, p2, [y0, y1, y2])
sage: coeffs = det(t * q[0].matrix() + q[1].matrix()).polynomial(t).
   →coefficients(sparse=False)
sage: q.Delta_prime_invariant() == coeffs[0]
True

F_covariant()

Return the \( F \) covariant.

EXAMPLES:

sage: R.<a00, a01, a11, a02, a12, b00, b01, b11, b02, b12, b22, x, y> = →QQ[]
sage: p1 = 73*x^2 + 96*x*y - 11*y^2 + 4*x + 63*y + 57
sage: p2 = 61*x^2 - 100*x*y - 72*y^2 - 81*x + 39*y - 7
sage: q = invariant_theory.ternary_biquadratic(p1, p2, [x, y])
sage: q.F_covariant()
-32566577*x^2 + 29060637/2*x*y + 20153633/4*y^2 - 30250497/2*x - 241241273/4*y - 323820473/16

J_covariant()

Return the \( J \) covariant.

EXAMPLES:

sage: R.<a00, a01, a11, a02, a12, b00, b01, b11, b02, b12, b22, x, y> = →QQ[]
sage: p1 = 73*x^2 + 96*x*y - 11*y^2 + 4*x + 63*y + 57
sage: p2 = 61*x^2 - 100*x*y - 72*y^2 - 81*x + 39*y - 7
sage: q = invariant_theory.ternary_biquadratic(p1, p2, [x, y])
sage: q.J_covariant()
105732402444*x*y^3 + 120053108829*x^2*y + 942116599708*x*y^2 + 98455303871*y^3 + 543715345505/2*x^2 - 306509356021/2*x*y + 755263948570*y^2 - 1118430692650*x - 509948695327/4*y + 3369951531745/8

Theta_invariant()

Return the \( \Theta \) invariant.

EXAMPLES:
Theta_prime_invariant()

Return the $\Theta'$ invariant.

EXAMPLES:

```python
sage: R.<a00, a01, a11, a02, a12, a22, b00, b01, b11, b02, b12, b22, y0, y1, y2, \n  t> = QQ[]
sage: p1 = a00*y0^2 + 2*a01*y0*y1 + a11*y1^2 + 2*a02*y0*y2 + 2*a12*y1*y2 + \n   a22*y2^2
sage: p2 = b00*y0^2 + 2*b01*y0*y1 + b11*y1^2 + 2*b02*y0*y2 + 2*b12*y1*y2 + \n   b22*y2^2
sage: q = invariant_theory.ternary_biquadratic(p1, p2, [y0, y1, y2])
sage: coeffs = det(t * q[0].matrix() + q[1].matrix()).polynomial(t).
   --coefficients(sparse=False)
sage: q.Theta_prime_invariant() == coeffs[1]
True
```

syzygy($\Delta$, $\Theta$, $\Theta'$, $\Delta'$, S, S', F, J)

Return the syzygy evaluated on the invariants and covariants.

INPUT:

- $\Delta$, $\Theta$, $\Theta'$, $\Delta'$, S, S', F, J – polynomials from the same polynomial ring.

OUTPUT:

Zero if $S$ is the first polynomial, $S'$ the second polynomial, and the remaining input are the invariants and covariants of a ternary biquadratic.

EXAMPLES:

```python
sage: R.<x,y,z> = QQ[]
sage: monomials = [x^2, x*y, y^2, x*z, y*z, z^2]
sage: def q_rnd(): return sum(randint(-1000,1000)*m \n   for m in monomials)
sage: biquadratic = invariant_theory.ternary_biquadratic(q_rnd(), q_rnd(), [x,y,\n   z])
sage: Delta = biquadratic.Delta_invariant()
sage: Theta = biquadratic.Theta_invariant()
sage: Theta_prime = biquadratic.Theta_prime_invariant()
sage: Delta_prime = biquadratic.Delta_prime_invariant()
sage: S = biquadratic.first().polynomial()
sage: S_prime = biquadratic.second().polynomial()
sage: F = biquadratic.F_covariant()
```

(continues on next page)
sage: J = biquadratic.J_covariant()
sage: biquadratic.syzygy(Delta, Theta, Theta_prime, Delta_prime, S, S_prime, F, J)
0
If the arguments are not the invariants and covariants then the output is some (generically non-zero) polynomial:

sage: biquadratic.syzygy(1, 1, 1, 1, 1, 1, 1, x)
1/64*x^2 + 1

sage.rings.invariants.invariant_theory.transvectant(f, g, h=1, scale='default')
Return the h-th transvectant of f and g.

INPUT:

• f, g – two homogeneous binary forms in the same polynomial ring.
• h – the order of the transvectant. If it is not specified, the first transvectant is returned.
• scale – the scaling factor applied to the result. Possible values are 'default' and 'none'. The 'default' scaling factor is the one that appears in the output statement below, if the scaling factor is 'none' the quotient of factorials is left out.

OUTPUT:

The h-th transvectant of the listed forms f and g:

$$(f, g)_h = \frac{(d_f - h)! \cdot (d_g - h)!}{d_f! \cdot d_g!} \left( \left( \frac{\partial}{\partial x} \frac{\partial}{\partial z'} - \frac{\partial}{\partial x'} \frac{\partial}{\partial z} \right)^h (f(x, z) \cdot g(x', z')) \right)_{(x', z') = (x, z)}$$

EXAMPLES:

sage: from sage.rings.invariants.invariant_theory import AlgebraicForm, transvectant
sage: R.<x,y> = QQ[]
sage: f = AlgebraicForm(2, 5, x^5 + 5*x^4*y + 5*x*y^4 + y^5)
sage: transvectant(f, f, 4)
Binary quadratic given by 2*x^2 - 4*x*y + 2*y^2
sage: transvectant(f, f, 8)
Binary form of degree -6 given by 0

The default scaling will yield an error for fields of positive characteristic below $d_f!$ or $d_g!$ as the denominator of the scaling factor will not be invertible in that case. The scale argument 'none' can be used to compute the transvectant in this case:

sage: R.<a0,a1,a2,a3,a4,a5,x0,x1> = GF(5)[]
sage: p = a0*x1^5 + a1*x1^4*x0 + a2*x1^3*x0^2 + a3*x1^2*x0^3 + a4*x1*x0^4 + a5*x0^5
sage: f = AlgebraicForm(2, 5, p, x0, x1)
sage: transvectant(f, f, 4)
Traceback (most recent call last):
  ... ZeroDivisionError
sage: transvectant(f, f, 4, scale='none')
Binary quadratic given by -a3^2*x0^2 + a2*a4*x0^2 + a2*a3*x0^2 - a1*a4*x0^2 - a2^2*x1^2 + a1*a3*x1^2

3.2. Classical Invariant Theory
The additional factors that appear when `scale='none'` is used can be seen if we consider the same transvectant over the rationals and compare it to the scaled version:

```
sage: R.<a0,a1,a2,a3,a4,a5,x0,x1> = QQ[]
sage: p = a0*x1^5 + a1*x1^4*x0 + a2*x1^3*x0^2 + a3*x1^2*x0^3 + a4*x1*x0^4 + a5*x0^5
sage: f = AlgebraicForm(2, 5, p, x0, x1)
sage: transvectant(f, f, 4)
Binary quadratic given by 3/50*a3^2*x0^2 - 4/25*a2*a4*x0^2
+ 2/5*a1*a5*x0^2 + 1/25*a2*a3*x0*x1 - 6/25*a1*a4*x0*x1 + 2*a0*a5*x0*x1
+ 3/50*a2^2*x1^2 - 4/25*a1*a3*x1^2 + 2/5*a0*a4*x1^2
sage: transvectant(f, f, 4, scale='none')
Binary quadratic given by 864*a3^2*x0^2 - 2304*a2*a4*x0^2
+ 5760*a1*a5*x0^2 + 5760*a2*a3*x0*x1 - 3456*a1*a4*x0*x1
+ 28800*a0*a5*x0*x1 + 864*a2^2*x1^2 - 2304*a1*a3*x1^2 + 5760*a0*a4*x1^2
```

If the forms are given as inhomogeneous polynomials, the homogenisation might fail if the polynomial ring has multiple variables. You can circumvent this by making sure the base ring of the polynomial has only one variable:

```
sage: R.<x,y> = QQ[]
sage: quintic = invariant_theory.binary_quintic(x^5+x^3+2*x^2+y^5, x)
sage: transvectant(quintic, quintic, 2)
Traceback (most recent call last):
... ValueError: polynomial is not homogeneous
sage: R.<y> = QQ[]
sage: S.<x> = R[]
sage: quintic = invariant_theory.binary_quintic(x^5+x^3+2*x^2+y^5, x)
sage: transvectant(quintic, quintic, 2)
Binary sextic given by 1/5*x^6 + 6/5*x^5*h - 3/25*x^4*h^2
+ (50*y^5 - 8)/25*x^3*h^3 - 12/25*x^2*h^4 + (3*y^5)/5*x*h^5
+ (2*y^5)/5*h^6
```

### 3.2.2 Reconstruction of Algebraic Forms

This module reconstructs algebraic forms from the values of their invariants. Given a set of (classical) invariants, it returns a form that attains these values as invariants (up to scaling).

AUTHORS:

- Jesper Noordsij (2018-06): initial version

```python
sage.rings.invariants.reconstruction.binary_cubic_coefficients_from_invariants(discriminant, invariant_choice='default')
```

Reconstruct a binary cubic from the value of its discriminant.

**INPUT:**

- `discriminant` – The value of the discriminant of the binary cubic.

- `invariant_choice` – The type of invariants provided. The accepted options are 'discriminant' and 'default', which are the same. No other options are implemented.

**OUTPUT:**

A set of coefficients of a binary cubic, whose discriminant is equal to the given discriminant up to a scaling.
EXAMPLES:

```python
sage: from sage.rings.invariants.reconstruction import binary_cubic_coefficients_from_invariants
sage: coeffs = binary_cubic_coefficients_from_invariants(1)
sage: coeffs
(0, 1, -1, 0)
sage: R.<x> = QQ[]
sage: R(coeffs).discriminant()
1
```

The two non-equivalent cubics $x^3$ and $x^2z$ with discriminant 0 can't be distinguished based on their discriminant, hence an error is raised:

```python
sage: binary_cubic_coefficients_from_invariants(0)
Traceback (most recent call last):
  ... ValueError: no unique reconstruction possible for binary cubics with a double root
```

Reconstruct a binary quadratic from the value of its discriminant.

**INPUT:**

- `discriminant` – The value of the discriminant of the binary quadratic.
- `invariant_choice` – The type of invariants provided. The accepted options are 'discriminant' and 'default', which are the same. No other options are implemented.

**OUTPUT:**

A set of coefficients of a binary quadratic, whose discriminant is equal to the given discriminant up to a scaling.

**EXAMPLES:**

```python
sage: from sage.rings.invariants.reconstruction import binary_quadratic_coefficients_from_invariants
sage: quadratic = invariant_theory.binary_form_from_invariants(2, [24]) # indirect doctest
sage: quadratic
Binary quadratic with coefficients (1, -6, 0)
sage: quadratic.discriminant()
24
sage: binary_quadratic_coefficients_from_invariants(0)
(1, 0, 0)
```

Reconstruct a binary quintic from the values of its (Clebsch) invariants.

**INPUT:**

sage.rings.invariants.reconstruction.binary_quintic_coefficients_from_invariants(invariants, K=None, invariant_choice='default', scaling='none')
• **invariants** – A list or tuple of values of the three or four invariants. The default option requires the Clebsch invariants $A, B, C$ and $R$ of the binary quintic.

• **K** – The field over which the quintic is defined.

• **invariant_choice** – The type of invariants provided. The accepted options are 'clebsch' and 'default', which are the same. No other options are implemented.

• **scaling** – How the coefficients should be scaled. The accepted values are 'none' for no scaling, 'normalized' to scale in such a way that the resulting coefficients are independent of the scaling of the input invariants and 'coprime' which scales the input invariants by dividing them by their gcd.

**OUTPUT:**

A set of coefficients of a binary quintic, whose invariants are equal to the given invariants up to a scaling.

**EXAMPLES:**

First we check the general case, where the invariant $M$ is non-zero:

```python
sage: R.<x0, x1> = QQ[]

sage: p = 3*x1^5 + 6*x1^4*x0 + 3*x1^3*x0^2 + 4*x1^2*x0^3 - 5*x1*x0^4 + 4*x0^5

sage: quintic = invariant_theory.binary_quintic(p, x0, x1)

sage: invs = quintic.clebsch_invariants(as_tuple=True)

sage: reconstructed = invariant_theory.binary_form_from_invariants(5, invs, variables=quintic.variables())

sage: reconstructed
Binary quintic with coefficients (959267437341790539005557/244140625000000000,
214929692820762556323004064707/6103515625000000000,
1114961890347700974453304786783/7629394531250000000,
122650775751894638395648891202734239/476837158203125000000,
32399663094570652847286334593218447/1192092895507812500000,
150450650364468395841632538558481466127/149011611193847656250000)
```

We can see that the invariants of the reconstructed form match the ones of the original form by scaling the invariants $B$ and $C$:

```python
sage: scale = invs[0]/reconstructed.A_invariant()

True

True
```

If we compare the form obtained by this reconstruction to the one found by letting the covariants $\alpha$ and $\beta$ be the coordinates of the form, we find the forms are the same up to a power of the determinant of $\alpha$ and $\beta$:

```python
sage: alpha = quintic.alpha_covariant()

sage: beta = quintic.beta_covariant()

sage: g = matrix([[alpha(x0=1, x1=0), alpha(x0=0, x1=1)],
              [beta(x0=1, x1=0), beta(x0=0, x1=1)]])^-1

sage: transformed = tuple([g.determinant()^-5*x for x in quintic.transformed(g).coeffs()])

sage: transformed == reconstructed.coeffs()
True
```

This can also be seen by computing the $\alpha$ covariant of the obtained form:
If the invariant $M$ vanishes, then the coefficients are computed in a different way:

```python
sage: [A,B,C] = [3,1,2]
sage: M = 2*A*B - 3*C
sage: M
0
sage: from sage.rings.invariants.reconstruction import binary_quintic_coefficients_from_invariants
sage: reconstructed = binary_quintic_coefficients_from_invariants([A,B,C])
sage: reconstructed
(-66741943359375/2097152, -125141143798828125/134217728, 0, 52793920040130615234375/34359738368, 19797720015048980712890625/1099511627776, -45448700338602666400390625/17592186044416)
sage: newform = sum([ reconstructed[i]*x0^i*x1^(5-i) for i in range(6) ])  
sage: newquintic = invariant_theory.binary_quintic(newform, x0, x1)
sage: scale = 3/newquintic.A_invariant()
sage: [3, newquintic.B_invariant()*scale^2, newquintic.C_invariant()*scale^3]
[3, 1, 2]
```

Several special cases:

```python
sage: quintic = invariant_theory.binary_quintic(x0^5 - x1^5, x0, x1)
sage: invs = quintic.clebsch_invariants(as_tuple=True)
sage: binary_quintic_coefficients_from_invariants(invs)
(1, 0, 0, 0, 1)
sage: quintic = invariant_theory.binary_quintic(x0^3*x1^2 - 15*x0*x1^4, x0, x1)
sage: invs = quintic.clebsch_invariants(as_tuple=True)
sage: binary_quintic_coefficients_from_invariants(invs)
(1, 0, 10, 0, -15, 0)
sage: quintic = invariant_theory.binary_quintic(x0^4*x1^4, x0, x1)
sage: invs = quintic.clebsch_invariants(as_tuple=True)
sage: binary_quintic_coefficients_from_invariants(invs)
(1, 0, 0, 1, 0)
sage: quintic = invariant_theory.binary_quintic(x0^3*x1^3, x0, x1)
sage: invs = quintic.clebsch_invariants(as_tuple=True)
sage: binary_quintic_coefficients_from_invariants(invs)
(1, 0, 0, 0, 0)
```

For fields of characteristic 2, 3 or 5, there is no reconstruction implemented. This is part of github issue #26786.
3.3 Educational Versions of Groebner Basis Related Algorithms

3.3.1 Educational versions of Groebner basis algorithms

Following [BW1993], the original Buchberger algorithm (algorithm GROEBNER in [BW1993]) and an improved version of Buchberger’s algorithm (algorithm GROEBNERNEW2 in [BW1993]) are implemented.

No attempt was made to optimize either algorithm as the emphasis of these implementations is a clean and easy presentation. To compute a Groebner basis most efficiently in Sage, use the `MPolynomialIdeal.groebner_basis()` method on multivariate polynomial objects instead.

**Note:** The notion of ‘term’ and ‘monomial’ in [BW1993] is swapped from the notion of those words in Sage (or the other way around, however you prefer it). In Sage a term is a monomial multiplied by a coefficient, while in [BW1993] a monomial is a term multiplied by a coefficient. Also, what is called LM (the leading monomial) in Sage is called HT (the head term) in [BW1993].

**EXAMPLES:**

Consider Katsura-6 with respect to a `degrevlex` ordering.

```sage
sage: from sage.rings.polynomial.toy_buchberger import *
sage: P.<a,b,c,e,f,g,h,i,j,k> = PolynomialRing(GF(32003))
sage: I = sage.rings.ideal.Katsura(P, 6)
sage: g1 = buchberger(I)
sage: g2 = buchberger_improved(I)
sage: g3 = I.groebner_basis()
```

All algorithms actually compute a Groebner basis:

```sage
sage: Ideal(g1).basis_is_groebner()
True
sage: Ideal(g2).basis_is_groebner()
True
sage: Ideal(g3).basis_is_groebner()
True
```

The results are correct:

```sage
sage: Ideal(g1) == Ideal(g2) == Ideal(g3)
True
```

If `get_verbose()` is $\geq 1$, a protocol is provided:
```python
sage: from sage.misc.verbose import set_verbose
sage: set_verbose(1)

sage: P.<a,b,c> = PolynomialRing(GF(127))

sage: I = sage.rings.ideal.Katsura(P)

sage: I
Ideal (a + 2*b + 2*c - 1, a^2 + 2*b*a + 2*b*c - b, a^2 + 2*b^2 + 2*c^2 - a, -2*b^2 - 6*b*c - 6*c^2 + b + 2*c) of Multivariate Polynomial Ring in a, b, c over Finite Field of size 127

sage: buchberger(I)  # random
(a + 2*b + 2*c - 1, a^2 + 2*b*a + 2*b*c - b) => -5*b^2*c - 6*c^2 + 63*b + 2*c
G: set([a + 2*b + 2*c - 1, 2*a*b + 2*b*c - b, a^2 + 2*b^2 + 2*c^2 - a, -2*b^2 - 6*b*c - 6*c^2 + b + 2*c])

(2*a*b + 2*b*c - b, a + 2*b + 2*c - 1) => 0
G: set([a + 2*b + 2*c - 1, 2*a*b + 2*b*c - b, a^2 + 2*b^2 + 2*c^2 - a, -2*b^2 - 6*b*c - 6*c^2 + b + 2*c])

(a + 2*b + 2*c - 1, 2*a*b + 2*b*c - b) => -5*b^2*c - 6*c^2 + 63*b + 2*c
G: set([a + 2*b + 2*c - 1, 2*a*b + 2*b*c - b, a^2 + 2*b^2 + 2*c^2 - a, -2*b^2 - 6*b*c - 6*c^2 + b + 2*c])

(2*a*b + 2*b*c - b, a + 2*b + 2*c - 1) => 0
G: set([a + 2*b + 2*c - 1, 2*a*b + 2*b*c - b, a^2 + 2*b^2 + 2*c^2 - a, -2*b^2 - 6*b*c - 6*c^2 + b + 2*c])

(2*a*b + 2*b*c - b, -5*b^2*c - 6*c^2 + 63*b + 2*c) => -22*c^3 + 24*c^2 + 60*b - 62*c
G: set([a + 2*b + 2*c - 1, 2*a*b + 2*b*c - b, a^2 + 2*b^2 + 2*c^2 - a, -2*b^2 - 6*b*c - 6*c^2 + b + 2*c])

(2*a*b + 2*b*c - b, -5*b^2*c - 6*c^2 + 63*b + 2*c) => -22*c^3 + 24*c^2 + 60*b - 62*c
G: set([a + 2*b + 2*c - 1, 2*a*b + 2*b*c - b, a^2 + 2*b^2 + 2*c^2 - a, -2*b^2 - 6*b*c - 6*c^2 + b + 2*c])

(2*a*b + 2*b*c - b, 2*a*b + 2*b*c - b) => 0
G: set([a + 2*b + 2*c - 1, 2*a*b + 2*b*c - b, a^2 + 2*b^2 + 2*c^2 - a, -2*b^2 - 6*b*c - 6*c^2 + b + 2*c])

(2*a*b + 2*b*c - b, -5*b^2*c - 6*c^2 + 63*b + 2*c) => 0
G: set([a + 2*b + 2*c - 1, 2*a*b + 2*b*c - b, a^2 + 2*b^2 + 2*c^2 - a, -2*b^2 - 6*b*c - 6*c^2 + b + 2*c])

(2*a*b + 2*b*c - b, 2*a*b + 2*b*c - b) => 0
G: set([a + 2*b + 2*c - 1, 2*a*b + 2*b*c - b, a^2 + 2*b^2 + 2*c^2 - a, -2*b^2 - 6*b*c - 6*c^2 + b + 2*c])

(2*a*b + 2*b*c - b, 2*a*b + 2*b*c - b) => 0
G: set([a + 2*b + 2*c - 1, 2*a*b + 2*b*c - b, a^2 + 2*b^2 + 2*c^2 - a, -2*b^2 - 6*b*c - 6*c^2 + b + 2*c])

(2*a*b + 2*b*c - b, 2*a*b + 2*b*c - b) => 0
G: set([a + 2*b + 2*c - 1, 2*a*b + 2*b*c - b, a^2 + 2*b^2 + 2*c^2 - a, -2*b^2 - 6*b*c - 6*c^2 + b + 2*c])

(2*a*b + 2*b*c - b, 2*a*b + 2*b*c - b) => 0
G: set([a + 2*b + 2*c - 1, 2*a*b + 2*b*c - b, a^2 + 2*b^2 + 2*c^2 - a, -2*b^2 - 6*b*c - 6*c^2 + b + 2*c])

(2*a*b + 2*b*c - b, 2*a*b + 2*b*c - b) => 0
G: set([a + 2*b + 2*c - 1, 2*a*b + 2*b*c - b, a^2 + 2*b^2 + 2*c^2 - a, -2*b^2 - 6*b*c - 6*c^2 + b + 2*c])
```

(continues on next page)
\begin{verbatim}
(-2 + 2*a^2 - a, -2*b^2 - 6*b*c - 6*c^2 + b + 2*c, -5*b*c - 6*c^2 - 63*b + 2*c])

(a^2 + 2*b^2 + 2*c^2 - a, -5*b*c - 6*c^2 - 63*b + 2*c) => 0

G: set([a + 2*b + 2*c - 1, -22*c^3 + 24*c^2 - 60*b - 62*c, 2*a*b + 2*b^2*c - b, a^2 + 2*b^2 - 2 + 2*c^2 - a, -2*b^2 - 6*b*c - 6*c^2 + b + 2*c, -5*b*c - 6*c^2 - 63*b + 2*c])

(-5*b*c - 6*c^2 - 63*b + 2*c, -22*c^3 + 24*c^2 - 60*b - 62*c) => 0

G: set([a + 2*b + 2*c - 1, -22*c^3 + 24*c^2 - 60*b - 62*c, 2*a*b + 2*b^2*c - b, a^2 + 2*b^2 - 2 + 2*c^2 - a, -2*b^2 - 6*b*c - 6*c^2 + b + 2*c, -5*b*c - 6*c^2 - 63*b + 2*c])

(a + 2*b + 2*c - 1, -22*c^3 + 24*c^2 - 60*b - 62*c) => 0

G: set([a + 2*b + 2*c - 1, -22*c^3 + 24*c^2 - 60*b - 62*c, 2*a*b + 2*b^2*c - b, a^2 + 2*b^2 - 2 + 2*c^2 - a, -2*b^2 - 6*b*c - 6*c^2 + b + 2*c, -5*b*c - 6*c^2 - 63*b + 2*c])

(-2*b^2 - 6*b*c - 6*c^2 + b + 2*c, -22*c^3 + 24*c^2 - 60*b - 62*c) => 0

G: set([a + 2*b + 2*c - 1, -22*c^3 + 24*c^2 - 60*b - 62*c, 2*a*b + 2*b^2*c - b, a^2 + 2*b^2 - 2 + 2*c^2 - a, -2*b^2 - 6*b*c - 6*c^2 + b + 2*c, -5*b*c - 6*c^2 - 63*b + 2*c])

(2*a*b + 2*b^2*c - b, -22*c^3 + 24*c^2 - 60*b - 62*c) => 0

G: set([a + 2*b + 2*c - 1, -22*c^3 + 24*c^2 - 60*b - 62*c, 2*a*b + 2*b^2*c - b, a^2 + 2*b^2 - 2 + 2*c^2 - a, -2*b^2 - 6*b*c - 6*c^2 + b + 2*c, -5*b*c - 6*c^2 - 63*b + 2*c])

(a^2 + 2*b^2 + 2*c^2 - a, -22*c^3 + 24*c^2 - 60*b - 62*c) => 0

G: set([a + 2*b + 2*c - 1, -22*c^3 + 24*c^2 - 60*b - 62*c, 2*a*b + 2*b^2*c - b, a^2 + 2*b^2 - 2 + 2*c^2 - a, -2*b^2 - 6*b*c - 6*c^2 + b + 2*c, -5*b*c - 6*c^2 - 63*b + 2*c])

15 reductions to zero.

[a + 2*b + 2*c - 1, -22*c^3 + 24*c^2 - 60*b - 62*c, 2*a*b + 2*b^2*c - b, a^2 + 2*b^2 + 2*c^2 - a - 2*b^2 - 6*b*c - 6*c^2 + b + 2*c, -5*b*c - 6*c^2 - 63*b + 2*c]
\end{verbatim}

The original Buchberger algorithm performs 15 useless reductions to zero for this example:

```
sage: gb = buchberger(I)
...
15 reductions to zero.
```

The ‘improved’ Buchberger algorithm in contrast only performs 1 reduction to zero:

```
sage: gb = buchberger_improved(I)
...
1 reductions to zero.
sage: sorted(gb)
[a + 2*b + 2*c - 1, b*c + 52*c^2 + 38*b + 25*c, b^2 - 26*c^2 - 51*b + 51*c, c^3 + 22*c^2 - 55*b + 49*c]
```

AUTHORS:

- Marshall Hampton (2009-07-08): some doctest additions
sage.rings.polynomial.toy_buchberger.LCM(f, g)
sage.rings.polynomial.toy_buchberger.LM(f)
sage.rings.polynomial.toy_buchberger.LT(f)
sage.rings.polynomial.toy_buchberger.buchberger(F)

Compute a Groebner basis using the original version of Buchberger’s algorithm as presented in [BW1993], page 214.

INPUT:

• F – an ideal in a multivariate polynomial ring

OUTPUT: a Groebner basis for F

Note: The verbosity of this function may be controlled with a set_verbose() call. Any value >=1 will result in this function printing intermediate bases.

EXAMPLES:

```python
sage: from sage.rings.polynomial.toy_buchberger import buchberger
sage: R.<x,y,z> = PolynomialRing(QQ)
sage: I = R.ideal([x^2 - z - 1, z^2 - y - 1, x*y^2 - x - 1])
sage: set_verbose(0)
sage: gb = buchberger(I)
sage: gb.is_groebner()
True
sage: gb.ideal() == I
True
```

sage.rings.polynomial.toy_buchberger.buchberger_improved(F)

Compute a Groebner basis using an improved version of Buchberger’s algorithm as presented in [BW1993], page 232.

This variant uses the Gebauer-Moeller Installation to apply Buchberger’s first and second criterion to avoid useless pairs.

INPUT:

• F – an ideal in a multivariate polynomial ring

OUTPUT: a Groebner basis for F

Note: The verbosity of this function may be controlled with a set_verbose() call. Any value >=1 will result in this function printing intermediate Groebner bases.

EXAMPLES:

```python
sage: from sage.rings.polynomial.toy_buchberger import buchberger_improved
sage: R.<x,y,z> = PolynomialRing(QQ)
sage: set_verbose(0)
sage: sorted(buchberger_improved(R.ideal([x^4 - y - z, x*y*z - 1])))
[x*y*z - 1, x^3 - y^2*z - y*z^2, y^3*z^2 + y^2*z^3 - x^2]
```
sage.rings.polynomial.toy_buchberger.inter_reduction(Q)

Compute inter-reduced polynomials from a set of polynomials.

INPUT:
• Q – a set of polynomials

OUTPUT:
if Q is the set \( \{f_1, \ldots, f_n\} \), this method returns \( \{g_1, \ldots, g_s\} \) such that:
• \( Q = \langle f_1, \ldots, f_n \rangle = \langle g_1, \ldots, g_s \rangle \)
• \( LM(g_i) \neq LM(g_j) \) for all \( i \neq j \)
• \( LM(g_i) \) does not divide \( m \) for all monomials \( m \) of \( \{g_1, \ldots, g_{i-1}, g_{i+1}, \ldots, g_s\} \)
• \( LC(g_i) = 1 \) for all \( i \).

EXAMPLES:

```python
sage: from sage.rings.polynomial.toy_buchberger import inter_reduction
sage: inter_reduction(set())
set()
```

```python
sage: P.<x,y> = QQ[]
sage: reduced = inter_reduction(set([x^2 - 5*y^2, x^3]))
sage: reduced == set([x*y^2, x^2-5*y^2])
True
sage: reduced == inter_reduction(set([2*(x^2 - 5*y^2), x^3]))
True
```

sage.rings.polynomial.toy_buchberger.select(P)

Select a polynomial using the normal selection strategy.

INPUT:
• P – a list of critical pairs

OUTPUT: an element of P

EXAMPLES:

```python
sage: from sage.rings.polynomial.toy_buchberger import select
sage: R.<x,y,z> = PolynomialRing(QQ, order='lex')
sage: ps = [x^3 - z -1, z^3 - y - 1, x^5 - y - 2]
sage: pairs = [[ps[i], ps[j]] for i in range(3) for j in range(i+1, 3)]
sage: select(pairs)
[x^3 - z - 1, -y + z^3 - 1]
```

sage.rings.polynomial.toy_buchberger.spol(f, g)

Compute the S-polynomial of \( f \) and \( g \).

INPUT:
• \( f, g \) – polynomials

OUTPUT: the S-polynomial of \( f \) and \( g \)

EXAMPLES:
sage: R.<x,y,z> = PolynomialRing(QQ)
sage: from sage.rings.polynomial.toy_buchberger import spol
sage: spol(x^2 - z - 1, z^2 - y - 1)
x^2*y - z^3 + x^2 - z^2

sage.rings.polynomial.toy_buchberger.update(G, B, h)
Update G using the set of critical pairs B and the polynomial h as presented in [BW1993], page 230. For this, Buchberger's first and second criterion are tested.

This function implements the Gebauer-Moeller Installation.

INPUT:
• G – an intermediate Groebner basis
• B – a set of critical pairs
• h – a polynomial

OUTPUT: a tuple of
• an intermediate Groebner basis
• a set of critical pairs

EXAMPLES:

```python
sage: from sage.rings.polynomial.toy_buchberger import update
tage: R.<x,y,z> = PolynomialRing(QQ)
sage: set_verbose(0)
sage: update(set(), set(), x*y*z)
({x*y*z}, set())
sage: G, B = update(set(), set(), x*y*z - 1)
sage: G, B = update(G, B, x*y^2 - 1)
sage: G, B
({x*y^2 - 1}, {(x*y^2 - 1, x*y*z - 1)})
```

3.3.2 Educational versions of Groebner basis algorithms: triangular factorization

In this file is the implementation of two algorithms in [Laz1992].

The main algorithm is Triangular; a secondary algorithm, necessary for the first, is ElimPolMin. As per Lazard’s formulation, the implementation works with any term ordering, not only lexicographic.

Lazard does not specify a few of the subalgorithms implemented as the functions

• is_triangular,
• is_linearly_dependent, and
• linear_representation.

The implementations are not hard, and the choice of algorithm is described with the relevant function.

No attempt was made to optimize these algorithms as the emphasis of this implementation is a clean and easy presentation.

Examples appear with the appropriate function.

AUTHORS:
sage.rings.polynomial.toy_variety.coefficient_matrix(polys)

Generate the matrix $M$ whose entries are the coefficients of $polys$.

The entries of row $i$ of $M$ consist of the coefficients of $polys[i]$.

**INPUT:**
- $polys$ – a list/tuple of polynomials

**OUTPUT:**
A matrix $M$ of the coefficients of $polys$

**EXAMPLES:**

```python
sage: from sage.rings.polynomial.toy_variety import coefficient_matrix
sage: R.<x,y> = PolynomialRing(QQ)
sage: coefficient_matrix([x^2 + 1, y^2 + 1, x*y + 1])
[1 0 0 1]
[0 0 1 1]
[0 1 0 1]
```

**Note:** This function may be merged with `sage.rings.polynomial.multi_polynomial_sequence.PolynomialSequence_generic.coefficient_matrix()` in the future.

sage.rings.polynomial.toy_variety.elim_pol(B, n=-1)

Find the unique monic polynomial of lowest degree and lowest variable in the ideal described by $B$.

For the purposes of the triangularization algorithm, it is necessary to preserve the ring, so $n$ specifies which variable to check. By default, we check the last one, which should also be the smallest.

The algorithm may not work if you are trying to cheat: $B$ should describe the Groebner basis of a zero-dimensional ideal. However, it is not necessary for the Groebner basis to be lexicographic.

The algorithm is taken from a 1993 paper by Lazard [Laz1992].

**INPUT:**
- $B$ – a list/tuple of polynomials or a multivariate polynomial ideal
- $n$ – the variable to check (see above) (default: -1)

**EXAMPLES:**

```python
sage: from sage.misc.verbose import set_verbose
sage: setVerbose(0)
sage: from sage.rings.polynomial.toy_variety import elim_pol
sage: R.<x,y,z> = PolynomialRing(GF(32003))
sage: p1 = x^2*(x-1)^3*y^2*(z-3)^3
sage: p2 = z^2 - z
sage: p3 = (x-2)^2*(y-1)^3
sage: I = R.ideal(p1,p2,p3)
sage: elim_pol(I.groebner_basis())
z^2 - z
```
sage.rings.polynomial.toy_variety.is_linearly_dependent(polys)

Decide whether the polynomials of polys are linearly dependent.

Here polys is a collection of polynomials.

The algorithm creates a matrix of coefficients of the monomials of polys. It computes the echelon form of the matrix, then checks whether any of the rows is the zero vector.

Essentially this relies on the fact that the monomials are linearly independent, and therefore is building a linear map from the vector space of the monomials to the canonical basis of \( \mathbb{R}^n \), where \( n \) is the number of distinct monomials in polys. There is a zero vector iff there is a linear dependence among polys.

The case where polys=[] is considered to be not linearly dependent.

INPUT:

• polys – a list/tuple of polynomials

OUTPUT:

True if the elements of polys are linearly dependent; False otherwise.

EXAMPLES:

```
sage: from sage.rings.polynomial.toy_variety import is_linearly_dependent
sage: R.<x,y> = PolynomialRing(QQ)
sage: B = [x^2 + 1, y^2 + 1, x*y + 1]
sage: is_linearly_dependent(B + [p])
True
sage: p = x*B[0]
```

sage.rings.polynomial.toy_variety.is_triangular(B)

Check whether the basis B of an ideal is triangular.

That is: check whether the largest variable in B[i] with respect to the ordering of the base ring R is R.gens()[i].

The algorithm is based on the definition of a triangular basis, given by Lazard in 1992 in [Laz1992].

INPUT:

• B – a list/tuple of polynomials or a multivariate polynomial ideal

OUTPUT:

True if the basis is triangular; False otherwise.

EXAMPLES:

```
sage: from sage.rings.polynomial.toy_variety import is_triangular
sage: R.<x,y,z> = PolynomialRing(QQ)
sage: p1 = x^2*y + z^2
sage: p2 = y*z + z^3
sage: p3 = y+z
sage: is_triangular(R.ideal(p1,p2,p3))
False
sage: p3 = z^2 - 3
(continues on next page)```
sage: is_triangular(R.ideal(p1,p2,p3))
True

```python
sage.rings.polynomial.toy_variety.linear_representation(p, polys)
```

Assuming that \( p \) is a linear combination of \( \text{polys} \), determine coefficients that describe the linear combination.

This probably does not work for any inputs except \( p \), a polynomial, and \( \text{polys} \), a sequence of polynomials. If \( p \) is not in fact a linear combination of \( \text{polys} \), the function raises an exception.

The algorithm creates a matrix of coefficients of the monomials of \( \text{polys} \) and \( p \), with the coefficients of \( p \) in the last row. It augments this matrix with the appropriate identity matrix, then computes the echelon form of the augmented matrix. The last row should contain zeroes in the first columns, and the last columns contain a linear dependence relation. Solving for the desired linear relation is straightforward.

**INPUT:**
- \( p \) – a polynomial
- \( \text{polys} \) – a list/tuple of polynomials

**OUTPUT:**
If \( n == \text{len(\text{polys})} \), returns \([a[0],a[1],...,a[n-1]]\) such that \( p == a[0]*\text{\text{polys}}[0] + ... + a[n-1]*\text{\text{polys}[n-1]} \).

**EXAMPLES:**

```python
sage: from sage.rings.polynomial.toy_variety import linear_representation
sage: R.<x,y> = PolynomialRing(GF(32003))
sage: B = [x^2 + 1, y^2 + 1, x*y + 1]
```

```python
```

```python
sage: linear_representation(p, B)
[3, 32001, 1]
```

```python
sage.rings.polynomial.toy_variety.triangular_factorization(B, n=-1)
```

Compute the triangular factorization of the Groebner basis \( B \) of an ideal.

This will not work properly if \( B \) is not a Groebner basis!

The algorithm used is that described in a 1992 paper by Daniel Lazard [Laz1992]. It is not necessary for the term ordering to be lexicographic.

**INPUT:**
- \( B \) – a list/tuple of polynomials or a multivariate polynomial ideal
- \( n \) – the recursion parameter (default: -1)

**OUTPUT:**
A list \( T \) of triangular sets \( T_0, T_1, \text{etc.} \).

**EXAMPLES:**

```python
sage: from sage.misc.verbose import set_verbose
sage: set_verbose(0)
```

```python
sage: from sage.rings.polynomial.toy_variety import triangular_factorization
```

```python
sage: R.<x,y,z> = PolynomialRing(GF(32003))
```

```python
sage: p1 = x^2*(x-1)^3*y^2*(z-3)^3
sage: p2 = z^2 - z
```

(continues on next page)
3.3.3 Educational version of the \(d\)-Groebner basis algorithm over PIDs

No attempt was made to optimize this algorithm as the emphasis of this implementation is a clean and easy presentation.

**Note:** The notion of ‘term’ and ‘monomial’ in [BW1993] is swapped from the notion of those words in Sage (or the other way around, however you prefer it). In Sage a term is a monomial multiplied by a coefficient, while in [BW1993] a monomial is a term multiplied by a coefficient. Also, what is called LM (the leading monomial) in Sage is called HT (the head term) in [BW1993].

**EXAMPLES:**

```python
sage: from sage.rings.polynomial.toy_d_basis import d_basis
```

First, consider an example from arithmetic geometry:

```python
sage: A.<x,y> = PolynomialRing(ZZ, 2)
sage: B.<X,Y> = PolynomialRing(Rationals(),2)
sage: f = -y^2 - y + x^3 + 7*x + 1
sage: fx = f.derivative(x)
sage: fy = f.derivative(y)
sage: I = B.ideal([B(f),B(fx),B(fy)])
sage: I.groebner_basis()
[1]
```

Since the output is 1, we know that there are no generic singularities.

To look at the singularities of the arithmetic surface, we need to do the corresponding computation over \(\mathbb{Z}\):

```python
sage: I = A.ideal([f,fx,fy])
sage: gb = d_basis(I); gb
[x - 2020, y - 11313, 22627]
sage: gb[-1].factor()
11^3 * 17
```

This Groebner Basis gives a lot of information. First, the only fibers (over \(\mathbb{Z}\)) that are not smooth are at 11 = 0, and 17 = 0. Examining the Groebner Basis, we see that we have a simple node in both the fiber at 11 and at 17. From the factorization, we see that the node at 17 is regular on the surface (an \(I_1\) node), but the node at 11 is not. After blowing up this non-regular point, we find that it is an \(I_3\) node.

Another example. This one is from the Magma Handbook:
To compute modulo 4, we can add the generator 4 to our basis:

```python
sage: I = ideal( x^2 - 1, y^2 - 1, 2*x*y - z, 4)
sage: gb = d_basis(I)
sage: R = P.change_ring(IntegerModRing(4))
sage: gb = [R(f) for f in gb if R(f)]; gb
[x^2 - 1, x*z + 2*y, 2*x - y*z, y^2 - 1, z^2, 2*z]
```

A third example is also from the Magma Handbook.

This example shows how one can use Groebner bases over the integers to find the primes modulo which a system of equations has a solution, when the system has no solutions over the rationals.

We first form a certain ideal $I$ in $\mathbb{Z}[x, y, z]$, and note that the Groebner basis of $I$ over $\mathbb{Q}$ contains 1, so there are no solutions over $\mathbb{Q}$ or an algebraic closure of it (this is not surprising as there are 4 equations in 3 unknowns).

```python
sage: P.<x, y, z> = PolynomialRing(IntegerRing(), 3, order='degneglex')
sage: I = ideal( x^2 - 3*y, y^3 - x*y, z^3 - x, x^4 - y*z + 1 )
sage: I.change_ring(P.change_ring(RationalField())).groebner_basis()
[1]
```

However, when we compute the Groebner basis of $I$ (defined over $\mathbb{Z}$), we note that there is a certain integer in the ideal which is not 1:

```python
sage: gb = d_basis(I); gb
[z ..., y ..., x ..., 282687803443]
```

Now for each prime $p$ dividing this integer 282687803443, the Groebner basis of $I$ modulo $p$ will be non-trivial and will thus give a solution of the original system modulo $p$.

```python
sage: factor(282687803443)
101 * 103 * 27173681
sage: I.change_ring( P.change_ring( GF(101) ) ).groebner_basis()
[z - 33, y + 48, x + 19]
sage: I.change_ring( P.change_ring( GF(103) ) ).groebner_basis()
[z - 18, y + 8, x + 39]
sage: I.change_ring( P.change_ring( GF(27173681) ) ).groebner_basis()
[z + 1038032, y + 3186055, x - 536027]
```

Of course, modulo any other prime the Groebner basis is trivial so there are no other solutions. For example:

```python
sage: I.change_ring( P.change_ring( GF(3) ) ).groebner_basis()
[1]
```

AUTHOR:
• Martin Albrecht (2008-08): initial version

```
sage.rings.polynomial.toy_d_basis.LC(f)
sage.rings.polynomial.toy_d_basis.LM(f)
sage.rings.polynomial.toy_d_basis.d_basis(F, strat=True)
```

Return the \( d \)-basis for the Ideal \( F \) as defined in \[BW1993\].

**INPUT:**
- \( F \) – an ideal
- \( \text{strat} \) – use update strategy (default: True)

**EXAMPLES:**
```
sage: from sage.rings.polynomial.toy_d_basis import d_basis
sage: A.<x,y> = PolynomialRing(ZZ, 2)
sage: f = -y^2 - y + x^3 + 7*x + 1
sage: fx = f.derivative(x)
sage: fy = f.derivative(y)
sage: I = A.ideal([f,fx,fy])
sage: gb = d_basis(I); gb
[x - 2020, y - 11313, 22627]
```

```
sage.rings.polynomial.toy_d_basis.gpol(g1, g2)
```

Return the G-Polynomial of \( g_1 \) and \( g_2 \).

Let \( a_i t_i \) be \( LT(g_i) \), \( a = a_i * c_i + a_j * c_j \) with \( a = \text{GCD}(a_i, a_j) \), and \( s_i = t/t_i \) with \( t = \text{LCM}(t_i, t_j) \). Then the G-Polynomial is defined as: \( c_1 s_1 g_1 - c_2 s_2 g_2 \).

**INPUT:**
- \( g1 \) – polynomial
- \( g2 \) – polynomial

**EXAMPLES:**
```
sage: from sage.rings.polynomial.toy_d_basis import gpol
sage: P.<x, y, z> = PolynomialRing(IntegerRing(), 3, order='lex')
sage: f = x^2 - 1
sage: g = 2*x*y - z
sage: gpol(f,g)
x^2*y - y
```

```
sage.rings.polynomial.toy_d_basis.select(P)
```

The normal selection strategy.

**INPUT:**
- \( P \) – a list of critical pairs

**OUTPUT:**
- an element of \( P \)

**EXAMPLES:**

3.3. Educational Versions of Groebner Basis Related Algorithms
sage: from sage.rings.polynomial.toy_d_basis import select
sage: A.<x,y> = PolynomialRing(ZZ, 2)
sage: f = -y^2 - y + x^3 + 7*x + 1
sage: fx = f.derivative(x)
sage: fy = f.derivative(y)
sage: G = [f, fx, fy]
sage: B = set((f1, f2) for f1 in G for f2 in G if f1 != f2)
sage: select(B)
(-2*y - 1, 3*x^2 + 7)

sage.rings.polynomial.toy_d_basis.spol(g1, g2)

Return the S-Polynomial of g_1 and g_2.

Let $a_i t_i$ be $LT(g_i)$, $b_i = a_i / a$ with $a = LCM(a_i, a_j)$, and $s_i = t / t_i$ with $t = LCM(t_i, t_j)$. Then the S-Polynomial is defined as: $b_1 s_1 g_1 - b_2 s_2 g_2$.

INPUT:

- g1 – polynomial
- g2 – polynomial

EXAMPLES:

sage: from sage.rings.polynomial.toy_d_basis import spol
sage: P.<x, y, z> = PolynomialRing(IntegerRing(), 3, order=’lex’)
sage: f = x^2 - 1
sage: g = 2*x*y - z
sage: spol(f,g)
x*z - 2*y

sage.rings.polynomial.toy_d_basis.update(G, B, h)

Update G using the list of critical pairs B and the polynomial h as presented in [BW1993], page 230. For this, Buchberger’s first and second criterion are tested.

This function uses the Gebauer-Moeller Installation.

INPUT:

- G – an intermediate Groebner basis
- B – a list of critical pairs
- h – a polynomial

OUTPUT:

G, B where G and B are updated

EXAMPLES:

sage: from sage.rings.polynomial.toy_d_basis import update
sage: A.<x,y> = PolynomialRing(ZZ, 2)
sage: G = set([3*x^2 + 7, 2*y + 1, x^3 - y^2 + 7*x - y + 1])
sage: B = set()
sage: h = x^2*y - x + y - 3
sage: update(G, B, h)
({2*y + 1, 3*x^2 + 7, x^2*y - x^2 + y - 3, x^3 - y^2 + 7*x - y + 1},
 {x^2*y - x^2 + y - 3, 2*y + 1})
(x^2 y - x^2 + y - 3, 3 x^2 + 7),
(x^2 y - x^2 + y - 3, x^3 - y^2 + 7 x - y + 1))
4.1 Fraction Field of Integral Domains

AUTHORS:

- William Stein (with input from David Joyner, David Kohel, and Joe Wetherell)
- Burcin Erocal
- Julian Rüth (2017-06-27): embedding into the field of fractions and its section

EXAMPLES:

Quotienting is a constructor for an element of the fraction field:

```sage
R.<x> = QQ[]
sage: (x^2-1)/(x+1)
x - 1
sage: parent((x^2-1)/(x+1))
Fraction Field of Univariate Polynomial Ring in x over Rational Field
```

The GCD is not taken (since it doesn’t converge sometimes) in the inexact case:

```sage
Z.<z> = CC[]
sage: I = CC.gen()
sage: (1+I+z)/(z+0.1*I)
(z + 1.00000000000000 + I)/(z + 0.100000000000000*I)
sage: (1+I*z)/(z+1.1)
(I*z + 1.00000000000000)/(z + 1.10000000000000)
```

`sage.rings.fraction_field.FractionField(R, names=None)`

Create the fraction field of the integral domain R.

INPUT:

- R – an integral domain
- names – ignored

EXAMPLES:

We create some example fraction fields:

```sage
FractionField(IntegerRing())
Rational Field
sage: FractionField(PolynomialRing(RationalField(),'x'))
```

(continues on next page)
Fraction Field of Univariate Polynomial Ring in x over Rational Field
\texttt{sage: FractionField(PolynomialRing(IntegerRing(),'x'))}
Fraction Field of Univariate Polynomial Ring in x over Integer Ring
\texttt{sage: FractionField(PolynomialRing(RationalField(),2,'x'))}
Fraction Field of Multivariate Polynomial Ring in x0, x1 over Rational Field

Dividing elements often implicitly creates elements of the fraction field:

\begin{verbatim}
\texttt{sage: x = PolynomialRing(RationalField(), 'x').gen()}
\texttt{sage: f = x/(x+1)}
\texttt{sage: g = x**3/(x+1)}
\texttt{sage: f/g}
\texttt{1/x^2}
\texttt{sage: g/f}
\texttt{x^2}
\end{verbatim}

The input must be an integral domain:

\begin{verbatim}
\texttt{sage: Frac(Integers(4))}
Traceback (most recent call last):
...  
TypeError: R must be an integral domain.
\end{verbatim}

\textbf{class} \texttt{sage.rings.fraction_field.FractionFieldEmbedding}
\texttt{Bases: DefaultConvertMap_unique}

The embedding of an integral domain into its field of fractions.

\textbf{EXAMPLES:}

\begin{verbatim}
\texttt{sage: R.<x> = QQ[]}
\texttt{sage: f = R.fraction_field().coerce_map_from(R); f}
Coercion map:
From: Univariate Polynomial Ring in x over Rational Field
To: Fraction Field of Univariate Polynomial Ring in x over Rational Field
\texttt{\textbf{is_injective}()}
Return whether this map is injective.

\textbf{EXAMPLES:}

The map from an integral domain to its fraction field is always injective:

\begin{verbatim}
\texttt{sage: R.<x> = QQ[]}
\texttt{sage: R.fraction_field().coerce_map_from(R).is_injective()}
True
\end{verbatim}

\texttt{\textbf{is_surjective}()}
Return whether this map is surjective.

\textbf{EXAMPLES:}

\begin{verbatim}
\texttt{sage: R.<x> = QQ[]}
\texttt{sage: R.fraction_field().coerce_map_from(R).is_surjective()}
False
\end{verbatim}
section()

Return a section of this map.

EXAMPLES:

```
sage: R.<x> = QQ[]
sage: R.fraction_field().coerce_map_from(R).section()
Section map:
  From: Fraction Field of Univariate Polynomial Ring in x over Rational Field
  To:   Univariate Polynomial Ring in x over Rational Field
```

class sage.rings.fraction_field.FractionFieldEmbeddingSection

Bases: Section

The section of the embedding of an integral domain into its field of fractions.

EXAMPLES:

```
sage: R.<x> = QQ[]
sage: f = R.fraction_field().coerce_map_from(R).section(); f
Section map:
  From: Fraction Field of Univariate Polynomial Ring in x over Rational Field
  To:   Univariate Polynomial Ring in x over Rational Field
```

class sage.rings.fraction_field.FractionField_1poly_field(R, element_class=<class 'sage.rings.fraction_field_element.FractionFieldElement_1poly_field'>)

Bases: FractionField_generic

The fraction field of a univariate polynomial ring over a field.

Many of the functions here are included for coherence with number fields.

class_number()

Here for compatibility with number fields and function fields.

EXAMPLES:

```
sage: R.<t> = GF(5)[]; K = R.fraction_field()
sage: K.class_number()
1
```

function_field()

Return the isomorphic function field.

EXAMPLES:

```
sage: R.<t> = GF(5)[]
sage: K = R.fraction_field()
sage: K.function_field()
Rational function field in t over Finite Field of size 5
```

See also:

```
sage.rings.function_field.RationalFunctionField.field()
```

maximal_order()

Return the maximal order in this fraction field.

EXAMPLES:
```python
sage: K = FractionField(GF(5)['t'])
sage: K.maximal_order()
Univariate Polynomial Ring in t over Finite Field of size 5
```

**ring_of_integers()**

Return the ring of integers in this fraction field.

**EXAMPLES:**

```python
sage: K = FractionField(GF(5)['t'])
sage: K.ring_of_integers()
Univariate Polynomial Ring in t over Finite Field of size 5
```

class `sage.rings.fraction_field.FractionField_generic`

```
Bases: Field

The fraction field of an integral domain.

**base_ring()**

Return the base ring of self.

This is the base ring of the ring which this fraction field is the fraction field of.

**EXAMPLES:**

```python
sage: R = Frac(ZZ['t'])
sage: R.base_ring()
Integer Ring
```

**characteristic()**

Return the characteristic of this fraction field.

**EXAMPLES:**

```python
sage: R = Frac(ZZ['t'])
sage: R.base_ring()
Integer Ring
sage: R = Frac(ZZ['t']); R.characteristic()
0
sage: R = Frac(GF(5)['w']); R.characteristic()
5
```

**construction()**

**EXAMPLES:**

```python
sage: Frac(ZZ['x']).construction()
(FractionField, Univariate Polynomial Ring in x over Integer Ring)
sage: K = Frac(GF(3)['t'])
sage: f, R = K.construction()
sage: f(R)
Fraction Field of Univariate Polynomial Ring in t over Finite Field of size 3
sage: f(R) == K
True
```
**gen**($i=0$)

Return the $i$-th generator of *self*.

**EXAMPLES:**

```
sage: R = Frac(PolynomialRing(QQ,'z',10)); R
Fraction Field of Multivariate Polynomial Ring in z0, z1, z2, z3, z4, z5, z6, ....
                       ~z7, z8, z9 over Rational Field
sage: R.0
z0
sage: R.gen(3)
z3
sage: R.3
z3
```

**is_exact()**

Return if *self* is exact which is if the underlying ring is exact.

**EXAMPLES:**

```
sage: Frac(ZZ['x']).is_exact()
True
sage: Frac(CDF['x']).is_exact()
False
```

**is_field**(proof=True)

Return True, since the fraction field is a field.

**EXAMPLES:**

```
sage: Frac(ZZ).is_field()
True
```

**is_finite()**

Tells whether this fraction field is finite.

**Note:** A fraction field is finite if and only if the associated integral domain is finite.

**EXAMPLES:**

```
sage: Frac(QQ['a','b','c']).is_finite()
False
```

**ngens()**

This is the same as for the parent object.

**EXAMPLES:**

```
sage: R = Frac(PolynomialRing(QQ,'z',10)); R
Fraction Field of Multivariate Polynomial Ring in z0, z1, z2, z3, z4, z5, z6, ....
                       ~z7, z8, z9 over Rational Field
sage: R.ngens()
10
```
random_element(*args, **kwds)

Return a random element in this fraction field.

The arguments are passed to the random generator of the underlying ring.

EXAMPLES:

```python
sage: F = ZZ['x'].fraction_field()
sage: F.random_element()  # random
(2*x - 8)/(-x^2 + x)
```

```python
sage: f = F.random_element(degree=5)
sage: f.numerator().degree() == f.denominator().degree()
True
sage: f.denominator().degree() <= 5
True
sage: while f.numerator().degree() != 5:
    ....: f = F.random_element(degree=5)
```

ring()

Return the ring that this is the fraction field of.

EXAMPLES:

```python
sage: R = Frac(QQ['x,y'])
sage: R
Fraction Field of Multivariate Polynomial Ring in x, y over Rational Field
sage: R.ring()
Multivariate Polynomial Ring in x, y over Rational Field
```

some_elements()

Return some elements in this field.

EXAMPLES:

```python
sage: R.<x> = QQ[]
sage: R.fraction_field().some_elements()
[0, 1, x, 2*x, x/(x^2 + 2*x + 1), 1/x^2, ...
 (2*x^2 + 2)/(x^2 + 2*x + 1), (2*x^2 + 2)/x^3,
 (2*x^2 + 2)/(x^2 - 1), 2]
```

sage.rings.fraction_field.is_FractionField(x)

Test whether or not x inherits from FractionField_generic.

EXAMPLES:
4.2 Fraction Field Elements

AUTHORS:

- William Stein (input from David Joyner, David Kohel, and Joe Wetherell)
- Sebastian Pancratz (2010-01-06): Rewrite of addition, multiplication and derivative to use Henrici’s algorithms [Hor1972]

```
sage: from sage.rings.fraction_field import is_FractionField
sage: is_FractionField(Frac(ZZ['x']))
True
sage: is_FractionField(QQ)
False
```

class sage.rings.fraction_field_element.FractionFieldElement

Bases: FieldElement

EXAMPLES:

```
sage: K = FractionField(PolynomialRing(QQ, 'x'))
sage: K
Fraction Field of Univariate Polynomial Ring in x over Rational Field
sage: loads(K.dumps()) == K
True
sage: x = K.gen()
sage: f = (x^3 + x)/(17 - x^19); f
(-x^3 - x)/(x^19 - 17)
sage: loads(f.dumps()) == f
True
```

denominator()

Return the denominator of self.

EXAMPLES:

```
sage: R.<x,y> = ZZ[]
sage: f = x/y+1; f
(x + y)/y
sage: f.denominator()
y
```

is_one()

Return True if this element is equal to one.

EXAMPLES:

```
sage: F = ZZ['x,y'].fraction_field()
sage: x,y = F.gens()
sage: (x/x).is_one()
True
sage: (x/y).is_one()
False
```
is_square(root=False)

Return whether or not self is a perfect square.

If the optional argument root is True, then also returns a square root (or None, if the fraction field element is not square).

INPUT:

• root – whether or not to also return a square root (default: False)

OUTPUT:

• bool - whether or not a square

• object - (optional) an actual square root if found, and None otherwise.

EXAMPLES:

```
sage: R.<t> = QQ[]
sage: (1/t).is_square()
False
sage: (1/t^6).is_square()
True
sage: ((1+t)^4/t^6).is_square()
True
sage: (4*(1+t)^4/t^6).is_square()
True
sage: (2*(1+t)^4/t^6).is_square()
False
sage: ((1+t)/t^6).is_square()
False
sage: (4*(1+t)^4/t^6).is_square(root=True)
(True, (2*t^2 + 4*t + 2)/t^3)
sage: (2*(1+t)^4/t^6).is_square(root=True)
(False, None)
sage: R.<x> = QQ[]
sage: a = 2*(x+1)^2 / (2*(x-1)^2); a
(x^2 + 2*x + 1)/(x^2 - 2*x + 1)
sage: a.is_square()
True
sage: (0/x).is_square()
True
```

is_zero()

Return True if this element is equal to zero.

EXAMPLES:

```
sage: F = ZZ['x,y'].fraction_field()
sage: x,y = F.gens()
sage: t = F(0)/x
sage: t.is_zero()
True
sage: u = 1/x - 1/x
sage: u.is_zero()
```

(continues on next page)
True
sage: u.parent() is F
True

nth_root(n)

Return a n-th root of this element.

EXAMPLES:

```
sage: R = QQ['t'].fraction_field()
sage: t = R.gen()
sage: p = (t+1)^3 / (t^2+t-1)^3
sage: p.nth_root(3)
(t + 1)/(t^2 + t - 1)
sage: p = (t+1) / (t-1)
sage: p.nth_root(2)
Traceback (most recent call last):
... ValueError: not a 2nd power
```

numerator()

Return the numerator of self.

EXAMPLES:

```
sage: R.<x,y> = ZZ[]
sage: f = x/y+1; f
(x + y)/y
sage: f.numerator()
x + y
```

reduce()

Reduce this fraction.

Divides out the gcd of the numerator and denominator. If the denominator becomes a unit, it becomes 1. Additionally, depending on the base ring, the leading coefficients of the numerator and the denominator may be normalized to 1.

Automatically called for exact rings, but because it may be numerically unstable for inexact rings it must be called manually in that case.

EXAMPLES:

```
sage: R.<x> = RealField(10)[]
sage: f = (x^2+2*x+1)/(x+1); f
(x^2 + 2.0*x + 1.0)/(x + 1.0)
sage: f.reduce(); f
x + 1.0
```

specialization(D=None, phi=None)

Returns the specialization of a fraction element of a polynomial ring
valuation(v=None)

Return the valuation of self, assuming that the numerator and denominator have valuation functions defined on them.

EXAMPLES:

```python
sage: x = PolynomialRing(RationalField(), 'x').gen()
sage: f = (x^3 + x)/(x^2 - 2*x^3)
sage: f
(-1/2*x^2 - 1/2)/(x^2 - 1/2*x)
sage: f.valuation()
-1
sage: f.valuation(x^2+1)
1
```

class sage.rings.fraction_field_element.FractionFieldElement_1poly_field

Bases: FractionFieldElement

A fraction field element where the parent is the fraction field of a univariate polynomial ring over a field.

Many of the functions here are included for coherence with number fields.

is_integral()

Returns whether this element is actually a polynomial.

EXAMPLES:

```python
sage: R.<t> = QQ[]
sage: elt = (t^2 + t - 2) / (t + 2); elt
# == (t + 2)*(t - 1)/(t + 2)
t - 1
sage: elt.is_integral()
True
sage: elt = (t^2 - t) / (t+2); elt
# == t*(t - 1)/(t + 2)
(t^2 - t)/(t + 2)
sage: elt.is_integral()
False
```

reduce()

Pick a normalized representation of self.

In particular, for any a == b, after normalization they will have the same numerator and denominator.

EXAMPLES:

For univariate rational functions over a field, we have:

```python
sage: R.<x> = QQ[]
sage: (2 + 2*x) / (4*x) # indirect doctest
(1/2*x + 1/2)/x
```

Compare with:

```python
sage: R.<x> = ZZ[]
sage: (2 + 2*x) / (4*x)
(x + 1)/(2*x)
```
support()

Returns a sorted list of primes dividing either the numerator or denominator of this element.

EXAMPLES:

```python
sage: R.<t> = QQ[]
sage: h = (t^14 + 2*t^12 - 4*t^11 - 8*t^9 + 6*t^8 + 12*t^6 - 4*t^5 - 8*t^3 + t^2 + 2)/(t^6 + 6*t^5 + 9*t^4 - 2*t^2 - 12*t - 18)
sage: h.support()
[t - 1, t + 3, t^2 + 2, t^2 + t + 1, t^4 - 2]
```

sage.rings.fraction_field_element.is_FractionFieldElement(x)

Return whether or not x is a *FractionFieldElement*.

EXAMPLES:

```python
sage: from sage.rings.fraction_field_element import is_FractionFieldElement
sage: R.<x> = ZZ[]
sage: is_FractionFieldElement(x/2)
False
sage: is_FractionFieldElement(2/x)
True
sage: is_FractionFieldElement(1/3)
False
```

sage.rings.fraction_field_element.make_element(parent, numerator, denominator)

Used for unpickling *FractionFieldElement* objects (and subclasses).

EXAMPLES:

```python
sage: from sage.rings.fraction_field_element import make_element
sage: R = ZZ['x,y']
sage: x,y = R.gens()
sage: F = R.fraction_field()
sage: make_element(F, 1+x, 1+y)
(x + 1)/(y + 1)
```

sage.rings.fraction_field_element.make_element_old(parent, cdict)

Used for unpickling old *FractionFieldElement* pickles.

EXAMPLES:

```python
sage: from sage.rings.fraction_field_element import make_element_old
sage: R.<x,y> = ZZ[]
sage: F = R.fraction_field()
sage: make_element_old(F, {'_FractionFieldElement__numerator':x+y,'_FractionFieldElement__denominator':x-y})
(x + y)/(x - y)
```
4.3 Univariate rational functions over prime fields

```python
class sage.rings.fraction_field_FpT.FpT(R, names=None):
    Bases: FractionField_1poly_field

    This class represents the fraction field GF(p)(T) for \(2 < p < \sqrt{2^{31} - 1}\).

    EXAMPLES:
    sage: R.<T> = GF(71)[]
    sage: K = FractionField(R); K
    Fraction Field of Univariate Polynomial Ring in T over Finite Field of size 71
    sage: 1-1/T
    (T + 70)/T
    sage: parent(1-1/T) is K
    True

    INTEGER_LIMIT = 46341

    iter(bound=None, start=None)
    EXAMPLES:
    sage: from sage.rings.fraction_field_FpT import *
    sage: R.<t> = FpT(GF(5)['t'])
    sage: list(R.iter(2))[350:355]
    [(t^2 + t + 1)/(t + 2),
     (t^2 + t + 2)/(t + 2),
     (t^2 + t + 4)/(t + 2),
     (t^2 + 2*t + 1)/(t + 2),
     (t^2 + 2*t + 2)/(t + 2)]```

class sage.rings.fraction_field_FpT.FpTElement

Bases: FieldElement

An element of an FpT fraction field.

denom()

Return the denominator of this element, as an element of the polynomial ring.

EXAMPLES:

```python
sage: K = GF(11)['t'].fraction_field()
 sage: t = K.gen(0); a = (t + 1/t)^3 - 1
 sage: a.denom()
t^3```

denominator()

Return the denominator of this element, as an element of the polynomial ring.

EXAMPLES:

```python
sage: K = GF(11)['t'].fraction_field()
 sage: t = K.gen(0); a = (t + 1/t)^3 - 1
 sage: a.denominator()
t^3```
factor()

EXAMPLES:

```
sage: K = Frac(GF(5)[t])
sage: t = K.gen()
sage: f = 2 * (t+1) * (t^2+t+1)^2 / (t-1)
sage: factor(f)
(2) * (t + 4)^-1 * (t + 1) * (t^2 + t + 1)^2
```

is_square()

Return True if this element is the square of another element of the fraction field.

EXAMPLES:

```
sage: K = GF(13)[t].fraction_field(); t = K.gen()
sage: t.is_square()
False
sage: (1/t^2).is_square()
True
sage: K(0).is_square()
True
```

next()

This function iterates through all polynomials, returning the “next” polynomial after this one.

The strategy is as follows:

- We always leave the denominator monic.
- We progress through the elements with both numerator and denominator monic, and with the denominator less than the numerator. For each such, we output all the scalar multiples of it, then all of the scalar multiples of its inverse.
- So if the leading coefficient of the numerator is less than p-1, we scale the numerator to increase it by 1.
- Otherwise, we consider the multiple with numerator and denominator monic.
  - If the numerator is less than the denominator (lexicographically), we return the inverse of that element.
  - If the numerator is greater than the denominator, we invert, and then increase the numerator (remaining monic) until we either get something relatively prime to the new denominator, or we reach the new denominator. In this case, we increase the denominator and set the numerator to 1.

EXAMPLES:

```
sage: from sage.rings.fraction_field_FpT import *
sage: R.<t> = FpT(GF(3)[t])
sage: a = R(0)
sage: for _ in range(30):
....:     a = a.next()
....:     print(a)
1
2
1/t
2/t
t
```

(continues on next page)
numerator()  
Return the numerator of this element, as an element of the polynomial ring.

EXAMPLES:

```
sage: K = GF(11)['t'].fraction_field()
sage: t = K.gen(0); a = (t + 1/t)^3 - 1
t^6 + 3*t^4 + 10*t^3 + 3*t^2 + 1
```

numerator()  
Return the numerator of this element, as an element of the polynomial ring.

EXAMPLES:

```
sage: K = GF(11)['t'].fraction_field()
sage: t = K.gen(0); a = (t + 1/t)^3 - 1
sage: a.numerator()
t^6 + 3*t^4 + 10*t^3 + 3*t^2 + 1
```

sqrt(extend=True, all=False)
Return the square root of this element.

INPUT:

- `extend` - bool (default: True); if True, return a square root in an extension ring, if necessary. Otherwise, raise a ValueError if the square is not in the base ring.
- `all` - bool (default: False); if True, return all square roots of self, instead of just one.
EXAMPLES:

```python
sage: from sage.rings.fraction_field_FpT import *
sage: K = GF(7)['t'].fraction_field(); t = K.gen(0)
sage: p = (t + 2)^2/(3*t^3 + 1)^4
sage: p.sqrt()
(3*t + 6)/(t^6 + 3*t^3 + 4)
sage: p.sqrt()^2 == p
True
```

```python
subs(*args, **kwds)
```

EXAMPLES:

```python
sage: K = Frac(GF(11)['t'])
sage: t = K.gen()
sage: f = (t+1)/(t-1)
sage: f.subs(t=2)
3
sage: f.subs(X=2)
(t + 1)/(t + 10)
```

```python
valuation(v)
```

Return the valuation of self at v.

EXAMPLES:

```python
sage: R.<t> = GF(5)[]
sage: f = (t+1)^2 * (t^2+t+1) / (t-1)^3
sage: f.valuation(t+1)
2
sage: f.valuation(t-1)
-3
sage: f.valuation(t)
0
```

```python
class sage.rings.fraction_field_FpT.FpT_Fp_section
```

This class represents the section from GF(p)(t) back to GF(p)[t]

EXAMPLES:

```python
sage: R.<t> = GF(5)[]
sage: K = R.fraction_field()
sage: f = GF(5).convert_map_from(K); f
Section map:
  From: Fraction Field of Univariate Polynomial Ring in t over Finite Field of size 5
  To:  Finite Field of size 5
sage: type(f)
<class 'sage.rings.fraction_field_FpT.FpT_Fp_section'>
```

**Warning:** Comparison of FpT_Fp_section objects is not currently implemented. See [github issue #23469](https://github.com).
class sage.rings.fraction_field_FpT.FpT_Polyring_section

Bases: Section

This class represents the section from $GF(p)(t)$ back to $GF(p)[t]$

EXAMPLES:

```python
sage: R.<t> = GF(5)[]
sage: K = R.fraction_field()
sage: f = R.convert_map_from(K); f
Section map:
  From: Fraction Field of Univariate Polynomial Ring in t over Finite Field of size 5
  To:  Univariate Polynomial Ring in t over Finite Field of size 5
sage: type(f)
<class 'sage.rings.fraction_field_FpT.FpT_Polyring_section'>
```

Warning: Comparison of FpT_Polyring_section objects is not currently implemented. See github issue #23469.

```python
sage: fprime = loads(dumps(f))
sage: fprime == f
False
sage: fprime(1+t) == f(1+t)
True
```

class sage.rings.fraction_field_FpT.FpT_iter

Bases: object

Return a class that iterates over all elements of an FpT.

EXAMPLES:

```python
sage: K = GF(3)['t'].fraction_field()
sage: I = K.iter(1)
sage: list(I)
[0, 1, 2, t, t + 1, t + 2, 2*t, 2*t + 1,
```
2*t + 2,
1/t,
2/t,
(t + 1)/t,
(t + 2)/t,
(2*t + 1)/t,
(2*t + 2)/t,
1/(t + 1),
2/(t + 1),
t/(t + 1),
(t + 2)/(t + 1),
2*t/(t + 1),
(2*t + 1)/(t + 1),
1/(t + 2),
2/(t + 2),
t/(t + 2),
(t + 1)/(t + 2),
2*t/(t + 2),
(2*t + 2)/(t + 2)]

class sage.rings.fraction_field_FpT.Fp_FpT_coerce

Bases: RingHomomorphism

This class represents the coercion map from GF(p) to GF(p)(t)

EXAMPLES:

```python
sage: R.<t> = GF(5)[]
sage: K = R.fraction_field()
sage: f = K.coerce_map_from(GF(5)); f
Ring morphism:
  From: Finite Field of size 5
  To: Fraction Field of Univariate Polynomial Ring in t over Finite Field of size 5
sage: type(f)
<class 'sage.rings.fraction_field_FpT.Fp_FpT_coerce'>
```

`section()`

Return the section of this inclusion: the partially defined map from GF(p)(t) back to GF(p), defined on constant elements.

EXAMPLES:

```python
sage: R.<t> = GF(5)[]
sage: K = R.fraction_field()
sage: f = K.coerce_map_from(GF(5))
sage: g = f.section(); g
Section map:
  From: Fraction Field of Univariate Polynomial Ring in t over Finite Field of size 5
  To: Finite Field of size 5
sage: t = K.gen()
sage: g(f(1,3,reduce=False))
```

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2
sage: g(t)
Traceback (most recent call last):
...
ValueError: not constant
sage: g(1/t)
Traceback (most recent call last):
...
ValueError: not integral

**class** sage.rings.fraction_field_FpT.Polring_FpT_coerce
Bases: RingHomomorphism
This class represents the coercion map from GF(p)[t] to GF(p)(t)

**EXAMPLES:**

```python
sage: R.<t> = GF(5)[]
sage: K = R.fraction_field()
sage: f = K.coerce_map_from(R); f
Ring morphism:
  From: Univariate Polynomial Ring in t over Finite Field of size 5
  To:  Fraction Field of Univariate Polynomial Ring in t over Finite Field of size
       → 5
sage: type(f)
<class 'sage.rings.fraction_field_FpT.Polring_FpT_coerce'>
```

**section()**
Return the section of this inclusion: the partially defined map from GF(p)(t) back to GF(p)[t], defined on elements with unit denominator.

**EXAMPLES:**

```python
sage: R.<t> = GF(5)[]
sage: K = R.fraction_field()
sage: f = K.coerce_map_from(R)
sage: g = f.section(); g
Section map:
  From: Fraction Field of Univariate Polynomial Ring in t over Finite Field of size
       → 5
  To:  Univariate Polynomial Ring in t over Finite Field of size 5
sage: t = K.gen()
sage: g(t)
t
sage: g(1/t)
Traceback (most recent call last):
...
ValueError: not integral
```

**class** sage.rings.fraction_field_FpT.ZZ_FpT_coerce
Bases: RingHomomorphism
This class represents the coercion map from ZZ to GF(p)(t)

**EXAMPLES:**

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```
sage: R.<t> = GF(17)[]
sage: K = R.fraction_field()
sage: f = K.coerce_map_from(ZZ); f
Ring morphism:
  From: Integer Ring
  To:  Fraction Field of Univariate Polynomial Ring in t over Finite Field of size 17
sage: type(f)
<class 'sage.rings.fraction_field_FpT.ZZ_FpT_coerce'>
```

**section()**

Return the section of this inclusion: the partially defined map from \( \mathbb{F}_p(t) \) back to \( \mathbb{Z} \), defined on constant elements.

**EXAMPLES:**

```
sage: R.<t> = GF(5)[]
sage: K = R.fraction_field()
sage: f = K.coerce_map_from(ZZ)
sage: g = f.section(); g
Composite map:
  From: Fraction Field of Univariate Polynomial Ring in t over Finite Field of size 5
  To:  Integer Ring
  Defn: Section map:
    From: Fraction Field of Univariate Polynomial Ring in t over Finite Field of size 5
    To:  Finite Field of size 5
    then
    Lifting map:
      From: Finite Field of size 5
      To:  Integer Ring
sage: t = K.gen()
sage: g(f(1,3,reduce=False))
2
sage: g(t)
Traceback (most recent call last):
  ... ValueError: not constant
sage: g(1/t)
Traceback (most recent call last):
  ... ValueError: not integral
```

```
sage.rings.fraction_field_FpT.unpickle_FpT_element(K, numer, denom)
```

Used for pickling.
5.1 Ring of Laurent Polynomials (base class)

If \( R \) is a commutative ring, then the ring of Laurent polynomials in \( n \) variables over \( R \) is \( R[x_1^{\pm 1}, x_2^{\pm 1}, \ldots, x_n^{\pm 1}] \).

AUTHORS:

- David Roe (2008-2-23): created
- David Loeffler (2009-07-10): cleaned up docstrings

class sage.rings.polynomial.laurent_polynomial_ring_base.LaurentPolynomialRing_generic(R)

Bases: CommutativeRing, Parent

Laurent polynomial ring (base class).

EXAMPLES:

This base class inherits from CommutativeRing. Since github issue #11900, it is also initialised as such:

```
sage: R.<x1,x2> = LaurentPolynomialRing(QQ)
sage: R.category()
Join of Category of unique factorization domains and Category of commutative algebras over (number fields and quotient fields and metric spaces) and Category of infinite sets

sage: TestSuite(R).run()
```

change_ring(base_ring=None, names=None, sparse=False, order=None)

EXAMPLES:

```
sage: R = LaurentPolynomialRing(QQ, 2, 'x')
sage: R.change_ring(ZZ)
Multivariate Laurent Polynomial Ring in x0, x1 over Integer Ring
```

Check that the distinction between a univariate ring and a multivariate ring with one generator is preserved:

```
sage: P.<x> = LaurentPolynomialRing(QQ, 1)
sage: P
Multivariate Laurent Polynomial Ring in x over Rational Field

sage: K.<i> = CyclotomicField(4) # optional - sage.rings.number_field

sage: P.change_ring(K) # optional - sage.rings.number_field
```
Multivariate Laurent Polynomial Ring in x over
Cyclotomic Field of order 4 and degree 2

**characteristic()**

Returns the characteristic of the base ring.

EXAMPLES:

```python
sage: LaurentPolynomialRing(QQ,2,'x').characteristic()
0
sage: LaurentPolynomialRing(GF(3), 2, 'x').characteristic() # optional - sage.libs.pari
3
```

**completion(p=\text{None}, prec=20, extras=\text{None})**

Return the completion of self.

Currently only implemented for the ring of formal Laurent series. The `prec` variable controls the precision used in the Laurent series ring. If `prec` is ∞, then this returns a `LazyLaurentSeriesRing`.

EXAMPLES:

```python
sage: P.<x> = LaurentPolynomialRing(QQ)
sage: P
Univariate Laurent Polynomial Ring in x over Rational Field
sage: PP = P.completion(x)
sage: PP
Laurent Series Ring in x over Rational Field
sage: f = 1 - 1/x
sage: PP(f)
-x^-1 + 1
sage: g = 1 / PP(f); g
-x - x^2 - x^3 - x^4 - x^5 - x^6 - x^7 - x^8 - x^9 - x^10 - x^11
- x^12 - x^13 - x^14 - x^15 - x^16 - x^17 - x^18 - x^19 - x^20 + O(x^21)
sage: 1 / g
-x^-1 + 1 + O(x^19)
sage: PP = P.completion(x, prec=oo); PP
Lazy Laurent Series Ring in x over Rational Field
sage: g = 1 / PP(f); g
-x - x^2 - x^3 + O(x^4)
sage: 1 / g == f
True
```

**construction()**

Return the construction of self.

EXAMPLES:

```python
sage: LaurentPolynomialRing(QQ,2,'x,y').construction()
(LaurentPolynomialFunctor,
 Univariate Laurent Polynomial Ring in x over Rational Field)
```
fraction_field()

The fraction field is the same as the fraction field of the polynomial ring.

EXAMPLES:

```
sage: L.<x> = LaurentPolynomialRing(QQ)
sage: L.fraction_field()
Fraction Field of Univariate Polynomial Ring in x over Rational Field
sage: (x^-1 + 2) / (x - 1)
(2*x + 1)/(x^2 - x)
```

gen(i=0)

Returns the \(i^{th}\) generator of self. If \(i\) is not specified, then the first generator will be returned.

EXAMPLES:

```
sage: LaurentPolynomialRing(QQ,2,'x').gen()
x0
sage: LaurentPolynomialRing(QQ,2,'x').gen(0)
x0
sage: LaurentPolynomialRing(QQ,2,'x').gen(1)
x1
```

ideal(*args, **kwds)

EXAMPLES:

```
sage: LaurentPolynomialRing(QQ,2,'x').ideal([1])
Ideal (1) of Multivariate Laurent Polynomial Ring in x0, x1 over Rational Field
```

is_exact()

Returns True if the base ring is exact.

EXAMPLES:

```
sage: LaurentPolynomialRing(QQ,2,'x').is_exact()
True
sage: LaurentPolynomialRing(RDF,2,'x').is_exact()
False
```

is_field(proof=True)

EXAMPLES:

```
sage: LaurentPolynomialRing(QQ,2,'x').is_field()
False
```

is_finite()

EXAMPLES:

```
sage: LaurentPolynomialRing(QQ,2,'x').is_finite()
False
```

is_integral_domain(proof=True)

Returns True if self is an integral domain.

EXAMPLES:
sage: LaurentPolynomialRing(QQ, 2, 'x').is_integral_domain()
True

The following used to fail; see github issue #7530:

sage: L = LaurentPolynomialRing(ZZ, 'X')
sage: L['Y']
Univariate Polynomial Ring in Y over Univariate Laurent Polynomial Ring in X over Integer Ring

is_noetherian()
Returns True if self is Noetherian.

EXAMPLES:

sage: LaurentPolynomialRing(QQ, 2, 'x').is_noetherian()
Traceback (most recent call last):
... Not ImplementedError

krull_dimension()
EXAMPLES:

sage: LaurentPolynomialRing(QQ, 2, 'x').krull_dimension()
Traceback (most recent call last):
... Not ImplementedError

ngens()
Return the number of generators of self.

EXAMPLES:

sage: LaurentPolynomialRing(QQ, 2, 'x').ngens()
2
sage: LaurentPolynomialRing(QQ, 1, 'x').ngens()
1

polynomial_ring()
Returns the polynomial ring associated with self.

EXAMPLES:

sage: LaurentPolynomialRing(QQ, 2, 'x').polynomial_ring()
Multivariate Polynomial Ring in x0, x1 over Rational Field
sage: LaurentPolynomialRing(QQ, 1, 'x').polynomial_ring()
Multivariate Polynomial Ring in x over Rational Field

random_element(low_degree=-2, high_degree=2, terms=5, choose_degree=False, *args, **kwds)
EXAMPLES:

sage: LaurentPolynomialRing(QQ, 2, 'x').random_element()
Traceback (most recent call last):
... Not ImplementedError
.. include:: /5.2.txt

5.2 Ring of Laurent Polynomials

If \( R \) is a commutative ring, then the ring of Laurent polynomials in \( n \) variables over \( R \) is \( R[x_1^{\pm 1}, x_2^{\pm 1}, \ldots, x_n^{\pm 1}] \). We implement it as a quotient ring

\[
R[x_1, y_1, x_2, y_2, \ldots, x_n, y_n] / (x_1 y_1 - 1, x_2 y_2 - 1, \ldots, x_n y_n - 1).
\]

AUTHORS:

- David Roe (2008-2-23): created
- David Loeffler (2009-07-10): cleaned up docstrings

.. raw:: html

   <div class="highlight">
   <pre class="highlight-default">
   sage.rings.polynomial.laurent_polynomial_ring.LaurentPolynomialRing(base_ring, *args, **kwds)
   </pre>
   </div>

Return the globally unique univariate or multivariate Laurent polynomial ring with given properties and variable name or names.

There are four ways to call the Laurent polynomial ring constructor:
1. LaurentPolynomialRing(base_ring, name, sparse=False)
2. LaurentPolynomialRing(base_ring, names, order='degrevlex')
3. LaurentPolynomialRing(base_ring, name, n, order='degrevlex')
4. LaurentPolynomialRing(base_ring, n, name, order='degrevlex')

The optional arguments sparse and order must be explicitly named, and the other arguments must be given positionally.

INPUT:
- base_ring – a commutative ring
- name – a string
- names – a list or tuple of names, or a comma separated string
- n – a positive integer
- sparse – bool (default: False), whether or not elements are sparse
- order – string or TermOrder, e.g.,
  - 'degrevlex' (default) – degree reverse lexicographic
  - 'lex' – lexicographic
  - 'deglex' – degree lexicographic
  - TermOrder('deglex',3) + TermOrder('deglex',3) – block ordering

OUTPUT:
LaurentPolynomialRing(base_ring, name, sparse=False) returns a univariate Laurent polynomial ring; all other input formats return a multivariate Laurent polynomial ring.

UNIQUENESS and IMMUTABILITY: In Sage there is exactly one single-variate Laurent polynomial ring over each base ring in each choice of variable and sparseness. There is also exactly one multivariate Laurent polynomial ring over each base ring for each choice of names of variables and term order.

```sage
R.<x,y> = LaurentPolynomialRing(QQ,2); R
Multivariate Laurent Polynomial Ring in x, y over Rational Field
sage: f = x^2 - 2*y^-2
```

You can’t just globally change the names of those variables. This is because objects all over Sage could have pointers to that polynomial ring.

```
sage: R._assign_names(['z','w'])
Traceback (most recent call last):
  ... ValueError: variable names cannot be changed after object creation.
```

EXAMPLES:

1. LaurentPolynomialRing(base_ring, name, sparse=False)

```sage
LaurentPolynomialRing(QQ, 'w')
Univariate Laurent Polynomial Ring in w over Rational Field
```

Use the diamond brackets notation to make the variable ready for use after you define the ring:
sage: R.<w> = LaurentPolynomialRing(QQ)
sage: (1 + w)^3
1 + 3*w + 3*w^2 + w^3

You must specify a name:

sage: LaurentPolynomialRing(QQ)
Traceback (most recent call last):
...
TypeError: you must specify the names of the variables

sage: R.<abc> = LaurentPolynomialRing(QQ, sparse=True); R
Univariate Laurent Polynomial Ring in abc over Rational Field

sage: R.<w> = LaurentPolynomialRing(PolynomialRing(GF(7), 'k')); R
Univariate Laurent Polynomial Ring in w over Univariate Polynomial Ring in k over Finite Field of size 7

Rings with different variables are different:

sage: LaurentPolynomialRing(QQ, 'x') == LaurentPolynomialRing(QQ, 'y')
False

2. LaurentPolynomialRing(base_ring, names, order='degrevlex')

sage: R = LaurentPolynomialRing(QQ, 'a,b,c'); R
Multivariate Laurent Polynomial Ring in a, b, c over Rational Field

sage: S = LaurentPolynomialRing(QQ, ['a','b','c']); S
Multivariate Laurent Polynomial Ring in a, b, c over Rational Field

sage: T = LaurentPolynomialRing(QQ, ('a','b','c')); T
Multivariate Laurent Polynomial Ring in a, b, c over Rational Field

All three rings are identical.

sage: (R is S) and (S is T)
True

There is a unique Laurent polynomial ring with each term order:

sage: R = LaurentPolynomialRing(QQ, 'x,y,z', order='degrevlex'); R
Multivariate Laurent Polynomial Ring in x, y, z over Rational Field

sage: S = LaurentPolynomialRing(QQ, 'x,y,z', order='invlex'); S
Multivariate Laurent Polynomial Ring in x, y, z over Rational Field

sage: S is LaurentPolynomialRing(QQ, 'x,y,z', order='invlex')
True

sage: R == S
False

3. LaurentPolynomialRing(base_ring, name, n, order='degrevlex')

If you specify a single name as a string and a number of variables, then variables labeled with numbers are created.
By calling the \texttt{inject_variables()} method, all those variable names are available for interactive use:

\begin{verbatim}
  sage: R = LaurentPolynomialRing(GF(7),15,'w'); R
  Multivariate Laurent Polynomial Ring in w0, w1, w2, w3, w4, w5, w6, w7, w8, w9, w10, w11, w12, w13, w14 over Finite Field of size 7
  sage: R.inject_variables()
  Defining w0, w1, w2, w3, w4, w5, w6, w7, w8, w9, w10, w11, w12, w13, w14
  sage: (w0 + 2*w8 + w13)^2
  w0^2 + 4*w0*w8 + 4*w8^2 + 2*w0*w13 + 4*w8*w13 + w13^2
\end{verbatim}

\textbf{class} \texttt{sage.rings.polynomial.laurent_polynomial_ring.LaurentPolynomialRing_mpair}(\texttt{R})

\textbf{Bases:} \texttt{LaurentPolynomialRing_generic}

\textbf{EXAMPLES:}

\begin{verbatim}
  sage: L = LaurentPolynomialRing(QQ,2,'x')
  sage: type(L)
  <class 'sage.rings.polynomial.laurent_polynomial_ring.LaurentPolynomialRing_mpair_with_category'>
  sage: L == loads(dumps(L))
  True
\end{verbatim}

\textbf{Element}

alias of \texttt{LaurentPolynomial_mpair}

\textbf{monomial(\texttt{\textast args})}

Return the monomial whose exponents are given in argument.

\textbf{EXAMPLES:}

\begin{verbatim}
  sage: L = LaurentPolynomialRing(QQ, 'x', 2)
  sage: L.monomial(-3, 5)
  x0^(-3)*x1^5
  sage: L.monomial(1, 1)
  x0^1*x1^1
  sage: L.monomial(0, 0)
  1
  sage: L.monomial(-2, -3)
  x0^(-2)*x1^(-3)
  sage: x0, x1 = L.gens()
  sage: L.monomial(-1, 2) == x0^(-1) * x1^2
\end{verbatim}
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True

`sage`: L.monomial(1, 2, 3)
Traceback (most recent call last):
...
TypeError: tuple key must have same length as ngens

class `sage.rings.polynomial.laurent_polynomial_ring.LaurentPolynomialRing_univariate(R)`

Bases: `LaurentPolynomialRing_generic`

EXAMPLES:

```python
sage: L = LaurentPolynomialRing(QQ, 'x')
sage: type(L)
<class 'sage.rings.polynomial.laurent_polynomial_ring.LaurentPolynomialRing_univariate_with_category'>
sage: L == loads(dumps(L))
True
```

Element

alias of `LaurentPolynomial_univariate`

`sage.rings.polynomial.laurent_polynomial_ring.from_fraction_field(L, x)`

Helper function to construct a Laurent polynomial from an element of its parent’s fraction field.

INPUT:

- `L` – an instance of `LaurentPolynomialRing_generic`
- `x` – an element of the fraction field of `L`

OUTPUT:

An instance of the element class of `L`. If the denominator fails to be a unit in `L` an error is raised.

EXAMPLES:

```python
sage: from sage.rings.polynomial.laurent_polynomial_ring import from_fraction_field
sage: L.<x, y> = LaurentPolynomialRing(ZZ)
sage: F = L.fraction_field()
sage: xi = F(~x)
sage: from_fraction_field(L, xi) == ~x
True
```

`sage.rings.polynomial.laurent_polynomial_ring.is_LaurentPolynomialRing(R)`

Returns True if and only if `R` is a Laurent polynomial ring.

EXAMPLES:

```python
sage: from sage.rings.polynomial.laurent_polynomial_ring import is_LaurentPolynomialRing
sage: P = PolynomialRing(QQ, 2, 'x')
sage: is_LaurentPolynomialRing(P)
doctest:warning...
DeprecationWarning: is_LaurentPolynomialRing is deprecated; use isinstance(...,
sage.rings.polynomial.laurent_polynomial_ring_base.LaurentPolynomialRing_generic)
...%
```

5.2. Ring of Laurent Polynomials

(continues on next page)
See https://github.com/sagemath/sage/issues/35229 for details.

False

```
sage: R = LaurentPolynomialRing(QQ,3,'x')
sage: is_LaurentPolynomialRing(R)
True
```

## 5.3 Elements of Laurent polynomial rings

class `sage.rings.polynomial.laurent_polynomial.LaurentPolynomial`

Bases: `CommutativeAlgebraElement`

Base class for Laurent polynomials.

`change_ring(R)`

Return a copy of this Laurent polynomial, with coefficients in \( R \).

**EXAMPLES:**

```
sage: R.<x> = LaurentPolynomialRing(QQ)
sage: a = x^2 + 3*x^3 + 5*x^-1
sage: a.change_ring(GF(3))
2*x^-1 + x^2
```

Check that github issue #22277 is fixed:

```
sage: R.<x, y> = LaurentPolynomialRing(QQ)
sage: a = 2*x^2 + 3*x^3 + 4*x^-1
sage: a.change_ring(GF(3))
-x^2 + x^-1
```

dict()

Abstract dict method.

**EXAMPLES:**

```
sage: R.<x> = LaurentPolynomialRing(ZZ)
sage: from sage.rings.polynomial.laurent_polynomial import LaurentPolynomial
sage: LaurentPolynomial.dict(x)
Traceback (most recent call last):
  ... Not Implemented Error
```

`hamming_weight()`

Return the hamming weight of \( self \).

The hamming weight is number of non-zero coefficients and also known as the weight or sparsity.

**EXAMPLES:**

...
```python
sage: R.<x> = LaurentPolynomialRing(ZZ)
sage: f = x^3 - 1
sage: f.hamming_weight()
2
```

**map_coefficients**(*f*, **new_base_ring=None**)

Apply *f* to the coefficients of *self*.

If *f* is a `sage.categories.map.Map`, then the resulting polynomial will be defined over the codomain of *f*. Otherwise, the resulting polynomial will be over the same ring as *self*. Set **new_base_ring** to override this behavior.

**INPUT:**

- *f* -- a callable that will be applied to the coefficients of *self*.
- **new_base_ring** (optional) -- if given, the resulting polynomial will be defined over this ring.

**EXAMPLES:**

```python
sage: k.<a> = GF(9)
sage: R.<x> = LaurentPolynomialRing(k)
sage: f = x*a + a
sage: f.map_coefficients(lambda a : a + 1)
(a + 1) + (a + 1)*x
sage: R.<x,y> = LaurentPolynomialRing(k, 2)
sage: f = x*a + 2*x^3*y*a + a
sage: f.map_coefficients(lambda a : a + 1)
(2*a + 1)*x^3*y + (a + 1)*x + a + 1
```

Examples with different base ring:

```python
sage: R.<r> = GF(9); S.<s> = GF(81)
sage: h = Hom(R,S)[0]; h
Ring morphism:
  From: Finite Field in r of size 3^2
  To:   Finite Field in s of size 3^4
  Defn: r |--> 2*s^3 + 2*s^2 + 1
sage: T.<X,Y> = LaurentPolynomialRing(R, 2)
sage: f = r*X+Y
sage: g = f.map_coefficients(h); g
(2*s^3 + 2*s^2 + 1)*X + Y
sage: g.parent()
Multivariate Laurent Polynomial Ring in X, Y over Finite Field in s of size 3^4
sage: h = lambda x: x.trace()
sage: g = f.map_coefficients(h); g
X - Y
sage: g.parent()
Multivariate Laurent Polynomial Ring in X, Y over Finite Field of size 3
```

**number_of_terms**()

Abstract method for number of terms

5.3. Elements of Laurent polynomial rings
EXAMPLES:

```python
sage: R.<x> = LaurentPolynomialRing(ZZ)
sage: from sage.rings.polynomial.laurent_polynomial import LaurentPolynomial
sage: LaurentPolynomial.number_of_terms(x)
Traceback (most recent call last):
  ... 
NotImplementedError
```

```python
class sage.rings.polynomial.laurent_polynomial.LaurentPolynomial_mpair
    Bases: LaurentPolynomial

    Multivariate Laurent polynomials.

    coefficient(mon)
    Return the coefficient of mon in self, where mon must have the same parent as self.
    The coefficient is defined as follows. If f is this polynomial, then the coefficient c_m is sum:
    
    \[ c_m := \sum_T T \frac{m}{m} \]
    
    where the sum is over terms T in f that are exactly divisible by m.
    A monomial m(x, y) 'exactly divides' f(x, y) if m(x, y)|f(x, y) and neither x·m(x, y) nor y·m(x, y) divides f(x, y).
    INPUT:
    • mon – a monomial
    OUTPUT:
    Element of the parent of self.
```

Note: To get the constant coefficient, call `constant_coefficient()`.

EXAMPLES:

```python
sage: P.<x,y> = LaurentPolynomialRing(QQ)
```

The coefficient returned is an element of the parent of self; in this case, P.

```python
sage: f = 2 * x * y
sage: c = f.coefficient(x*y); c
2
sage: c.parent()
Multivariate Laurent Polynomial Ring in x, y over Rational Field
```

```python
sage: f = (y^2 - x^9 - 7*x*y^2 + 5*x*y)*x^-3; f
-x^6 - 7*x^-2*y^2 + 5*x^-2*y + x^-3*y^2
sage: f.coefficient(y)
5*x^-2
sage: f.coefficient(y^2)
-7*x^-2 + x^-3
sage: f.coefficient(x*y)
(continues on next page)
```

(continues on next page)
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(continued from previous page)

\[
\begin{align*}
0 \\
sage: & f.coefficient(x^-2) \\
& -7*y^2 + 5*y \\
sage: & f.coefficient(x^-2*y^2) \\
& -7 \\
sage: & f.coefficient(1) \\
& -x^6 - 7*x^-2*y^2 + 5*x^-2*y + x^-3*y^2
\end{align*}
\]

coefficients()

Return the nonzero coefficients of self in a list.

The returned list is decreasingly ordered by the term ordering of self.parent().

EXAMPLES:

\[
\begin{align*}
sage: & L.<x,y,z> = LaurentPolynomialRing(QQ,order='degrevlex') \\
sage: & f = 4*x^7*z^-1 + 3*x^3*y + 2*x^4*z^-2 + x^6*y^-7 \\
sage: & f.coefficients() \\
& [4, 3, 2, 1] \\
sage: & L.<x,y,z> = LaurentPolynomialRing(QQ,order='lex') \\
sage: & f = 4*x^7*z^-1 + 3*x^3*y + 2*x^4*z^-2 + x^6*y^-7 \\
sage: & f.coefficients() \\
& [4, 1, 2, 3]
\end{align*}
\]

costant_coefficient()

Return the constant coefficient of self.

EXAMPLES:

\[
\begin{align*}
sage: & P.<x,y> = LaurentPolynomialRing(QQ) \\
sage: & f = (y^2 - x^9 - 7*x*y^2 + 5*x*y)*x^-3; f \\
& -x^6 - 7*x^-2*y^2 + 5*x^-2*y + x^-3*y^2 \\
sage: & f.constant_coefficient() \\
& 0 \\
sage: & f = (x^3 + 2*x^-2*y+y^3)*y^-3; f \\
& x^3*y^-3 + 1 + 2*x^-2*y^-2 \\
sage: & f.constant_coefficient() \\
& 1
\end{align*}
\]

degree(x=None)

Return the degree of x in self.

EXAMPLES:

\[
\begin{align*}
sage: & R.<x,y,z> = LaurentPolynomialRing(QQ) \\
sage: & f = 4*x^7*z^-1 + 3*x^3*y + 2*x^4*z^-2 + x^6*y^-7 \\
sage: & f.degree(x) \\
& 7 \\
sage: & f.degree(y) \\
& 1 \\
sage: & f.degree(z) \\
& 0
\end{align*}
\]

5.3. Elements of Laurent polynomial rings
derivative(*args)

The formal derivative of this Laurent polynomial, with respect to variables supplied in args.

Multiple variables and iteration counts may be supplied; see documentation for the global derivative() function for more details.

See also:
_.derivative()

EXAMPLES:

```python
sage: R = LaurentPolynomialRing(ZZ, 'x, y')
sage: x, y = R.gens()
sage: t = x**4*y + x*y + y + x**(-1) + y**(-3)
sage: t.derivative(x, x)
12*x^2*y + 2*x^-3
sage: t.derivative(y, 2)
12*y^-5
```

dict()

Return self represented as a dict.

EXAMPLES:

```python
sage: L.<x,y,z> = LaurentPolynomialRing(QQ)
sage: f = 4*x^7*z^-1 + 3*x^3*y + 2*x^4*z^-2 + x^6*y^-7
sage: sorted(f.dict().items())
[((3, 1, 0), 3), ((4, 0, -2), 2), ((6, -7, 0), 1), ((7, 0, -1), 4)]
```

diff(*args)

The formal derivative of this Laurent polynomial, with respect to variables supplied in args.

Multiple variables and iteration counts may be supplied; see documentation for the global derivative() function for more details.

See also:
_.derivative()

EXAMPLES:

```python
sage: R = LaurentPolynomialRing(ZZ, 'x, y')
sage: x, y = R.gens()
sage: t = x**4*y + x*y + y + x**(-1) + y**(-3)
sage: t.derivative(x, x)
12*x^2*y + 2*x^-3
sage: t.derivative(y, 2)
12*y^-5
```

differentiate(*args)

The formal derivative of this Laurent polynomial, with respect to variables supplied in args.

Multiple variables and iteration counts may be supplied; see documentation for the global derivative() function for more details.

See also:
_.derivative()
EXAMPLES:

```sage
sage: R = LaurentPolynomialRing(ZZ, 'x, y')
sage: x, y = R.gens()
sage: t = x**4*y+x*y+y+x**(-1)+y**(-3)
sage: t.derivative(x, x)
12*x^2*y + 2*x^-3
sage: t.derivative(y, 2)
12*y^-5
```

**exponents()**

Return a list of the exponents of self.

EXAMPLES:

```sage
sage: L.<w,z> = LaurentPolynomialRing(QQ)
sage: a = w^2*z^-1+3; a
w^2*z^-1 + 3
sage: e = a.exponents()
sage: e.sort(); e
[(0, 0), (2, -1)]
```

**factor()**

Returns a Laurent monomial (the unit part of the factorization) and a factored multi-polynomial.

EXAMPLES:

```sage
sage: L.<x,y,z> = LaurentPolynomialRing(QQ)
sage: f = 4*x^7*z^-1 + 3*x^3*y + 2*x^4*z^-2 + x^6*y^-7
sage: f.factor()
(x^3*y^-7*z^-2) * (4*x^4*y^7*z + 3*y^8*z^2 + 2*x*y^7 + x^3*z^2)
```

**has_any_inverse()**

Returns True if self contains any monomials with a negative exponent, False otherwise.

EXAMPLES:

```sage
sage: L.<x,y,z> = LaurentPolynomialRing(QQ)
sage: f = 4*x^7*z^-1 + 3*x^3*y + 2*x^4*z^-2 + x^6*y^-7
sage: f.has_any_inverse()
True
sage: g = x^2 + y^2
sage: g.has_any_inverse()
False
```

**has_inverse_of(i)**

INPUT:

- i – The index of a generator of self.parent()

OUTPUT:

Returns True if self contains a monomial including the inverse of self.parent().gen(i), False otherwise.

EXAMPLES:

```sage
```

5.3. Elements of Laurent polynomial rings 573
### is_constant()

Return whether this Laurent polynomial is constant.

**EXAMPLES:**

```python
sage: L.<a, b> = LaurentPolynomialRing(QQ)
sage: L(0).is_constant()  # True
sage: L(42).is_constant()   # True
sage: a.is_constant()      # False
sage: (1/b).is_constant()  # False
```

### is_monomial()

Return True if self is a monomial.

**EXAMPLES:**

```python
sage: k.<y,z> = LaurentPolynomialRing(QQ)
sage: z.is_monomial()  # True
sage: k(1).is_monomial()  # True
sage: (z+1).is_monomial()  # False
sage: (z^-2909).is_monomial()  # True
sage: (38*z^-2909).is_monomial()  # False
```

### is_square(root=False)

Test whether this Laurent polynomial is a square.

**INPUT:**

* root - boolean (default False) - if set to True then return a pair (True, sqrt) with sqrt a square root of this Laurent polynomial when it exists or (False, None).

**EXAMPLES:**

```python
sage: L.<x,y,z> = LaurentPolynomialRing(QQ)
sage: p = (1 + x*y + z^-3)
sage: (p**2).is_square()   # True
```
is_unit()

Return True if self is a unit.

The ground ring is assumed to be an integral domain.

This means that the Laurent polynomial is a monomial with unit coefficient.

EXAMPLES:

```python
sage: L.<x,y> = LaurentPolynomialRing(QQ)
sage: (x*y/2).is_unit()
True
sage: (x + y).is_unit()
False
sage: (L.zero()).is_unit()
False
sage: (L.one()).is_unit()
True
```

is_univariate()

Return True if this is a univariate or constant Laurent polynomial, and False otherwise.

EXAMPLES:

```python
sage: R.<x,y,z> = LaurentPolynomialRing(QQ)
sage: f = (x^3 + y^-3)*z
sage: f.is_univariate()
False
sage: g = f(1,y,4)
sage: g.is_univariate()
True
sage: R(1).is_univariate()
True
```

iterator_exp_coeff()

Iterate over self as pairs of (ETuple, coefficient).

EXAMPLES:
Polynomials, Release 10.0

```
sage: P.<x,y> = LaurentPolynomialRing(QQ)
sage: f = (y^2 - x^9 - 7*x*y^3 + 5*x*y)*x^-3
sage: list(f.iterator_exp_coeff())
[[(6, 0), -1], ((-2, 3), -7), ((-2, 1), 5), ((-3, 2), 1)]
```

**monomial_coefficient**(mon)

Return the coefficient in the base ring of the monomial mon in self, where mon must have the same parent as self.

This function contrasts with the function **coefficient()** which returns the coefficient of a monomial viewing this polynomial in a polynomial ring over a base ring having fewer variables.

**INPUT:**

- mon – a monomial

**See also:**

For coefficients in a base ring of fewer variables, see **coefficient()**.

**EXAMPLES:**

```
sage: P.<x,y> = LaurentPolynomialRing(QQ)
sage: f = (y^2 - x^9 - 7*x*y^3 + 5*x*y)*x^-3
sage: f.monomial_coefficient(x^-2*y^3)
-7
sage: f.monomial_coefficient(x^2)
0
```

**monomials()**

Return the list of monomials in self.

**EXAMPLES:**

```
sage: P.<x,y> = LaurentPolynomialRing(QQ)
sage: f = (y^2 - x^9 - 7*x*y^3 + 5*x*y)*x^-3
sage: sorted(f.monomials())
x^-3*y^2, x^-2*y, x^-2*y^3, x^6
```

**number_of_terms()**

Return the number of non-zero coefficients of self.

Also called weight, hamming weight or sparsity.

**EXAMPLES:**

```
sage: R.<x, y> = LaurentPolynomialRing(ZZ)
sage: f = x^3 - y
sage: f.number_of_terms()
2
sage: R(0).number_of_terms()
0
sage: f = (x+1/y)^100
sage: f.number_of_terms()
101
```

The method **hamming_weight()** is an alias:
Polynomials, Release 10.0

```
sage: f.hamming_weight()
101
```

**quो_rem** *(right)*

Divide this Laurent polynomial by *right* and return a quotient and a remainder.

**INPUT:**

- *right* – a Laurent polynomial

**OUTPUT:**

A pair of Laurent polynomials.

**EXAMPLES:**

```
sage: R.<s, t> = LaurentPolynomialRing(QQ)
sage: (s^2-t^2).quo_rem(s-t)
(s + t, 0)
sage: (s^-2-t^2).quo_rem(s-t)
(s + t, -s^2 + s^-2)
sage: (s^-2-t^2).quo_rem(s^-1-t)
(t + s^-1, 0)
```

**rescale_vars** *(d, h=None, new_ring=None)*

Rescale variables in a Laurent polynomial.

**INPUT:**

- *d* – a dict whose keys are the generator indices and values are the coefficients; so a pair *(i, v)* means \(x_i \mapsto vx_i\)
- *h* – (optional) a map to be applied to coefficients done after rescaling
- *new_ring* – (optional) a new ring to map the result into

**EXAMPLES:**

```
sage: L.<x,y> = LaurentPolynomialRing(QQ, 2)
sage: p = x^-2*y + x*y^-2
sage: p.rescale_vars({0: 2, 1: 3})
2/9*x*y^-2 + 3/4*x^-2*y
sage: F = GF(2)
sage: p.rescale_vars({0: 3, 1: 7}, new_ring=L.change_ring(F))
x*y^-2 + x^-2*y
```

Test for github issue #30331:

```
sage: F.<z> = CyclotomicField(3)
sage: p.rescale_vars({0: 2, 1: z}, new_ring=L.change_ring(F))
2*z*x*y^-2 + 1/4*z^3*x^-2*y
```

**subs** *(in_dict=None, **kwds)*

Substitute some variables in this Laurent polynomial.

Variable/value pairs for the substitution may be given as a dictionary or via keyword-value pairs. If both are present, the latter take precedence.

**INPUT:**

```
• \texttt{in\_dict} – dictionary (optional)
• **\texttt{kwargs} – keyword arguments

OUTPUT:
A Laurent polynomial.

EXAMPLES:

```python
sage: L.<x, y, z> = LaurentPolynomialRing(QQ)
sage: f = x + 2*y + 3*z
sage: f.subs(x=1)
2*y + 3*z + 1
sage: f.subs(y=1)
x + 3*z + 2
sage: f.subs(z=1)
x + 2*y + 3
sage: f.subs(x=1, y=1, z=1)
6
sage: f = x^-1
sage: f.subs(x=2)
1/2
sage: f.subs({x: 2})
1/2
sage: f = x + 2*y + 3*z
sage: f.subs({x: 1, y: 1, z: 1})
6
sage: f.substitute(x=1, y=1, z=1)
6
```

\textit{toric\_coordinate\_change}( M, h=\text{None}, new\_ring=\text{None})

Apply a matrix to the exponents in a Laurent polynomial.

For efficiency, we implement this directly, rather than as a substitution.

The optional argument h is a map to be applied to coefficients.

EXAMPLES:

```python
sage: L.<x, y> = LaurentPolynomialRing(QQ, 2)
sage: p = 2*x^2 + y - x*y
sage: p.toric_coordinate_change(Matrix([[1, -3], [1, 1]]))
2*x^2*y^2 - x^-2*y^2 + x^-3*y
sage: F = GF(2)
sage: p.toric_coordinate_change(Matrix([[1, -3], [1, 1]]), new_ring=L.change_ring(F))
x^-2*y^2 + x^-3*y
```

\textit{toric\_substitute}(v, v1, a, h=\text{None}, new\_ring=\text{None})

Perform a single-variable substitution up to a toric coordinate change.

The optional argument h is a map to be applied to coefficients.

EXAMPLES:
univariate_polynomial\( (R=\text{None}) \)

Returns a univariate polynomial associated to this multivariate polynomial.

INPUT:

- \( R \) - (default: \text{None}) a univariate Laurent polynomial ring

If this polynomial is not in at most one variable, then a \text{ValueError} exception is raised. The new polynomial is over the same base ring as the given \texttt{LaurentPolynomial} and in the variable \( x \) if no ring \( R \) is provided.

EXAMPLES:

```python
sage: R.<x, y> = LaurentPolynomialRing(ZZ)
sage: f = 3*x^2 - 2*y^-1 + 7*x^2*y^2 + 5
sage: f.univariate_polynomial()
Traceback (most recent call last):
  ...
TypeError: polynomial must involve at most one variable
sage: g = f(10, y); g
700*y^2 + 305 - 2*y^-1
sage: h = g.univariate_polynomial(); h
-2*y^-1 + 305 + 700*y^2
sage: h.parent()
Univariate Laurent Polynomial Ring in y over Integer Ring
sage: g.univariate_polynomial(LaurentPolynomialRing(QQ,'z'))
-2*z^-1 + 305 + 700*z^2
```

Here’s an example with a constant multivariate polynomial:

```python
sage: g = R(1)
sage: h = g.univariate_polynomial(); h
1
sage: h.parent()
Univariate Laurent Polynomial Ring in x over Integer Ring
```

variables\( (\text{sort=True}) \)

Return a tuple of all variables occurring in \texttt{self}.

INPUT:

- \text{sort} – specifies whether the indices shall be sorted

EXAMPLES:

```python
sage: L.<x,y,z> = LaurentPolynomialRing(QQ)
sage: f = 4*x^7*z^-1 + 3*x^3*y + 2*x^4*z^-2 + x^6*y^-7
sage: f.variables()
```

(continues on next page)
\[(z, y, x)\]
\[
sage: f.variables(sort=False) \# random\]
\[(y, z, x)\]

**class sage.rings.polynomial.laurent_polynomial.LaurentPolynomial_univariate**

Bases: *LaurentPolynomial*

A univariate Laurent polynomial in the form of \( t^n \cdot f \) where \( f \) is a polynomial in \( t \).

**INPUT:**

- `parent` – a Laurent polynomial ring
- `f` – a polynomial (or something can be coerced to one)
- `n` – (default: 0) an integer

**AUTHORS:**

- Tom Boothby (2011) copied this class almost verbatim from `laurent_series_ring_element.pyx`, so most of the credit goes to William Stein, David Joyner, and Robert Bradshaw
- Travis Scrimshaw (09-2013): Cleaned-up and added a few extra methods

**coefficients()**

Return the nonzero coefficients of `self`.

**EXAMPLES:**

\[
sage: R.<t> = LaurentPolynomialRing(QQ)
sage: f = -5/t^2 + t + t^2 - 10/3*t^3
sage: f.coefficients()
\[-5, 1, 1, -10/3\]
\]

**constant_coefficient()**

Return the coefficient of the constant term of `self`.

**EXAMPLES:**

\[
sage: R.<t> = LaurentPolynomialRing(QQ)
sage: f = 3*t^-2 - t^-1 + 3 + t^2
sage: f.constant_coefficient()
3
sage: g = -2*t^-2 + t^-1 + 3*t
sage: g.constant_coefficient()
0
\]

**degree()**

Return the degree of `self`.

**EXAMPLES:**

\[
sage: R.<x> = LaurentPolynomialRing(ZZ)
sage: g = x^2 - x^4
sage: g.degree()
4
sage: g = -10/x^5 + x^2 - x^7
\]

(continues on next page)
derivative(*args)

The formal derivative of this Laurent polynomial, with respect to variables supplied in args.

Multiple variables and iteration counts may be supplied. See documentation for the global derivative() function for more details.

See also:

_derivative()

EXAMPLES:

sage: R.<x> = LaurentPolynomialRing(QQ)
sage: g = 1/x^10 - x + x^2 - x^4
sage: g.derivative()
-10*x^-11 - 1 + 2*x - 4*x^3
sage: g.derivative(x)
-10*x^-11 - 1 + 2*x - 4*x^3

sage: R.<t> = PolynomialRing(ZZ)
sage: S.<x> = LaurentPolynomialRing(R)
sage: f = 2*t/x + (3*t^2 + 6*t)*x
sage: f.derivative()
-2*t*x^-2 + (3*t^2 + 6*t)
sage: f.derivative(x)
-2*t*x^-2 + (3*t^2 + 6*t)
sage: f.derivative(t)
2*x^-1 + (6*t + 6)*x

dict()

Return a dictionary representing self.

EXAMPLES:

sage: R.<x,y> = ZZ[]
sage: Q.<t> = LaurentPolynomialRing(R)
sage: f = (x^3 + y/t^3)^3 + t^2; f
y^3*t^-9 + 3*x^3*y*t^-6 + 3*x^6*y^2*t^-3 + x^9 + t^2
sage: f.dict()
{-9: y^3, -6: 3*x^3*y, -3: 3*x^6*y^2, 0: x^9, 2: 1}

exponents()

Return the exponents appearing in self with nonzero coefficients.

EXAMPLES:

sage: R.<t> = LaurentPolynomialRing(QQ)
sage: f = -5/t^(2) + t + t^2 - 10/3*t^3
sage: f.exponents()
[-2, 1, 2, 3]
factor()  
Return a Laurent monomial (the unit part of the factorization) and a factored polynomial.

EXAMPLES:

```python
sage: R.<t> = LaurentPolynomialRing(ZZ)
sage: f = 4*t^-7 + 3*t^3 + 2*t^4 + t^-6
sage: f.factor()
(t^-7) * (4 + t + 3*t^10 + 2*t^11)
```

gcd(right)  
Return the gcd of self with right where the common divisor d makes both self and right into polynomials with the lowest possible degree.

EXAMPLES:

```python
sage: R.<t> = LaurentPolynomialRing(QQ)
sage: t.gcd(2)
1
sage: gcd(t^-2 + 1, t^-4 + 3*t^-1)
t^-4
sage: gcd((t^-2 + t)*(t + t^-1), (t^5 + t^8)*(1 + t^-2))
t^-3 + t^-1 + 1 + t^2
```

integral()  
The formal integral of this Laurent series with 0 constant term.

EXAMPLES:

The integral may or may not be defined if the base ring is not a field.

```python
sage: t = LaurentPolynomialRing(ZZ, 't').0
sage: f = 2*t^-3 + 3*t^2
sage: f.integral()
-t^-2 + t^3
sage: f = t^3
sage: f.integral()
Traceback (most recent call last):
... ArithmeticError: coefficients of integral cannot be coerced into the base ring
```

The integral of \(1/t\) is \(\log(t)\), which is not given by a Laurent polynomial:

```python
sage: t = LaurentPolynomialRing(ZZ, 't').0
sage: f = -1/t^3 - 31/t
sage: f.integral()
Traceback (most recent call last):
... ArithmeticError: the integral of is not a Laurent polynomial, since \(t^{-1}\) has nonzero coefficient
```

Another example with just one negative coefficient:
```python
sage: A.<t> = LaurentPolynomialRing(QQ)
sage: f = -2*t^(-4)
sage: f.integral()
2/3*t^-3
sage: f.integral().derivative() == f
True
```

**inverse_of_unit()**

Return the inverse of self if a unit.

**EXAMPLES:**

```python
sage: R.<t> = LaurentPolynomialRing(QQ)
sage: (t^-2).inverse_of_unit()
t^2
sage: (t + 2).inverse_of_unit()
```

```
Traceback (most recent call last):
...
ArithmeticError: element is not a unit
```

**is_constant()**

Return whether this Laurent polynomial is constant.

**EXAMPLES:**

```python
sage: R.<x> = LaurentPolynomialRing(QQ)
sage: x.is_constant()
False
sage: R.one().is_constant()
True
sage: (x^-2).is_constant()
False
sage: (x^2).is_constant()
False
sage: (x^-2 + 2).is_constant()
False
sage: R(0).is_constant()
True
sage: R(42).is_constant()
True
sage: x.is_constant()
False
sage: (1/x).is_constant()
False
```

**is_monomial()**

Return True if self is a monomial; that is, if self is \(x^n\) for some integer \(n\).

**EXAMPLES:**

```python
sage: k.<z> = LaurentPolynomialRing(QQ)
sage: z.is_monomial()
True
sage: k(1).is_monomial()
```

(continues on next page)
is_square(root=False)

Return whether this Laurent polynomial is a square.

If root is set to True then return a pair made of the boolean answer together with None or a square root.

EXAMPLES:

```
sage: R.<t> = LaurentPolynomialRing(QQ)
sage: R.one().is_square()  # True
sage: R(2).is_square()      # False
sage: t.is_square()        # False
sage: (t**-2).is_square()  # True
```

Usage of the root option:

```
sage: p = (1 + t^-1 - 2*t^3)
sage: p.is_square(root=True)  # (False, None)
sage: (p**2).is_square(root=True)  # (True, -t^-1 - 1 + 2*t^3)
```

The answer is dependent of the base ring:

```
sage: S.<u> = LaurentPolynomialRing(QQbar)
sage: (2 + 4*u + 2*u^2).is_square()  # False
sage: (2 + 4*u + 2*u^2).is_square()  # True
```

is_unit()

Return True if this Laurent polynomial is a unit in this ring.

EXAMPLES:

```
sage: R.<t> = LaurentPolynomialRing(QQ)
sage: (2+t).is_unit()  # False
sage: f = 2*t
sage: f.is_unit()     # True
```

(continued from previous page)
sage: 1/f
1/2*t^-1
sage: R(0).is_unit()
False
sage: R.<s> = LaurentPolynomialRing(ZZ)
sage: g = 2*s
sage: g.is_unit()
False
sage: 1/g
1/2*s^-1

ALGORITHM: A Laurent polynomial is a unit if and only if its “unit part” is a unit.

is_zero()
Return 1 if self is 0, else return 0.

EXAMPLES:

sage: R.<x> = LaurentPolynomialRing(QQ)
sage: f = 1/x + x + x^2 + 3*x^4
sage: f.is_zero()
0
sage: z = 0*f
sage: z.is_zero()
1

number_of_terms()
Return the number of non-zero coefficients of self.
Also called weight, hamming weight or sparsity.

EXAMPLES:

sage: R.<x> = LaurentPolynomialRing(ZZ)
sage: f = x^3 - 1
sage: f.number_of_terms()
2
sage: R(0).number_of_terms()
0
sage: f = (x+1)^100
sage: f.number_of_terms()
101

The method hamming_weight() is an alias:

sage: f.hamming_weight()
101

polynomial_construction()
Return the polynomial and the shift in power used to construct the Laurent polynomial \( t^n u \).

OUTPUT:
A tuple \((u, n)\) where \( u \) is the underlying polynomial and \( n \) is the power of the exponent shift.

EXAMPLES:
```sage
R.<x> = LaurentPolynomialRing(QQ)
f = 1/x + x^2 + 3*x^4
f.polynomial_construction()
(3*x^5 + x^3 + 1, -1)
```

**quo_rem(other)**

Divide self by other and return a quotient q and a remainder r such that self == q * other + r.

**EXAMPLES:**

```sage
R.<t> = LaurentPolynomialRing(QQ)
(t^-3 - t^3).quo_rem(t^-1 - t)
(t^-2 + 1 + t^2, 0)
(t^-2 + 3 + t).quo_rem(t^-4)
(t^2 + 3*t^4 + t^5, 0)
n = t^-2 + t
d = t^-2 + 1
g, r = n.quo_rem(d)
q, r = n.quo_rem(d)
num == q * den + r
True
```

**residue()**

Return the residue of self.

The residue is the coefficient of \( t^{-1} \).

**EXAMPLES:**

```sage
R.<t> = LaurentPolynomialRing(QQ)
f = 3*t^-2 - t^-1 + 3 + t^2
f.residue()
-1
g = -2*t^-2 + 4 + 3*t
g.residue()
0
f.residue().parent()
Rational Field
```

**shift(k)**

Return this Laurent polynomial multiplied by the power \( t^n \). Does not change this polynomial.

**EXAMPLES:**

```sage
R.<t> = LaurentPolynomialRing(QQ['y'])
f = (t+t^-1)^4
f
```

```sage
f.shift(10)
t^-14 + 4*t^-12 + 6*t^-10 + 4*t^-8 + t^-6
f >> 10
```

```sage
1 + 4*t^2 + 6*t^4 + 4*t^6 + t^8
```
\texttt{truncate}(n)

Return a polynomial with degree at most \( n - 1 \) whose \( j \)-th coefficients agree with \texttt{self} for all \( j < n \).

\textbf{EXAMPLES:}

```
sage: R.<x> = Laurent Polynomial Ring(QQ)
sage: f = 1/x^12 + x^3 + x^5 + x^9
sage: f.truncate(10)
x^-12 + x^3 + x^5 + x^9
sage: f.truncate(5)
x^-12 + x^3
sage: f.truncate(-16)
0
```

\texttt{valuation}(p=\texttt{None})

Return the valuation of \texttt{self}.

The valuation of a Laurent polynomial \( t^n u \) is \( n \) plus the valuation of \( u \).

\textbf{EXAMPLES:}

```
sage: R.<x> = Laurent Polynomial Ring(ZZ)
sage: f = 1/x + x^2 + 3x^4
sage: g = 1 - x + x^2 - x^4
sage: f.valuation()
-1
sage: g.valuation()
0
```

\texttt{variable name}()

Return the name of variable of \texttt{self} as a string.

\textbf{EXAMPLES:}

```
sage: R.<x> = Laurent Polynomial Ring(QQ)
sage: f = 1/x + x^2 + 3x^4
sage: f.variable_name()
'x'
```

\texttt{variables}()

Return the tuple of variables occurring in this Laurent polynomial.

\textbf{EXAMPLES:}

```
sage: R.<x> = Laurent Polynomial Ring(QQ)
sage: f = 1/x + x^2 + 3x^4
sage: f.variables()
(x,)
sage: R.one().variables()
()
5.4 MacMahon’s Partition Analysis Omega Operator

This module implements MacMahon’s Omega Operator [Mac1915], which takes a quotient of Laurent polynomials and removes all negative exponents in the corresponding power series.

5.4.1 Examples

In the following example, all negative exponents of \( \mu \) are removed. The formula

\[
\Omega \geq \frac{1}{(1-x\mu)(1-y/\mu)} = \frac{1}{(1-x)(1-xy)}
\]

can be calculated and verified by

```sage
L.<mu, x, y> = LaurentPolynomialRing(ZZ)
sage: MacMahonOmega(mu, 1, [1 - x*mu, 1 - y/mu])
1 * (-x + 1)^-1 * (-x*y + 1)^-1
```

5.4.2 Various

AUTHORS:

• Daniel Krenn (2016)

ACKNOWLEDGEMENT:

• Daniel Krenn is supported by the Austrian Science Fund (FWF): P 24644-N26.

5.4.3 Functions

`sage.rings.polynomial.omega.MacMahonOmega`(var, expression, denominator=None, op=<built-in function \( \ge \)>, Factorization_sort=False, Factorization_simplify=True)

Return \( \Omega_{\text{op}} \) of expression with respect to var.

To be more precise, calculate

\[
\Omega_{\text{op}} \frac{n}{d_1 \ldots d_n}
\]

for the numerator \( n \) and the factors \( d_1, \ldots, d_n \) of the denominator, all of which are Laurent polynomials in var and return a (partial) factorization of the result.

INPUT:

• var – a variable or a representation string of a variable

• expression – a Factorization of Laurent polynomials or, if denominator is specified, a Laurent polynomial interpreted as the numerator of the expression

• denominator – a Laurent polynomial or a Factorization (consisting of Laurent polynomial factors) or a tuple/list of factors (Laurent polynomials)

• op – (default: operator.ge) an operator

At the moment only operator.ge is implemented.
• Factorization_sort (default: False) and Factorization_simplify (default: True) – are passed on to sage.structure.factorization.Factorization when creating the result

OUTPUT:

A (partial) Factorization of the result whose factors are Laurent polynomials

Note: The numerator of the result may not be factored.

REFERENCES:

• [Mac1915]
• [APR2001]

EXAMPLES:

\begin{verbatim}
sage: L.<mu, x, y, z, w> = LaurentPolynomialRing(ZZ)
sage: MacMahonOmega(mu, 1, [1 - x*mu, 1 - y/mu])
1 * (-x + 1)^-1 * (-x*y + 1)^-1
sage: MacMahonOmega(mu, 1, [1 - x*mu, 1 - y/mu, 1 - z/mu])
1 * (-x + 1)^-1 * (-x*y + 1)^-1 * (-x*z + 1)^-1
sage: MacMahonOmega(mu, 1, [1 - x*mu, 1 - y/mu, 1 - y^mu, 1 - z/mu])
(-x*y*z + 1) * (-y + 1)^-1 * (-y*z + 1)^-1 * (-y^z + 1)^-1
sage: MacMahonOmega(mu, 1, [1 - x*mu, 1 - y/mu^2])
1 * (-x + 1)^-1 * (-x^2*y + 1)^-1
sage: MacMahonOmega(mu, 1, [1 - x*mu, 1 - y/mu^2, 1 - y/mu])
(x^2*y + 1) * (-x + 1)^-1 * (-x*y^2 + 1)^-1
sage: MacMahonOmega(mu, 1, [1 - x*mu, 1 - y/mu^3])
(-x*y^3 + 1) * (-x^3*y + 1)^-1
sage: MacMahonOmega(mu, 1, [1 - x*mu, 1 - y/mu^4])
1 * (-x + 1)^-1 * (-x^4*y + 1)^-1
sage: MacMahonOmega(mu, 1, [1 - x*mu^3, 1 - y/mu])
(x*y^2 + x*y + 1) * (-x + 1)^-1 * (-x*y^3 + 1)^-1
sage: MacMahonOmega(mu, 1, [1 - x*mu^4, 1 - y/mu])
(x*y^3 + x*y^2 + 1)^-1 * (-x + 1)^-1 * (-x*y^4 + 1)^-1
sage: MacMahonOmega(mu, 1, [1 - x*mu^2, 1 - y/mu, 1 - z/mu])
(x^2*y + x*y + x*z + 1) * (-x + 1)^-1 * (-x*y^2 + 1)^-1
sage: MacMahonOmega(mu, 1, [1 - x*mu^2, 1 - y/mu, 1 - y^mu, 1 - z/mu])
(-x*y^z^2 - x*y^z + x*z + 1) * (-x + 1)^-1 * (-x^y*z + 1)^-1
sage: MacMahonOmega(mu, 1, [1 - x*mu^2, 1 - y/mu, 1 - y^mu, 1 - y^mu])
(-x*y^z^2 + x*y^z + x*z + 1) * (-x + 1)^-1 * (-x^y*z + 1)^-1
sage: MacMahonOmega(mu, 1, [1 - x*mu^2, 1 - y/mu^2, 1 - y^mu, 1 - y^mu])
(-x^y^z^w + x*y^z^w + x*z^w + 1) * (-x + 1)^-1 * (-x^y^z^w + 1)^-1
\end{verbatim}
We demonstrate the different allowed input variants:

```
sage: MacMahonOmega(mu, mu^2, 
....:                  Factorization(
....:                        [(1 - x*mu)^2, (1 - y/mu)^2]))
(-x*y^2 - x*y + y^2 + y + 1) * (-x + 1)^-1 * (-x*y + 1)^-1
```

```
sage: MacMahonOmega(mu, mu^2 / ((1 - x*mu)^2 / (1 - y/mu)))  
# not tested because not fully implemented
(-x*y^2 - x*y + y^2 + y + 1) * (-x + 1)^-1 * (-x*y + 1)^-1
```

`sage.rings.polynomial.omega.Omega_ge(exponents)`

Return $\Omega_\geq$ of the expression specified by the input.

To be more precise, calculate

$$\Omega_\geq \frac{\mu^n}{(1-z_0\mu^{e_0})...(1-z_{n-1}\mu^{e_{n-1}})}$$

and return its numerator and a factorization of its denominator. Note that $z_0, \ldots, z_{n-1}$ only appear in the output, but not in the input.

**INPUT:**

- a – an integer
- exponents – a tuple of integers

**OUTPUT:**

A pair representing a quotient as follows: Its first component is the numerator as a Laurent polynomial, its second component a factorization of the denominator as a tuple of Laurent polynomials, where each Laurent polynomial $z$ represents a factor $1 - z$.

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The parents of these Laurent polynomials is always a Laurent polynomial ring in $z_0, \ldots, z_{n-1}$ over $\mathbb{Z}$, where $n$ is the length of exponents.

EXAMPLES:

```
sage: from sage.rings.polynomial.omega import Omega_ge
sage: Omega_ge(0, (1, -2))
(1, (z0, z0^2*z1))
sage: Omega_ge(0, (1, -3))
(1, (z0, z0^3*z1))
sage: Omega_ge(0, (1, -4))
(1, (z0, z0^4*z1))

sage: Omega_ge(0, (2, -1))
(z0*z1 + 1, (z0, z0*z1^2))
sage: Omega_ge(0, (3, -1))
(z0^2*z1 + z0*z1 + 1, (z0, z0^2*z1^3))

sage: Omega_ge(0, (2, 1, -1))
(-z0*z1*z2^2 - z0*z1*z2 + z0*z2 + 1, (z0, z1, z0*z2^2, z1*z2))
```

sage.rings.polynomial.omega.homogeneous_symmetric_function($j$, $x$)

Return a complete homogeneous symmetric polynomial (Wikipedia article Complete_homogeneous_symmetric_polynomial).

INPUT:

- $j$ – the degree as a nonnegative integer
- $x$ – an iterable of variables

OUTPUT:

A polynomial of the common parent of all entries of $x$

EXAMPLES:
Polynomials, Release 10.0

```
sage: from sage.rings.polynomial.omega import homogeneous_symmetric_function
sage: P = PolynomialRing(ZZ, 'X', 3)
sage: homogeneous_symmetric_function(0, P.gens())
1
sage: homogeneous_symmetric_function(1, P.gens())
X0 + X1 + X2
sage: homogeneous_symmetric_function(2, P.gens())
X0^2 + X0*X1 + X1^2 + X0*X2 + X1*X2 + X2^2
sage: homogeneous_symmetric_function(3, P.gens())
X0^3 + X0^2*X1 + X0*X1^2 + X1^3 + X0^2*X2 +
   X0*X1*X2 + X1^2*X2 + X0*X2^2 + X1*X2^2 + X2^3
```

`sage.rings.polynomial.omega.partition(items, predicate=<class 'bool'>)`

Split items into two parts by the given predicate.

**INPUT:**

- *item* – an iterator
- *predicate* – a function

**OUTPUT:**

A pair of iterators; the first contains the elements not satisfying the `predicate`, the second the elements satisfying the predicate.

**ALGORITHM:**

Source of the code: http://nedbatchelder.com/blog/201306/filter_a_list_into_two_parts.html

**EXAMPLES:**

```
sage: from sage.rings.polynomial.omega import partition
sage: E, O = partition(srange(10), is_odd)
sage: tuple(E), tuple(O)
((0, 2, 4, 6, 8), (1, 3, 5, 7, 9))
```
6.1 Infinite Polynomial Rings

By Infinite Polynomial Rings, we mean polynomial rings in a countably infinite number of variables. The implementation consists of a wrapper around the current finite polynomial rings in Sage.

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An Infinite Polynomial Ring has finitely many generators $x_*, y_*$, ..., and infinitely many variables of the form $x_0, x_1, x_2, ..., y_0, y_1, y_2, ..., ...$. We refer to the natural number $n$ as the index of the variable $x_n$.

INPUT:
- $R$, the base ring. It has to be a commutative ring, and in some applications it must even be a field
- names, a finite list of generator names. Generator names must be alpha-numeric.
- order (optional string). The default order is 'lex' (lexicographic). 'deglex' is degree lexicographic, and 'degrevlex' (degree reverse lexicographic) is possible but discouraged.

Each generator $x$ produces an infinite sequence of variables $x[1], x[2], ...$ which are printed on screen as $x_1, x_2, ...$ and are latex typeset as $x_1, x_2$. Then, the Infinite Polynomial Ring is formed by polynomials in these variables.

By default, the monomials are ordered lexicographically. Alternatively, degree (reverse) lexicographic ordering is possible as well. However, we do not guarantee that the computation of Groebner bases will terminate in this case.

In either case, the variables of a Infinite Polynomial Ring $X$ are ordered according to the following rule:

$$X\text{.gen}(i)[m] > X\text{.gen}(j)[n] \text{ if and only if } i<j \text{ or } (i=j \text{ and } m>n)$$

We provide a ‘dense’ and a ‘sparse’ implementation. In the dense implementation, the Infinite Polynomial Ring carries a finite polynomial ring that comprises all variables up to the maximal index that has been used so far. This is potentially a very big ring and may also comprise many variables that are not used.

In the sparse implementation, we try to keep the underlying finite polynomial rings small, using only those variables that are really needed. By default, we use the dense implementation, since it usually is much faster.

EXAMPLES:

```
sage: X.<x,y> = InfinitePolynomialRing(ZZ, implementation='sparse')
sage: A.<alpha,beta> = InfinitePolynomialRing(QQ, order='deglex')
sage: f = x[5] + 2; f
```
Polynomials, Release 10.0

```plaintext
\[ x_5 + 2 \]
```
```
sage: g = 3*y[1]; g
3*y_1
```

It has some advantages to have an underlying ring that is not univariate. Hence, we always have at least two variables:

```
sage: g._p.parent()
Multivariate Polynomial Ring in y_1, y_0 over Integer Ring
```
```
sage: f2 = alpha[5] + 2; f2
alpha_5 + 2
```
```
sage: g2 = 3*beta[1]; g2
3*beta_1
```
```
sage: A.polynomial_ring()
Multivariate Polynomial Ring in alpha_5, alpha_4, alpha_3, alpha_2, alpha_1, alpha_0, → beta_5, beta_4, beta_3, beta_2, beta_1, beta_0 over Rational Field
```

Of course, we provide the usual polynomial arithmetic:

```
sage: f+g
x_5 + 3*y_1 + 2
```
```
sage: p = x[10]^2*(f+g); p
x_10^2*x_5 + 3*x_10^2*y_1 + 2*x_10^2
```
```
sage: p2 = alpha[10]^2*(f2+g2); p2
alpha_10^2*alpha_5 + 3*alpha_10^2*beta_1 + 2*alpha_10^2
```

There is a permutation action on the variables, by permuting positive variable indices:

```
sage: P = Permutation(((10,1)))
sage: p^P
x_5*x_1^2 + 3*x_1^2*y_10 + 2*x_1^2
```
```
sage: p2^P
alpha_5*alpha_1^2 + 3*alpha_1^2*beta_10 + 2*alpha_1^2
```

Note that \( x_0^P = x_0 \), since the permutations only change positive variable indices.

We also implemented ideals of Infinite Polynomial Rings. Here, it is thoroughly assumed that the ideals are set-wise invariant under the permutation action. We therefore refer to these ideals as Symmetric Ideals. Symmetric Ideals are finitely generated modulo addition, multiplication by ring elements and permutation of variables. If the base ring is a field, one can compute Symmetric Groebner Bases:

```
sage: J = A*(alpha[1]*beta[2])
sage: J.groebner_basis()
[alpha_1*beta_2, alpha_2*beta_1]
```

For more details, see SymmetricIdeal.

Infinite Polynomial Rings can have any commutative base ring. If the base ring of an Infinite Polynomial Ring is a (classical or infinite) Polynomial Ring, then our implementation tries to merge everything into one ring. The basic requirement is that the monomial orders match. In the case of two Infinite Polynomial Rings, the implementations must match. Moreover, name conflicts should be avoided. An overlap is only accepted if the order of variables can be uniquely inferred, as in the following example:
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```sage
A.<a,b,c> = InfinitePolynomialRing(ZZ)
sage: B.<b,c,d> = InfinitePolynomialRing(A)
sage: B
Infinite polynomial ring in a, b, c, d over Integer Ring
```

This is also allowed if finite polynomial rings are involved:

```sage
A.<a_3,a_1,b_1,c_2,c_0> = ZZ[]
sage: B.<b,c,d> = InfinitePolynomialRing(A, order='degrevlex')
sage: B
Infinite polynomial ring in b, c, d over Multivariate Polynomial Ring in a_3, a_1 over Integer Ring
```

It is no problem if one generator of the Infinite Polynomial Ring is called \( x \) and one variable of the base ring is also called \( x \). This is since no variable of the Infinite Polynomial Ring will be called \( x \). However, a problem arises if the underlying classical Polynomial Ring has a variable \( x_1 \), since this can be confused with a variable of the Infinite Polynomial Ring. In this case, an error will be raised:

```sage
X.<x,y_1> = ZZ[]
sage: Y.<x,z> = InfinitePolynomialRing(X)
```

Note that \( X \) is not merged into \( Y \); this is since the monomial order of \( X \) is ‘degrevlex’, but of \( Y \) is ‘lex’.

```sage
Y
Infinite polynomial ring in x, z over Multivariate Polynomial Ring in x, y_1 over Integer Ring
```

The variable \( x \) of \( X \) can still be interpreted in \( Y \), although the first generator of \( Y \) is called \( x \) as well:

```sage
x
x
sage: Y(X('x'))
x
sage: Y('x')
x
```

But there is only merging if the resulting monomial order is uniquely determined. This is not the case in the following examples, and thus an error is raised:

```sage
X.<y_1,x> = PolynomialRing(ZZ,order='lex')
sage: # y_1 and y_2 would be in opposite order in an Infinite Polynomial Ring
X.<x, y_1, y_2> = PolynomialRing(ZZ,order='lex')
sage: Y.<y> = InfinitePolynomialRing(X)
```

(continues on next page)
CoercionException: Overlapping variables ('y','y_1','y_2') are incompatible

If the type of monomial orderings (e.g., 'degrevlex' versus 'lex') or if the implementations do not match, there is no simplified construction available:

```python
sage: X.<x,y> = InfinitePolynomialRing(ZZ)
sage: Y.<z> = InfinitePolynomialRing(X,order='degrevlex')
sage: Y
Infinite polynomial ring in z over Infinite polynomial ring in x, y over Integer Ring
sage: Y.<z> = InfinitePolynomialRing(X,implementation='sparse')
sage: Y
Infinite polynomial ring in z over Infinite polynomial ring in x, y over Integer Ring
```

### class `sage.rings.polynomial.infinite_polynomial_ring.GenDictWithBasering(parent, start)`

Bases: object

A dictionary-like class that is suitable for usage in `sage_eval`.

This pseudo-dictionary accepts strings as index, and then walks down a chain of base rings of (infinite) polynomial rings until it finds one ring that has the given string as variable name, which is then returned.

**EXAMPLES:**

```python
sage: R.<a,b> = InfinitePolynomialRing(QQ['t'])
sage: D = R.gens_dict() # indirect doctest
sage: D
GenDict of Infinite polynomial ring in a, b over Univariate Polynomial Ring in t over Rational Field
sage: next(D)
GenDict of Univariate Polynomial Ring in t over Rational Field
sage: sage_eval('t^2', next(D))
t^2
```

### next()

Return a dictionary that can be used to interprete strings in the base ring of `self`.

**EXAMPLES:**

```python
sage: R.<a,b> = InfinitePolynomialRing(QQ['t'])
sage: D = R.gens_dict()
sage: D
GenDict of Infinite polynomial ring in a, b over Univariate Polynomial Ring in t over Rational Field
sage: next(D)
GenDict of Univariate Polynomial Ring in t over Rational Field
sage: sage_eval('t^2', next(D))
t^2
```

### class `sage.rings.polynomial.infinite_polynomial_ring.InfiniteGenDict(Gens)`

Bases: object

A dictionary-like class that is suitable for usage in `sage_eval`.

---

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The generators of an Infinite Polynomial Ring are not variables. Variables of an Infinite Polynomial Ring are returned by indexing a generator. The purpose of this class is to return a variable of an Infinite Polynomial Ring, given its string representation.

EXAMPLES:

```python
sage: R.<a,b> = InfinitePolynomialRing(ZZ)
sage: D = R.gens_dict() # indirect doctest
sage: D._D
[InfiniteGenDict defined by ['a', 'b'], {'1': 1}]
sage: D._D[0]['a_15']
a_15
sage: type(_)
<class 'sage.rings.polynomial.infinite_polynomial_element.InfinitePolynomial_dense'>
sage: sage_eval('3*a_3*b_5-1/2*a_7', D._D[0])
-1/2*a_7 + 3*a_3*b_5
```

class sage.rings.polynomial.infinite_polynomial_ring.InfinitePolynomialGen

Bases: SageObject

This class provides the object which is responsible for returning variables in an infinite polynomial ring (implemented in __getitem__).

EXAMPLES:

```python
sage: X.<x1,x2> = InfinitePolynomialRing(RR)
sage: x1
x1_*
sage: x1[5]
x1_5
sage: x1 == loads(dumps(x1))
True
```

class sage.rings.polynomial.infinite_polynomial_ring.InfinitePolynomialRingFactory

Bases: UniqueFactory

A factory for creating infinite polynomial ring elements. It handles making sure that they are unique as well as handling pickling. For more details, see UniqueFactory and infinite_polynomial_ring.

EXAMPLES:

```python
sage: A.<a> = InfinitePolynomialRing(QQ)
sage: B.<b> = InfinitePolynomialRing(A)
sage: B.construction()
[InfPoly[[a,b], "lex", "dense"], Rational Field]
sage: R.<a,b> = InfinitePolynomialRing(QQ)
sage: R is B
True
sage: X.<x> = InfinitePolynomialRing(QQ)
sage: X2.<x> = InfinitePolynomialRing(QQ, implementation='sparse')
sage: X is X2
False
sage: X is loads(dumps(X))
True
```

6.1. Infinite Polynomial Rings
create_key($R$, $names=('x',)$, $order='lex'$, $implementation='dense'$)

Creates a key which uniquely defines the infinite polynomial ring.

create_object($version$, $key$)

Return the infinite polynomial ring corresponding to the key $key$.

class sage.rings.polynomial.infinite_polynomial_ring.InfinitePolynomialRing_dense($R$, $names$, $order$)

Bases: InfinitePolynomialRing_sparse

Dense implementation of Infinite Polynomial Rings

Compared with InfinitePolynomialRing_sparse, from which this class inherits, it keeps a polynomial ring that comprises all elements that have been created so far.

collection()

Return the construction of $self$.

OUTPUT:

A pair $F, R$, where $F$ is a construction functor and $R$ is a ring, so that $F(R)$ is $self$.

EXAMPLES:

sage: $R.<x,y> = InfinitePolynomialRing(GF(5))$
sage: $R.construction()$
[InfPoly{[x,y], "lex", "dense"}, Finite Field of size 5]

collection_ring()

Return the underlying finite polynomial ring.

Note: The ring returned can change over time as more variables are used.

Since the rings are cached, we create here a ring with variable names that do not occur in other doc tests, so that we avoid side effects.

EXAMPLES:

sage: $X.<xx, yy> = InfinitePolynomialRing(ZZ)$
sage: $X.polynomial_ring()$
Multivariate Polynomial Ring in xx_0, yy_0 over Integer Ring

sage: $a = yy[3]$
sage: $X.polynomial_ring()$
Multivariate Polynomial Ring in xx_3, xx_2, xx_1, xx_0, yy_3, yy_2, yy_1, yy_0 over Integer Ring

tensor_with_ring($R$)

Return the tensor product of $self$ with another ring.

INPUT:

$R$ - a ring.

OUTPUT:

An infinite polynomial ring that, mathematically, can be seen as the tensor product of $self$ with $R$.

NOTE:
It is required that the underlying ring of self coerces into $R$. Hence, the tensor product is in fact merely an extension of the base ring.

**EXAMPLES:**

```python
sage: R.<a,b> = InfinitePolynomialRing(ZZ, implementation='sparse')
sage: R.tensor_with_ring(QQ)
Infinite polynomial ring in a, b over Rational Field
sage: R
Infinite polynomial ring in a, b over Integer Ring
```

The following tests against a bug that was fixed at [github issue #10468]:

```python
sage: R.<x,y> = InfinitePolynomialRing(QQ, implementation='sparse')
sage: R.tensor_with_ring(QQ) is R
True
```

```python
class sage.rings.polynomial.infinite_polynomial_ring.InfinitePolynomialRing_sparse(R, names, order)

Bases: CommutativeRing

Sparse implementation of Infinite Polynomial Rings.

An Infinite Polynomial Ring with generators $x_*, y_*, ...$ over a field $F$ is a free commutative $F$-algebra generated by $x_0, x_1, x_2, ...; y_0, y_1, y_2, ...$ and is equipped with a permutation action on the generators, namely $x_n^P = x_{P(n)}, y_n^P = y_{P(n)}, ...$ for any permutation $P$ (note that variables of index zero are invariant under such permutation).

It is known that any permutation invariant ideal in an Infinite Polynomial Ring is finitely generated modulo the permutation action – see `SymmetricIdeal` for more details.

Usually, an instance of this class is created using `InfinitePolynomialRing` with the optional parameter `implementation='sparse'`. This takes care of uniqueness of parent structures. However, a direct construction is possible, in principle:

```python
sage: X.<x,y> = InfinitePolynomialRing(QQ, implementation='sparse')
sage: Y.<x,y> = InfinitePolynomialRing(QQ, implementation='sparse')
sage: X is Y
True
sage: from sage.rings.polynomial.infinite_polynomial_ring import...
˓→InfinitePolynomialRing_sparse
sage: Z = InfinitePolynomialRing_sparse(QQ, ['x','y'], 'lex')
```

Nevertheless, since infinite polynomial rings are supposed to be unique parent structures, they do not evaluate equal.

```python
sage: Z == X
False
```

The last parameter (‘lex’ in the above example) can also be ‘deglex’ or ‘degrevlex’; this would result in an Infinite Polynomial Ring in degree lexicographic or degree reverse lexicographic order.

See `infinite_polynomial_ring` for more details.

```python
characteristic()

Return the characteristic of the base field.
```
EXAMPLES:

```python
sage: X.<x,y> = InfinitePolynomialRing(GF(25,'a'))
sage: X
Infinite polynomial ring in x, y over Finite Field in a of size 5^2
sage: X.characteristic()
5
```

`construction()`

Return the construction of `self`.

**OUTPUT:**

A pair `F, R`, where `F` is a construction functor and `R` is a ring, so that `F(R)` is `self`.

**EXAMPLES:**

```python
sage: R.<x,y> = InfinitePolynomialRing(GF(5))
sage: R.construction()
[InfPoly{[x,y], "lex", "dense"}, Finite Field of size 5]
```

`gen(i=None)`

Return the `i`th 'generator' (see the description in `ngens()`) of this infinite polynomial ring.

**EXAMPLES:**

```python
sage: X = InfinitePolynomialRing(QQ)
sage: x = X.gen()
sage: x[1]
x_1
sage: X.gen() is X.gen(0)
True
sage: XX = InfinitePolynomialRing(GF(5))
sage: XX.gen(0) is XX.gen()
True
```

`gens_dict()`

Return a dictionary-like object containing the infinitely many `{var_name:variable}` pairs.

**EXAMPLES:**

```python
sage: R = InfinitePolynomialRing(ZZ, 'a')
sage: D = R.gens_dict()
sage: D
GenDict of Infinite polynomial ring in a over Integer Ring
sage: D['a_5']
a_5
```

`is_field(*args, **kwds)`

Return `False` since Infinite Polynomial Rings are never fields.

Since Infinite Polynomial Rings must have at least one generator, they have infinitely many variables and thus never are fields.

**EXAMPLES:**

```python
An infinite polynomial ring is an integral domain if and only if the base ring is. Arguments are passed to `is_integral_domain` method of base ring.

**EXAMPLES:**

```python
sage: R.<x, y> = InfinitePolynomialRing(QQ)
sage: R.is_integral_domain()
True
```

`is_noetherian()`

Return `False`, since polynomial rings in infinitely many variables are never Noetherian rings.

Since Infinite Polynomial Rings must have at least one generator, they have infinitely many variables and are thus not noetherian, as a ring.

**Note:** Infinite Polynomial Rings over a field $F$ are noetherian as $F(G)$ modules, where $G$ is the symmetric group of the natural numbers. But this is not what the method `is_noetherian()` is answering.

**key_basis()**

Return the basis of `self` given by key polynomials.

**EXAMPLES:**

```python
sage: R.<x> = InfinitePolynomialRing(GF(2))
sage: R.key_basis()
Key polynomial basis over Finite Field of size 2
```

`krull_dimension(*args, **kwds)`

Return `Infinity`, since polynomial rings in infinitely many variables have infinite Krull dimension.

**EXAMPLES:**

```python
sage: R.<x, y> = InfinitePolynomialRing(QQ)
sage: R.krull_dimension()
+Infinity
```

`ngens()`

Return the number of generators for this ring.

Since there are countably infinitely many variables in this polynomial ring, by ‘generators’ we mean the number of infinite families of variables. See `infinite_polynomial_ring` for more details.

**EXAMPLES:**

```python
sage: X.<x> = InfinitePolynomialRing(ZZ)
sage: X.ngens()
1
sage: X.<x1,x2> = InfinitePolynomialRing(QQ)
```

(continues on next page)
Polynomials, Release 10.0

sage: X.ngens()
2

one()

order()

Return Infinity, since polynomial rings have infinitely many elements.

EXAMPLES:

sage: R.<x> = InfinitePolynomialRing(GF(2))
sage: R.order()
+Infinity

tensor_with_ring(R)

Return the tensor product of self with another ring.

INPUT:
R - a ring.

OUTPUT:
An infinite polynomial ring that, mathematically, can be seen as the tensor product of self with R.

NOTE:
It is required that the underlying ring of self coerces into R. Hence, the tensor product is in fact merely an extension of the base ring.

EXAMPLES:

sage: R.<a,b> = InfinitePolynomialRing(ZZ)
sage: R.tensor_with_ring(QQ)
Infinite polynomial ring in a, b over Rational Field
sage: R
Infinite polynomial ring in a, b over Integer Ring

The following tests against a bug that was fixed at github issue #10468:

sage: R.<x,y> = InfinitePolynomialRing(QQ)
sage: R.tensor_with_ring(QQ) is R
True

varname_key(x)

Key for comparison of variable names.

INPUT:
x – a string of the form a+'_'+str(n), where a is the name of a generator, and n is an integer

RETURN:
a key used to sort the variables

THEORY:
The order is defined as follows:
\[ x < y \iff \text{the string } x.\text{split('')}[0] \text{ is later in the list of generator names of self than } y.\text{split('')}[0], \text{ or } (x.\text{split('')}[0] == y.\text{split('')}[0] \text{ and int}(x.\text{split('')}[1]) < \text{int}(y.\text{split('')}[1])) \]

EXAMPLES:

```python
sage: X.<alpha,beta> = InfinitePolynomialRing(ZZ)

sage: X.varname_key('alpha_1')
(0, 1)

sage: X.varname_key('beta_10')
(-1, 10)

sage: X.varname_key('beta_1')
(-1, 1)

sage: X.varname_key('alpha_10')
(0, 10)

sage: X.varname_key('alpha_1')
(0, 1)
```

### 6.2 Elements of Infinite Polynomial Rings

**AUTHORS:**

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An Infinite Polynomial Ring has generators \( x, y, \ldots \), so that the variables are of the form \( x_0, x_1, x_2, \ldots, y_0, y_1, y_2, \ldots, \ldots \) (see `infinite_polynomial_ring`). Using the generators, we can create elements as follows:

```python
sage: X.<x,y> = InfinitePolynomialRing(QQ)

sage: a = x[3]
sage: b = y[4]
sage: a
x_3

sage: b
y_4

sage: c = a*b+a^3-2*b^4

sage: c
x_3^3 + x_3*y_4 - 2*y_4^4
```

Any Infinite Polynomial Ring \( X \) is equipped with a monomial ordering. We only consider monomial orderings in which:

\[ X.\text{gen}(i)[m] > X.\text{gen}(j)[n] \iff i < j, \text{ or } i = j \text{ and } m > n \]

Under this restriction, the monomial ordering can be lexicographic (default), degree lexicographic, or degree reverse lexicographic. Here, the ordering is lexicographic, and elements can be compared as usual:

```python
sage: X._order
'lex'

sage: a > b
True
```

Note that, when a method is called that is not directly implemented for ‘InfinitePolynomial’, it is tried to call this method for the underlying classical polynomial. This holds, e.g., when applying the latex function.
There is a permutation action on Infinite Polynomial Rings by permuting the indices of the variables:

```sage
P = Permutation(((4,5),(2,3))
c^P
x_2^3 + x_2*y_5 - 2*y_5^4
```

Note that \( P(0)==0 \), and thus variables of index zero are invariant under the permutation action. More generally, if \( P \) is any callable object that accepts non-negative integers as input and returns non-negative integers, then \( c^P \) means to apply \( P \) to the variable indices occurring in \( c \).

If you want to substitute variables you can use the standard polynomial methods, such as \( \text{subs()} \):

```sage
R.<x,y> = InfinitePolynomialRing(QQ)
f = x[1] + x[1]*x[2]*x[3]
f.subs({x[1]: x[0]})
x_3*x_2*x_0 + x_0
```

```sage
g = x[0] + x[1] + y[0]
g.subs({x[0]: y[0]})
x_1 + 2*y_0
```

**class** `sage.rings.polynomial.infinite_polynomial_element.InfinitePolynomial(A, p)`

Bases: `CommutativePolynomial`

Create an element of a Polynomial Ring with a Countably Infinite Number of Variables.

Usually, an InfinitePolynomial is obtained by using the generators of an Infinite Polynomial Ring (see `infinite_polynomial_ring`) or by conversion.

INPUT:

- \( A \) – an Infinite Polynomial Ring.
- \( p \) – a `classical` polynomial that can be interpreted in \( A \).

ASSUMPTIONS:

In the dense implementation, it must be ensured that the argument \( p \) coerces into \( A._P \) by a name preserving conversion map.

In the sparse implementation, in the direct construction of an infinite polynomial, it is not tested whether the argument \( p \) makes sense in \( A \).

EXAMPLES:

```sage
from sage.rings.polynomial.infinite_polynomial_element import InfinitePolynomial
X.<alpha> = InfinitePolynomialRing(ZZ)
P.<alpha_1,alpha_2> = ZZ[]
```

Currently, \( P \) and \( X._P \) (the underlying polynomial ring of \( X \)) both have two variables:

```sage
X._P
```

Multivariate Polynomial Ring in alpha_1, alpha_0 over Integer Ring

By default, a coercion from \( P \) to \( X._P \) would not be name preserving. However, this is taken care for; a name preserving conversion is impossible, and by consequence an error is raised:
When extending the underlying polynomial ring, the construction of an infinite polynomial works:

```python
sage: alpha[2]
alpha_2
sage: InfinitePolynomial(X, (alpha_1+alpha_2)^2)
alpha_2^2 + 2*alpha_2*alpha_1 + alpha_1^2
```

In the sparse implementation, it is not checked whether the polynomial really belongs to the parent, and when it does not, the results may be unexpected due to coercions:

```python
sage: Y.<alpha,beta> = InfinitePolynomialRing(GF(2), implementation='sparse')
sage: a = (alpha_1+alpha_2)^2
sage: InfinitePolynomial(Y, a)
alpha_0^2 + beta_0^2
```

However, it is checked when doing a conversion:

```python
sage: Y(a)
alpha_2^2 + alpha_1^2
```

**coefficient(monomial)**

Returns the coefficient of a monomial in this polynomial.

**INPUT:**

- A monomial (element of the parent of self) or
- a dictionary that describes a monomial (the keys are variables of the parent of self, the values are the corresponding exponents)

**EXAMPLES:**

We can get the coefficient in front of monomials:

```python
sage: X.<x> = InfinitePolynomialRing(QQ)
sage: a.coefficient(x[0])
2*x_1
sage: a.coefficient(x[1])
2*x_0 + 1
sage: a.coefficient(x[2])
1
sage: a.coefficient(x[0]*x[1])
2
```

We can also pass in a dictionary:

```python
sage: a.coefficient({x[0]:1, x[1]:1})
2
```
footprint()
Leading exponents sorted by index and generator.

OUTPUT:
D – a dictionary whose keys are the occurring variable indices.
D[s] is a list [i_1,...,i_n], where i_j gives the exponent of self.parent().gen(j)[s] in the leading term of self.

EXAMPLES:

```python
sage: X.<x,y> = InfinitePolynomialRing(QQ)
sage: sorted(p.footprint().items())
[(1, [2, 3]), (30, [1, 0])]
```

gcd(x)
computes the greatest common divisor

EXAMPLES:

```python
sage: R.<x>=InfinitePolynomialRing(QQ)
sage: p1=x[0]+x[1]**2
sage: gcd(p1,p1+3)
1
sage: gcd(p1,p1)==p1
True
```

is_nilpotent()
Return True if self is nilpotent, i.e., some power of self is 0.

EXAMPLES:

```python
sage: R.<x> = InfinitePolynomialRing(QQbar)
sage: (x[0]+x[1]).is_nilpotent()
False
sage: R(0).is_nilpotent()
True
sage: _.<x> = InfinitePolynomialRing(Zmod(4))
sage: (2*x[0]).is_nilpotent()
True
sage: (2+2*x[4]*x[7]).is_nilpotent()
False
sage: _.<y> = InfinitePolynomialRing(Zmod(100))
sage: (5+2*y[0] + 10*(y[0]^2+y[1]^2)).is_nilpotent()
False
True
```

is_unit()
Answer whether self is a unit.

EXAMPLES:
sage: R1.<x,y> = InfinitePolynomialRing(ZZ)
sage: R2.<a,b> = InfinitePolynomialRing(QQ)
sage: (1+x[2]).is_unit()
False
sage: R1(1).is_unit()
True
sage: R1(2).is_unit()
False
sage: R2(2).is_unit()
True
sage: (1+a[2]).is_unit()
False

Check that github issue #22454 is fixed:

sage: _.<x> = InfinitePolynomialRing(Zmod(4))
sage: (1 + 2*x[0]).is_unit()
True
sage: (x[0]*x[1]).is_unit()
False
sage: _.<x> = InfinitePolynomialRing(Zmod(900))
sage: (7+150*x[0] + 30*x[1] + 120*x[1]*x[100]).is_unit()
True

lc()
The coefficient of the leading term of self.

EXAMPLES:

sage: X.<x,y> = InfinitePolynomialRing(QQ)
sage: p.lc()
3

lm()
The leading monomial of self.

EXAMPLES:

sage: X.<x,y> = InfinitePolynomialRing(QQ)
sage: p.lm()
x_10*x_1^2*y_1^3

lt()
The leading term (= product of coefficient and monomial) of self.

EXAMPLES:

sage: X.<x,y> = InfinitePolynomialRing(QQ)
sage: p.lt()
3*x_10*x_1^2*y_1^3
max_index()

Return the maximal index of a variable occurring in self, or -1 if self is scalar.

EXAMPLES:

```
sage: X.<x,y> = InfinitePolynomialRing(QQ)
sage: p.max_index()
4
sage: x[0].max_index()
0
sage: X(10).max_index()
-1
```

polynomial()

Return the underlying polynomial.

EXAMPLES:

```
sage: X.<x,y> = InfinitePolynomialRing(GF(7))
sage: p = x[2]*y[1]+3*y[0]
sage: p
x_2*y_1 + 3*y_0
sage: p.polynomial()
x_2*y_1 + 3*y_0
sage: p.polynomial().parent()
Multivariate Polynomial Ring in x_2, x_1, x_0, y_2, y_1, y_0 over Finite Field of size 7
sage: p.parent()
Infinite polynomial ring in x, y over Finite Field of size 7
```

reduce(I, tailreduce=False, report=None)

Symmetrical reduction of self with respect to a symmetric ideal (or list of Infinite Polynomials).

INPUT:

- I – a SymmetricIdeal or a list of Infinite Polynomials.
- tailreduce – (bool, default False) Tail reduction is performed if this parameter is True.
- report – (object, default None) If not None, some information on the progress of computation is printed, since reduction of huge polynomials may take a long time.

OUTPUT:

Symmetrical reduction of self with respect to I, possibly with tail reduction.

THEORY:

Reducing an element $p$ of an Infinite Polynomial Ring $X$ by some other element $q$ means the following:

1. Let $M$ and $N$ be the leading terms of $p$ and $q$.
2. Test whether there is a permutation $P$ that does not diminish the variable indices occurring in $N$ and preserves their order, so that there is some term $T \in X$ with $TN^P = M$. If there is no such permutation, return $p$.
3. Replace $p$ by $p - Tq^P$ and continue with step 1.

EXAMPLES:
The preceding is correct: If a permutation turns $y[2]*x[1]^2$ into a factor of the leading monomial $y[2]*x[3]^3$ of $p$, then it interchanges the variable indices 1 and 2; this is not allowed in a symmetric reduction. However, reduction by $y[1]*x[2]^2$ works, since one can change variable index 1 into 2 and 2 into 3:

```
sage: p.reduce([y[1]*x[2]^2])
y_3*y_1^2
```

The next example shows that tail reduction is not done, unless it is explicitly advised. The input can also be a Symmetric Ideal:

```
sage: I = (y[3])*X
sage: p.reduce(I)
x_3^3*y_2 + y_3*y_1^2
sage: p.reduce(I, tailreduce=True)
x_3^3*y_2
```

Last, we demonstrate the report option:

```
sage: p.reduce(I, tailreduce=True, report=True)
:T[2]:
> x_1^2 + y_2^2
```

The output ‘:’ means that there was one reduction of the leading monomial. ‘T[2]’ means that a tail reduction was performed on a polynomial with two terms. At ‘>’, one round of the reduction process is finished (there could only be several non-trivial rounds if $I$ was generated by more than one polynomial).

### ring()

The ring which self belongs to.

This is the same as self.parent().

**EXAMPLES:**

```
sage: X.<x,y> = InfinitePolynomialRing(ZZ, implementation='sparse')
sage: p.ring()
Infinite polynomial ring in x, y over Integer Ring
```

### squeezed()

Reduce the variable indices occurring in self.

**OUTPUT:**

Apply a permutation to self that does not change the order of the variable indices of self but squeezes them into the range 1,2,...

**EXAMPLES:**
Polynomials, Release 10.0

```
sage: X.<x,y> = InfinitePolynomialRing(QQ, implementation='sparse')
sage: p = x[1]*y[100] + x[50]*y[1000]
sage: p.squeezed()
x_2*y_4 + x_1*y_3
```

**stretch** (*k*)

Stretch self by a given factor.

**INPUT:**

- *k* – an integer.

**OUTPUT:**

Replace *vₙ* with *vₙ·k* for all generators *vₙ* occurring in self.

**EXAMPLES:**

```
sage: X.<x> = InfinitePolynomialRing(QQ)
sage: a.stretch(2)
x_4 + x_2 + x_0
```

```
sage: X.<x,y> = InfinitePolynomialRing(QQ)
sage: a = x[0] + x[1] + y[0]*y[1]; a
x_1 + x_0 + y_1*y_0
sage: a.stretch(2)
x_2 + x_0 + y_2*y_0
```

**subs** (*fixed=None, **kwargs*)

Substitute variables in self.

**INPUT:**

- *fixed* – (optional) dict with {variable: value} pairs
- **kwargs** – named parameters

**OUTPUT:**

the resulting substitution

**EXAMPLES:**

```
sage: R.<x,y> = InfinitePolynomialRing(QQ)
sage: f = x[1] + x[1]*x[2]*x[3]
```

Passing *fixed={x[1]: x[0]}*. Note that the keys may be given using the generators of the infinite polynomial ring or as a string:

```
sage: f.subs({x[1]: x[0]})
x_3*x_2*x_0 + x_0
```

```
sage: f.subs({'x_1': x[0]})
x_3*x_2*x_0 + x_0
```

Passing the variables as names parameters:
The substitution returns the original polynomial if you try to substitute a variable not present:

```python
sage: g = x[0] + x[1]
sage: g.subs({y[0]: x[0]})
x_1 + x_0
```

The substitution can also handle matrices:

```python
sage: M = matrix([[1,0],[0,2]])
sage: N = matrix([[0,3],[4,0]])
sage: g = x[0]^2 + 3*x[1]
sage: g.subs({x[0]: M})
[3*x_1 + 1 0]
[0 3*x_1 + 4]
sage: g.subs({x[0]: M, x[1]: N})
[ 1 9]
[12 4]
```

If you pass both fixed and kwargs, any conflicts will defer to fixed:

```python
sage: R.<x,y> = InfinitePolynomialRing(QQ)
sage: f = x[0]
sage: f.subs({x[0]:1})
1
sage: f.subs(x_0=5)
5
sage: f.subs({x[0]:1}, x_0=5)
1
```

**symmetric_cancellation_order** *(other)*

Comparison of leading terms by Symmetric Cancellation Order, $\prec_{sc}$.

INPUT:

self, other -- two Infinite Polynomials

ASSUMPTION:

Both Infinite Polynomials are non-zero.

OUTPUT:

(c, sigma, w), where

- c = -1,0,1, or None if the leading monomial of self is smaller, equal, greater, or incomparable with respect to other in the monomial ordering of the Infinite Polynomial Ring
- sigma is a permutation witnessing self $\prec_{sc}$ other (resp. self $\succ_{sc}$ other) or is 1 if self. lm() == other.lm()
- w is 1 or is a term so that w*self.lt()^sigma == other.lt() if c $\leq$ 0, and w*other. lt()^sigma == self.lt() if c = 1

6.2. Elements of Infinite Polynomial Rings
THEORY:

If the Symmetric Cancellation Order is a well-quasi-ordering then computation of Groebner bases always terminates. This is the case, e.g., if the monomial order is lexicographic. For that reason, lexicographic order is our default order.

EXAMPLES:

```python
sage: X.<x,y> = InfinitePolynomialRing(QQ)
sage: (x[2]*x[1]).symmetric_cancellation_order(x[2]^2)
    (None, 1, 1)
sage: (x[2]*x[1]).symmetric_cancellation_order(x[2]*x[3]*y[1])
    (-1, [2, 3, 1], y_1)
sage: (x[2]*x[1]*y[1]).symmetric_cancellation_order(x[2]*x[3]*y[2])
    (None, 1, 1)
sage: (x[2]*x[1]*y[1]).symmetric_cancellation_order(x[2]*x[3]*y[2])
    (-1, [2, 3, 1], 1)
```

tail()

The tail of self (this is self minus its leading term).

EXAMPLES:

```python
sage: X.<x,y> = InfinitePolynomialRing(QQ)
sage: p.tail()
    2*x_10*y_30
```

variables()

Return the variables occurring in self (tuple of elements of some polynomial ring).

EXAMPLES:

```python
sage: X.<x> = InfinitePolynomialRing(QQ)
sage: p.variables()
    (x_3, x_2, x_1)
sage: x[1].variables()
    (x_1,)
sage: X(1).variables()
    ()
```

class sage.rings.polynomial.infinite_polynomial_element.InfinitePolynomial_dense(A, p)

Bases: InfinitePolynomial

Element of a dense Polynomial Ring with a Countably Infinite Number of Variables.

INPUT:

- `A` – an Infinite Polynomial Ring in dense implementation
- `p` – a classical polynomial that can be interpreted in `A`.

Of course, one should not directly invoke this class, but rather construct elements of `A` in the usual way.

This class inherits from InfinitePolynomial_sparse. See there for a description of the methods.
class sage.rings.polynomial.infinite_polynomial_element.InfinitePolynomial_sparse(A, p)

    Bases: InfinitePolynomial

    Element of a sparse Polynomial Ring with a Countably Infinite Number of Variables.

    INPUT:
    • A – an Infinite Polynomial Ring in sparse implementation
    • p – a *classical* polynomial that can be interpreted in A.

    Of course, one should not directly invoke this class, but rather construct elements of A in the usual way.

    EXAMPLES:

    sage: A.<a> = QQ[]
    sage: B.<b,c> = InfinitePolynomialRing(A, implementation='sparse')
    sage: p = a*b[100] + 1/2*c[4]
    sage: p
    a*b_100 + 1/2*c_4
    sage: p.parent()
    Infinite polynomial ring in b, c over Univariate Polynomial Ring in a over Rational Field
    sage: p.polynomial().parent()
    Multivariate Polynomial Ring in b_100, b_0, c_4, c_0 over Univariate Polynomial Ring in a over Rational Field

6.3 Symmetric Ideals of Infinite Polynomial Rings

This module provides an implementation of ideals of polynomial rings in a countably infinite number of variables that are invariant under variable permutation. Such ideals are called ‘Symmetric Ideals’ in the rest of this document. Our implementation is based on the theory of M. Aschenbrenner and C. Hillar.

AUTHORS:

• Simon King <simon.king@nuigalway.ie>

EXAMPLES:

Here, we demonstrate that working in quotient rings of Infinite Polynomial Rings works, provided that one uses symmetric Groebner bases.

    sage: R.<x> = InfinitePolynomialRing(QQ)
    sage: I = R.ideal([x[1]*x[2] + x[3]])

    sage: G = R*I.groebner_basis()
    sage: G
    Symmetric Ideal (x_1^2 + x_1, x_2 - x_1) of Infinite polynomial ring in x over Rational Field
    sage: Q = R.quotient(G)
    sage: Q(p)
    -2*x_1 + 3

Note that I is not a symmetric Groebner basis:
By the second generator of $G$, variable $x_n$ is equal to $x_1$ for any positive integer $n$. By the first generator of $G$, $x_3^1$ is equal to $x_1$ in $Q$. Indeed, we have

```
sage: Q(p)*x[2] == Q(p)*x[1]*x[3]*x[5]
True
```

**class** `sage.rings.polynomial.symmetric_ideal.SymmetricIdeal(ring, gens, coerce=True)`

Bases: `Ideal_generic`

Ideal in an Infinite Polynomial Ring, invariant under permutation of variable indices

**THEORY:**

An Infinite Polynomial Ring with finitely many generators $x_*, y_*, ...$ over a field $F$ is a free commutative $F$-algebra generated by infinitely many ‘variables’ $x_0, x_1, x_2, ..., y_0, y_1, y_2, ...$. We refer to the natural number $n$ as the index of the variable $x_n$. See more detailed description at `infinite_polynomial_ring`

Infinite Polynomial Rings are equipped with a permutation action by permuting positive variable indices, i.e., $x_n^P = x_{P(n)}$, $y_n^P = y_{P(n)}$, ... for any permutation $P$. Note that the variables $x_0, y_0, ...$ of index zero are invariant under that action.

A Symmetric Ideal is an ideal in an infinite polynomial ring $X$ that is invariant under the permutation action. In other words, if $\mathfrak{S}_\infty$ denotes the symmetric group of $1, 2, ..., \text{then a Symmetric Ideal is a right } X[\mathfrak{S}_\infty]\text{-submodule of } X$.

It is known by work of Aschenbrenner and Hillar [AB2007] that an Infinite Polynomial Ring $X$ with a single generator $x_*$ is Noetherian, in the sense that any Symmetric Ideal $I \subset X$ is finitely generated modulo addition, multiplication by elements of $X$, and permutation of variable indices (hence, it is a finitely generated right $X[\mathfrak{S}_\infty]$-module).

Moreover, if $X$ is equipped with a lexicographic monomial ordering with $x_1 < x_2 < x_3...$ then there is an algorithm of Buchberger type that computes a Groebner basis $G$ for $I$ that allows for computation of a unique normal form, that is zero precisely for the elements of $I$ – see [AB2008]. See `groebner_basis()` for more details.

Our implementation allows more than one generator and also provides degree lexicographic and degree reverse lexicographic monomial orderings – we do, however, not guarantee termination of the Buchberger algorithm in these cases.

**EXAMPLES:**

```
sage: X.<x,y> = InfinitePolynomialRing(QQ)
sage: I == loads(dumps(I))
True
sage: latex(I)
\left(x_1 y_2 y_1 + 2 x_1 y_2\right)
```

The default ordering is lexicographic. We now compute a Groebner basis:

```
sage: J = I.groebner_basis(); J  # about 3 seconds
[x_1*y_2*y_1 + 2*x_1*y_2, x_2*y_2*y_1 + 2*x_2*y_1, x_2*x_1*y_1^2 + 2*x_2*x_1*y_1, x_2*x_1^2*y_2 - x_2*x_1*y_1]
```

Note that even though the symmetric ideal can be generated by a single polynomial, its reduced symmetric Groebner basis comprises four elements. Ideal membership in $I$ can now be tested by commuting symmetric reduction modulo $J$:
The Groebner basis is not point-wise invariant under permutation:

```sage
P = Permutation([2, 1])
J[2]^P
```

However, any element of $J$ has symmetric reduction zero even after applying a permutation. This even holds when the permutations involve higher variable indices than the ones occurring in $J$:

```sage
[(p^P).reduce(I) for p in J] for P in Permutations(3)]
```

Since $I$ is not a Groebner basis, it is no surprise that it cannot detect ideal membership:

```sage
[p.reduce(I) for p in J]
```

Note that we give no guarantee that the computation of a symmetric Groebner basis will terminate in any order different from lexicographic.

When multiplying Symmetric Ideals or raising them to some integer power, the permutation action is taken into account, so that the product is indeed the product of ideals in the mathematical sense.

```sage
I = X*(x[1])
I*I
```

```
sage: groebner_basis(tailreduce=False, reduced=True, algorithm=None, report=None, use_full_group=False)
Return a symmetric Groebner basis (type Sequence) of self.
```

**INPUT:**

- `tailreduce` – (bool, default False) If True, use tail reduction in intermediate computations
- `reduced` – (bool, default True) If True, return the reduced normalised symmetric Groebner basis.
- `algorithm` – (string, default None) Determine the algorithm (see below for available algorithms).
- `report` – (object, default None) If not None, print information on the progress of computation.
- `use_full_group` – (bool, default False) If True then proceed as originally suggested by [AB2008]. Our default method should be faster; see `symmetrisation()` for more details.
The computation of symmetric Groebner bases also involves the computation of classical Groebner bases, i.e., of Groebner bases for ideals in polynomial rings with finitely many variables. For these computations, Sage provides the following ALGORITHMS:

```
's`
   autoselect (default)
'singular:groebner'
   Singular's groebner command
'singular:std'
   Singular's std command
'singular:stdhilb'
   Singular's stdhilb command
'singular:stdfglm'
   Singular's stdfglm command
'singular:slimgb'
   Singular's slimgb command
'libsingular:std'
   libSingular's std command
'libsingular:slimgb'
   libSingular's slimgb command
'toy:buchberger'
   Sage’s toy/educational buchberger without strategy
'toy:buchberger2'
   Sage’s toy/educational buchberger with strategy
'toy:d_basis'
   Sage’s toy/educational d_basis algorithm
'macaulay2:gb'
   Macaulay2’s gb command (if available)
'magma:GroebnerBasis'
   Magma’s GroebnerBasis command (if available)
```

If only a system is given - e.g. ‘magma’ - the default algorithm is chosen for that system.

**Note:** The Singular and libSingular versions of the respective algorithms are identical, but the former calls an external Singular process while the later calls a C function, i.e. the calling overhead is smaller.

**EXAMPLES:**

```
sage: X.<x,y> = InfinitePolynomialRing(QQ)
sage: I1 = X*(x[1]+x[2],x[1]*x[2])
sage: I1.groebner_basis()
[x_1]
sage: I2.groebner_basis()
[x_1*y_2 + y_2^2*y_1, x_2*y_1 + y_2*y_1^2]
```

Note that a symmetric Groebner basis of a principal ideal is not necessarily formed by a single polynomial.
When using the algorithm originally suggested by Aschenbrenner and Hillar, the result is the same, but the computation takes much longer:

```sage
I2.groebner_basis(use_full_group=True)
[x_1*y_2 + y_2^2*y_1, x_2*y_1 + y_2*y_1^2]
```

Last, we demonstrate how the report on the progress of computations looks like:

```sage
I1.groebner_basis(report=True, reduced=True)
Symmetric interreduction
[1/2] >
[2/2] :
[1/2] >
[2/2] >
Symmetrise 2 polynomials at level 2
Apply permutations
>
>
Symmetric interreduction
[1/3] >
[2/3] >
[3/3] :
-> 0
[1/2] >
[2/2] >
Symmetrisation done
Classical Groebner basis
-> 2 generators
Symmetric interreduction
[1/2] >
[2/2] >
Symmetrise 2 polynomials at level 3
Apply permutations
>
>
::>
::>
::>
Symmetric interreduction
[1/4] >
[2/4] :
-> 0
[3/4] :
-> 0
[4/4] :
-> 0
[1/1] >
Apply permutations
::>
::>
::>
Symmetric interreduction
[1/1] >
```

(continues on next page)
The Aschenbrenner-Hillar algorithm is only guaranteed to work if the base ring is a field. So, we raise a \texttt{TypeError} if this is not the case:

\begin{verbatim}
sage: R.<x,y> = InfinitePolynomialRing(ZZ)
sage: I = R*[x[1]+x[2],y[1]]
sage: I.groebner_basis()
Traceback (most recent call last):
  ...  
TypeError: The base ring (= Integer Ring) must be a field
\end{verbatim}

\texttt{interreduced\_basis()}

A fully symmetrically reduced generating set (type \texttt{Sequence}) of self.

This does essentially the same as \texttt{interreduction()} with the option ‘tailreduce’, but it returns a \texttt{Sequence} rather than a \texttt{SymmetricIdeal}.

EXAMPLES:

\begin{verbatim}
sage: X.<x> = InfinitePolynomialRing(QQ)
sage: I=X*[x[1]+x[2],x[1]*x[2]]
sage: I.interreduced\_basis()
[-x_1^2, x_2 + x_1]
\end{verbatim}

\texttt{interreduction(tailreduce=True, sorted=False, report=None, RStrat=None)}

Return symmetrically interreduced form of self.

INPUT:

- \texttt{tailreduce} – (bool, default True) If True, the interreduction is also performed on the non-leading monomials.
- \texttt{sorted} – (bool, default False) If True, it is assumed that the generators of self are already increasingly sorted.
• `report` – (object, default `None`) If not `None`, some information on the progress of computation is printed

• `RStrat` – (`SymmetricReductionStrategy`, default `None`) A reduction strategy to which the polynomials resulting from the interreduction will be added. If `RStrat` already contains some polynomials, they will be used in the interreduction. The effect is to compute in a quotient ring.

**OUTPUT:**

A Symmetric Ideal J (sorted list of generators) coinciding with self as an ideal, so that any generator is symmetrically reduced w.r.t. the other generators. Note that the leading coefficients of the result are not necessarily 1.

**EXAMPLES:**

```sage
X.<x> = InfinitePolynomialRing(QQ)
sage: I=X*(x[1]+x[2],x[1]*x[2])
sage: I.interreduction()
Symmetric Ideal (-x_1^2, x_2 + x_1) of Infinite polynomial ring in x over Rational Field
```

Here, we show the report option:

```sage
sage: I.interreduction(report=True)
Symmetric interreduction
[1/2] >
[2/2] :>
[1/2] >
Symmetric Ideal (-x_1^2, x_2 + x_1) of Infinite polynomial ring in x over Rational Field
```

`[m/n]` indicates that polynomial number `m` is considered and the total number of polynomials under consideration is `n`. ‘-> 0’ is printed if a zero reduction occurred. The rest of the report is as described in `sage.rings.polynomial.symmetric_reduction.SymmetricReductionStrategy.reduce()`.

Last, we demonstrate the use of the optional parameter `RStrat`:

```sage
sage: from sage.rings.polynomial.symmetric_reduction import SymmetricReductionStrategy
sage: R = SymmetricReductionStrategy(X)
sage: I.interreduction(RStrat=R)
Symmetric Ideal (-x_1^2, x_2 + x_1) of Infinite polynomial ring in x over Rational Field
```

```sage
sage: R = SymmetricReductionStrategy(X,[x[1]^2])
sage: I.interreduction(RStrat=R)
Symmetric Ideal (x_2 + x_1) of Infinite polynomial ring in x over Rational Field
```
**is_maximal()**

Answers whether self is a maximal ideal.

**ASSUMPTION:**

self is defined by a symmetric Groebner basis.

**NOTE:**

It is not checked whether self is in fact a symmetric Groebner basis. A wrong answer can result if this assumption does not hold. A `NotImplementedError` is raised if the base ring is not a field, since symmetric Groebner bases are not implemented in this setting.

**EXAMPLES:**

```python
sage: R.<x,y> = InfinitePolynomialRing(QQ)
sage: I = R.ideal([x[1]+y[2], x[2]-y[1]])
sage: I = R*I.groebner_basis()
sage: I
Symmetric Ideal (y_1, x_1) of Infinite polynomial ring in x, y over Rational Field
sage: I.is_maximal()
False
```

The preceding answer is wrong, since it is not the case that I is given by a symmetric Groebner basis:

```python
sage: I = R*I.groebner_basis()
sage: I
Symmetric Ideal (y_1, x_1) of Infinite polynomial ring in x, y over Rational Field
sage: I.is_maximal()
True
```

**normalisation()**

Return an ideal that coincides with self, so that all generators have leading coefficient 1. Possibly occurring zeroes are removed from the generator list.

**EXAMPLES:**

```python
sage: X.<x> = InfinitePolynomialRing(QQ)
sage: I = X*(1/2*x[1]+2/3*x[2], 0, 4/5*x[1]*x[2])
sage: I.normalisation()
Symmetric Ideal (x_2 + 3/4*x_1, x_2*x_1) of Infinite polynomial ring in x over Rational Field
```

**reduce(I, tailreduce=False)**

Symmetric reduction of self by another Symmetric Ideal or list of Infinite Polynomials, or symmetric reduction of a given Infinite Polynomial by self.

**INPUT:**

- I – an Infinite Polynomial, or a Symmetric Ideal or a list of Infinite Polynomials.
- tailreduce – (bool, default False) If True, the non-leading terms will be reduced as well.

**OUTPUT:**

Symmetric reduction of self with respect to I.
THEORY:

Reduction of an element $p$ of an Infinite Polynomial Ring $X$ by some other element $q$ means the following:

1. Let $M$ and $N$ be the leading terms of $p$ and $q$.
2. Test whether there is a permutation $P$ that does not diminish the variable indices occurring in $N$ and preserves their order, so that there is some term $T \in X$ with $TNP = M$. If there is no such permutation, return $p$.
3. Replace $p$ by $p - TqP$ and continue with step 1.

EXAMPLES:

```sage
sage: X.<x,y> = InfinitePolynomialRing(QQ)
sage: I.reduce([x[1]^2*y[2]])
Symmetric Ideal (x_3^2*y_1 + y_3*y_1^2) of Infinite polynomial ring in x, y over Rational Field

The preceding is correct, since any permutation that turns $x[1]^2*y[2]$ into a factor of $x[3]^2*y[2]$ interchanges the variable indices 1 and 2 – which is not allowed. However, reduction by $x[2]^2*y[1]$ works, since one can change variable index 1 into 2 and 2 into 3:

```sage
sage: I.reduce([x[2]^2*y[1]])
Symmetric Ideal (y_3*y_1^2) of Infinite polynomial ring in x, y over Rational Field
```

The next example shows that tail reduction is not done, unless it is explicitly advised. The input can also be a symmetric ideal:

```sage
sage: J = (y[2])*X
sage: I.reduce(J)
Symmetric Ideal (x_3^2*y_1 + y_3*y_1^2) of Infinite polynomial ring in x, y over Rational Field
sage: I.reduce(J, tailreduce=True)
Symmetric Ideal (x_3^2*y_1) of Infinite polynomial ring in x, y over Rational Field
```

`squeezed()`

Reduce the variable indices occurring in `self`.

OUTPUT:

A Symmetric Ideal whose generators are the result of applying `squeezed()` to the generators of `self`.

NOTE:

The output describes the same Symmetric Ideal as `self`.

EXAMPLES:

```sage
sage: X.<x,y> = InfinitePolynomialRing(QQ,implementation='sparse')
sage: I = X.(x[1000]*y[100],x[50]*y[1000])
sage: I.squeezed()
Symmetric Ideal (x_2*y_1, x_1*y_2) of Infinite polynomial ring in x, y over Rational Field
```
**symmetric_basis()**

A symmetrised generating set (type Sequence) of self.

This does essentially the same as `symmetrisation()` with the option ‘tailreduce’, and it returns a Sequence rather than a SymmetricIdeal.

**EXAMPLES:**

```sage
sage: X.<x> = InfinitePolynomialRing(QQ)
sage: I = X*(x[1]+x[2], x[1]*x[2])
sage: I.symmetric_basis()
[x_1^2, x_2 + x_1]
```

**symmetrisation(N=None, tailreduce=False, report=None, use_full_group=False)**

Apply permutations to the generators of self and interreduce

**INPUT:**

- N – (integer, default None) Apply permutations in Sym(N). If it is not given then it will be replaced by the maximal variable index occurring in the generators of `self.interreduction().squeezed()`.
- tailreduce – (bool, default False) If True, perform tail reductions.
- report – (object, default None) If not None, report on the progress of computations.
- use_full_group (optional) – If True, apply all elements of Sym(N) to the generators of self (this is what [AB2008] originally suggests). The default is to apply all elementary transpositions to the generators of `self.squeezed()`, interreduce, and repeat until the result stabilises, which is often much faster than applying all of Sym(N), and we are convinced that both methods yield the same result.

**OUTPUT:**

A symmetrically interreduced symmetric ideal with respect to which any Sym(N)-translate of a generator of self is symmetrically reducible, where by default N is the maximal variable index that occurs in the generators of `self.interreduction().squeezed()`.

**NOTE:**

If I is a symmetric ideal whose generators are monomials, then `I.symmetrisation()` is its reduced Groebner basis. It should be noted that without symmetrisation, monomial generators, in general, do not form a Groebner basis.

**EXAMPLES:**

```sage
sage: X.<x> = InfinitePolynomialRing(QQ)
sage: I = X*(x[1]+x[2], x[1]*x[2])
sage: I.symmetrisation()Symmetric Ideal (-x_1^2, x_2 + x_1) of Infinite polynomial ring in x over Rational Field
sage: I.symmetrisation(N=3)Symmetric Ideal (-2*x_1) of Infinite polynomial ring in x over Rational Field
sage: I.symmetrisation(N=3, use_full_group=True)Symmetric Ideal (-2*x_1) of Infinite polynomial ring in x over Rational Field
```
6.4 Symmetric Reduction of Infinite Polynomials

SymmetricReductionStrategy provides a framework for efficient symmetric reduction of Infinite Polynomials, see infinite_polynomial_element.

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THEORY:

According to M. Aschenbrenner and C. Hillar [AB2007], Symmetric Reduction of an element $p$ of an Infinite Polynomial Ring $X$ by some other element $q$ means the following:

1. Let $M$ and $N$ be the leading terms of $p$ and $q$.

2. Test whether there is a permutation $P$ that does not diminish the variable indices occurring in $N$ and preserves their order, so that there is some term $T \in X$ with $TN^P = M$. If there is no such permutation, return $p$.

3. Replace $p$ by $p - Tq^P$ and continue with step 1.

When reducing one polynomial $p$ with respect to a list $L$ of other polynomials, there usually is a choice of order on which the efficiency crucially depends. Also it helps to modify the polynomials on the list in order to simplify the basic reduction steps.

The preparation of $L$ may be expensive. Hence, if the same list is used many times then it is reasonable to perform the preparation only once. This is the background of SymmetricReductionStrategy.

Our current strategy is to keep the number of terms in the polynomials as small as possible. For this, we sort $L$ by increasing number of terms. If several elements of $L$ allow for a reduction of $p$, we choose the one with the smallest number of terms. Later on, it should be possible to implement further strategies for choice.

When adding a new polynomial $q$ to $L$, we first reduce $q$ with respect to $L$. Then, we test heuristically whether it is possible to reduce the number of terms of the elements of $L$ by reduction modulo $q$. That way, we see best chances to keep the number of terms in intermediate reduction steps relatively small.

EXAMPLES:

First, we create an infinite polynomial ring and one of its elements:

```sage
sage: X.<x,y> = InfinitePolynomialRing(QQ)
```

We want to symmetrically reduce it by another polynomial. So, we put this other polynomial into a list and create a Symmetric Reduction Strategy object:

```sage
sage: from sage.rings.polynomial.symmetric_reduction import SymmetricReductionStrategy
sage: S = SymmetricReductionStrategy(X, [y[2]^2*x[1]])
sage: S
Symmetric Reduction Strategy in Infinite polynomial ring in x, y over Rational Field, → modulo x_1*y_2^2
sage: S.reduce(p)
x_3*y_1^2 + y_3*y_1
```

The preceding is correct, since any permutation that turns $y[2]^2*x[1]$ into a factor of $y[1]^2*x[3]$ interchanges the variable indices 1 and 2 – which is not allowed in a symmetric reduction. However, reduction by $y[1]^2*x[2]$ works, since one can change variable index 1 into 2 and 2 into 3. So, we add this to $S$:
sage: S.add_generator(y[1]^2*x[2])
sage: S
Symmetric Reduction Strategy in Infinite polynomial ring in x, y over Rational Field, modulo
   x_2*y_1^2, x_1*y_2^2
sage: S.reduce(p)
y_3*y_1

The next example shows that tail reduction is not done, unless it is explicitly advised:

x_3 + 2*x_2*y_1^2 + 3*x_1*y_2^2
x_3

However, it is possible to ask for tailreduction already when the Symmetric Reduction Strategy is created:

sage: S2
Symmetric Reduction Strategy in Infinite polynomial ring in x, y over Rational Field, modulo
   x_2*y_1^2, x_1*y_2^2
with tailreduction
x_3

class sage.rings.polynomial.symmetric_reduction.SymmetricReductionStrategy

Bases: object

A framework for efficient symmetric reduction of InfinitePolynomial, see infinite_polynomial_element.

INPUT:

* Parent – an Infinite Polynomial Ring, see infinite_polynomial_element.

* L – (list, default the empty list) List of elements of Parent with respect to which will be reduced.

* good_input – (bool, default None) If this optional parameter is true, it is assumed that each element of L is symmetrically reduced with respect to the previous elements of L.

EXAMPLES:

sage: X.<y> = InfinitePolynomialRing(QQ)
sage: from sage.rings.polynomial.symmetric_reduction import SymmetricReductionStrategy
y_3 + 3*y_2^2*y_1 + 2*y_2*y_1^2
y_3

add_generator(p, good_input=None)

Add another polynomial to self.

INPUT:
• \( p \) – An element of the underlying infinite polynomial ring.

• \( \text{good_input} \) – (bool, default None) If True, it is assumed that \( p \) is reduced with respect to \( \text{self} \). Otherwise, this reduction will be done first (which may cost some time).

**Note:** Previously added polynomials may be modified. All input is prepared in view of an efficient symmetric reduction.

**EXAMPLES:**

```sage
from sage.rings.polynomial.symmetric_reduction import SymmetricReductionStrategy

X.<x,y> = InfinitePolynomialRing(QQ)
S = SymmetricReductionStrategy(X)
S
Symmetric Reduction Strategy in Infinite polynomial ring in x, y over Rational Field
S
Symmetric Reduction Strategy in Infinite polynomial ring in x, y over Rational Field, modulo x_3*y_1 + x_1*y_1 + y_3
```

Note that the first added polynomial will be simplified when adding a suitable second polynomial:

```sage
S.add_generator(x[2]+x[1])
S
Symmetric Reduction Strategy in Infinite polynomial ring in x, y over Rational Field, modulo y_3,
 x_2 + x_1
```

By default, reduction is applied to any newly added polynomial. This can be avoided by specifying the optional parameter ‘good_input’:

```sage
S.add_generator(y[2]+y[1]*x[2])
S
Symmetric Reduction Strategy in Infinite polynomial ring in x, y over Rational Field, modulo y_3,(x[3]+x[1])
S.reduce(x[3]+x[2])
-2*x_1
S.add_generator(x[3]+x[2], good_input=True)
S
Symmetric Reduction Strategy in Infinite polynomial ring in x, y over Rational Field, modulo y_3,
 x_3 + x_2, x_1*y_1 - y_2, x_2 + x_1
```

In the previous example, \( x[3] + x[2] \) is added without being reduced to zero.
**gens()**

Return the list of Infinite Polynomials modulo which self reduces.

**EXAMPLES:**

```python
sage: X.<y> = InfinitePolynomialRing(QQ)
sage: from sage.rings.polynomial.symmetric_reduction import SymmetricReductionStrategy
sage: S
Symmetric Reduction Strategy in Infinite polynomial ring in y over Rational Field, modulo y_2*y_1^2, y_2^2*y_1
sage: S.gens()
[y_2*y_1^2, y_2^2*y_1]
```

**reduce**(p, notail=False, report=None)

Symmetric reduction of an infinite polynomial.

**INPUT:**

- p – an element of the underlying infinite polynomial ring.
- notail – (bool, default False) If True, tail reduction is avoided (but there is no guarantee that there will be no tail reduction at all).
- report – (object, default None) If not None, print information on the progress of the computation.

**OUTPUT:**

Reduction of p with respect to self.

**Note:** If tail reduction shall be forced, use `tailreduce()`.

**EXAMPLES:**

```python
sage: from sage.rings.polynomial.symmetric_reduction import SymmetricReductionStrategy
sage: X.<x,y> = InfinitePolynomialRing(QQ)
sage: S = SymmetricReductionStrategy(X, [y[3]], tailreduce=True)
sage: S.reduce(y[4]*x[1] + y[1]*x[4])
x_4*y_1
sage: S.reduce(y[4]*x[1] + y[1]*x[4], notail=True)
x_4*y_1 + x_1*y_4
```

Last, we demonstrate the ‘report’ option:

```python
sage: S
Symmetric Reduction Strategy in Infinite polynomial ring in x, y over Rational Field, modulo y_3 + y_2,
x_2 + y_1,
x_1*y_2 + y_4 - y_3*y_1
```

(continues on next page)
:::>
x_1*y_1 + y_4 - y_3*y_1 - y_1

Each `:` indicates that one reduction of the leading monomial was performed. Eventually, the `>` indicates that the computation is finished.

**reset()**

Remove all polynomials from self.

**EXAMPLES:**

```python
sage: X.<y> = InfinitePolynomialRing(QQ)
sage: from sage.rings.polynomial.symmetric_reduction import SymmetricReductionStrategy
sage: S = SymmetricReductionStrategy(X, [y^2*y_1, y_1^2*y_2])
sage: S
Symmetric Reduction Strategy in Infinite polynomial ring in y over Rational Field, modulo y_2*y_1^2, y_2^2*y_1
sage: S.reset()
sage: S
Symmetric Reduction Strategy in Infinite polynomial ring in y over Rational Field
```

**setgens(L)**

Define the list of Infinite Polynomials modulo which self reduces.

**INPUT:**

L – a list of elements of the underlying infinite polynomial ring.

**Note:** It is not tested if L is a good input. That method simply assigns a copy of L to the generators of self.

**EXAMPLES:**

```python
sage: from sage.rings.polynomial.symmetric_reduction import SymmetricReductionStrategy
sage: X.<y> = InfinitePolynomialRing(QQ)
sage: S = SymmetricReductionStrategy(X, [y^2*y_1, y_1^2*y_2])
sage: R = SymmetricReductionStrategy(X)
sage: R.setgens(S.gens())
sage: R
Symmetric Reduction Strategy in Infinite polynomial ring in y over Rational Field
sage: R.gens() == S.gens()
True
```
**tailreduce**(*p*, *report=None*)

Symmetric reduction of an infinite polynomial, with forced tail reduction.

**INPUT:**

- *p* – an element of the underlying infinite polynomial ring.
- *report* – (object, default None) If not None, print information on the progress of the computation.

**OUTPUT:**

Reduction (including the non-leading elements) of *p* with respect to self.

**EXAMPLES:**

```python
sage: from sage.rings.polynomial.symmetric_reduction import SymmetricReductionStrategy
sage: X.<x,y> = InfinitePolynomialRing(QQ)
X
sage: S = SymmetricReductionStrategy(X, [y[3]])
S
sage: S.reduce(y[4]*x[1] + y[1]*x[4])
x_4*y_1 + x_1*y_4
sage: S.tailreduce(y[4]*x[1] + y[1]*x[4])
x_4*y_1
```

Last, we demonstrate the ‘report’ option:

```python
S
Symmetric Reduction Strategy in Infinite polynomial ring in x, y over Rational Field, modulo
  y_3 + y_2,
  x_2 + y_1,
  x_1*y_2 + y_4 + y_1^2
T[3]:::>
T[3]:>
  x_1*y_1 - y_2 + y_1^2 - y_1
```

The protocol means the following.

- ‘T[3]’ means that we currently do tail reduction for a polynomial with three terms.
- ‘:::’ means that there were three reductions of leading terms.
- The tail of the result of the preceding reduction still has three terms. One reduction of leading terms was possible, and then the final result was obtained.
CHAPTER
SEVEN

BOOLEAN POLYNOMIALS

7.1 Boolean Polynomials

Elements of the quotient ring
\[ \mathbb{F}_2[x_1, ..., x_n]/(x_1^2 + x_1 + 1, ..., x_n^2 + x_n) \]
are called boolean polynomials. Boolean polynomials arise naturally in cryptography, coding theory, formal logic, chip design and other areas. This implementation is a thin wrapper around the PolyBoRi library by Michael Brickenstein and Alexander Dreyer.

“Boolean polynomials can be modelled in a rather simple way, with both coefficients and degree per variable lying in \{0, 1\}. The ring of Boolean polynomials is, however, not a polynomial ring, but rather the quotient ring of the polynomial ring over the field with two elements modulo the field equations \(x_i^2 = x_i\) for each variable \(x_i\). Therefore, the usual polynomial data structures seem not to be appropriate for fast Groebner basis computations. We introduce a specialised data structure for Boolean polynomials based on zero-suppressed binary decision diagrams (ZDDs), which is capable of handling these polynomials more efficiently with respect to memory consumption and also computational speed. Furthermore, we concentrate on high-level algorithmic aspects, taking into account the new data structures as well as structural properties of Boolean polynomials.” - [BD2007]

For details on the internal representation of polynomials see
http://polybori.sourceforge.net/zdd.html

AUTHORS:
• Michael Brickenstein: PolyBoRi author
• Alexander Dreyer: PolyBoRi author
• Burcin Erocal <burcin@erocal.org>: main Sage wrapper author
• Martin Albrecht <malb@informatik.uni-bremen.de>: some contributions to the Sage wrapper
• Simon King <simon.king@uni-jena.de>: Adopt the new coercion model. Fix conversion from univariate polynomial rings. Pickling of BooleanMonomialMonoid (via UniqueRepresentation) and BooleanMonomial.
• Charles Bouillaguet <charles.bouillaguet@gmail.com>: minor changes to improve compatibility with MPolynomial and make the variety() function work on ideals of BooleanPolynomial’s.

EXAMPLES:
Consider the ideal
\[ < ab + cd + 1, ace + de, abc + ce, bc + cde + 1 > \]
First, we compute the lexicographical Groebner basis in the polynomial ring
\[ R = \mathbb{F}_2[a, b, c, d, e]. \]
If one wants to solve this system over the algebraic closure of \( \mathbb{F}_2 \) then this Groebner basis was the one to consider. If one wants solutions over \( \mathbb{F}_2 \) only then one adds the field polynomials to the ideal to force the solutions in \( \mathbb{F}_2 \).

If one wants solutions over \( \mathbb{F}_2 \) only then one adds the field polynomials to the ideal to force the solutions in \( \mathbb{F}_2 \).

So the solutions over \( \mathbb{F}_2 \) are \{e = 0, d = 1, c = 1, b = 1, a = 0\} and \{e = 0, d = 0, c = 1, b = 1, a = 1\}.

We can express the restriction to \( \mathbb{F}_2 \) by considering the quotient ring. If \( I \) is an ideal in \( \mathbb{F}[x_1, ..., x_n] \) then the ideals in the quotient ring \( \mathbb{F}[x_0, ..., x_n]/I \) are in one-to-one correspondence with the ideals of \( \mathbb{F}[x_0, ..., x_n] \) containing \( I \) (that is, the ideals \( J \) satisfying \( I \subset J \subset P \)).

This quotient ring is exactly what PolyBoRi handles well:

Note that \( d^2 + d \) is not representable in \( B = Q \). Also note, that PolyBoRi cannot play out its strength in such small examples, i.e. working in the polynomial ring might be faster for small examples like this.
7.1.1 Implementation specific notes

PolyBoRi comes with a Python wrapper. However this wrapper does not match Sage’s style and is written using Boost. Thus Sage’s wrapper is a reimplementation of Python bindings to PolyBoRi’s C++ library. This interface is written in Cython like all of Sage’s C/C++ library interfaces. An interface in PolyBoRi style is also provided which is effectively a reimplementation of the official Boost wrapper in Cython. This means that some functionality of the official wrapper might be missing from this wrapper and this wrapper might have bugs not present in the official Python interface.

7.1.2 Access to the original PolyBoRi interface

The re-implementation PolyBoRi’s native wrapper is available to the user too:

```python
sage: from sage.rings.polynomial.pbori import *
sage: declare_ring([Block('x',2), Block('y',3)], globals())
Boolean PolynomialRing in x0, x1, y0, y1, y2
sage: r
Boolean PolynomialRing in x0, x1, y0, y1, y2

sage: [Variable(i, r) for i in range(r.ngens())]
[x(0), x(1), y(0), y(1), y(2)]
```

For details on this interface see:


Also, the interface provides functions for compatibility with Sage accepting convenient Sage data types which are slower than their native PolyBoRi counterparts. For instance, sets of points can be represented as tuples of tuples (Sage) or as `BooleSet` (PolyBoRi) and naturally the second option is faster.

```python
class sage.rings.polynomial.pbori.pbori.BooleConstant
    Bases: object
    
    Construct a boolean constant (modulo 2) from integer value:
    
    INPUT:
    
    • i - an integer
    
    EXAMPLES:

sage: from sage.rings.polynomial.pbori.pbori import BooleConstant
sage: [BooleConstant(i) for i in range(5)]
[0, 1, 0, 1, 0]

deg()
    Get degree of boolean constant.
    
    EXAMPLES:

sage: from sage.rings.polynomial.pbori.pbori import BooleConstant
sage: BooleConstant(0).deg()
-1
sage: BooleConstant(1).deg()
0
```

7.1. Boolean Polynomials
**has_constant_part()**

This is true for \textit{BooleConstant}(1).

**EXAMPLES:**

```
sage: from sage.rings.polynomial.pbori.pbori import BooleConstant
sage: BooleConstant(1).has_constant_part()
True
sage: BooleConstant(0).has_constant_part()
False
```

**is_constant()**

This is always true for in this case.

**EXAMPLES:**

```
sage: from sage.rings.polynomial.pbori.pbori import BooleConstant
sage: BooleConstant(1).is_constant()
True
sage: BooleConstant(0).is_constant()
True
```

**is_one()**

Check whether boolean constant is one.

**EXAMPLES:**

```
sage: from sage.rings.polynomial.pbori.pbori import BooleConstant
sage: BooleConstant(0).is_one()
False
sage: BooleConstant(1).is_one()
True
```

**is_zero()**

Check whether boolean constant is zero.

**EXAMPLES:**

```
sage: from sage.rings.polynomial.pbori.pbori import BooleConstant
sage: BooleConstant(0).is_zero()
True
sage: BooleConstant(1).is_zero()
False
```

**variables()**

Get variables (return always and empty tuple).

**EXAMPLES:**

```
sage: from sage.rings.polynomial.pbori.pbori import BooleConstant
sage: BooleConstant(0).variables()
[]
sage: BooleConstant(1).variables()
[]
```
class sage.rings.polynomial.pbori.pbori.BooleSet
Bases: object

Return a new set of boolean monomials. This data type is also implemented on the top of ZDDs and allows to see polynomials from a different angle. Also, it makes high-level set operations possible, which are in most cases faster than operations handling individual terms, because the complexity of the algorithms depends only on the structure of the diagrams.

Objects of type BooleanPolynomial can easily be converted to the type BooleSet by using the member function BooleanPolynomial.set().

INPUT:

• param - either a CCuddNavigator, a BooleSet or None.
• ring - a boolean polynomial ring.

EXAMPLES:

```python
sage: from sage.rings.polynomial.pbori.pbori import BooleSet
sage: B.<a,b,c,d> = BooleanPolynomialRing(4)

sage: BS = BooleSet(a.set())
sage: BS
{{a}}

sage: BS = BooleSet((a*b + c + 1).set())
sage: BS
{{a,b}, {c}, {}}

sage: from sage.rings.polynomial.pbori.pbori import *
sage: from sage.rings.polynomial.pbori.PyPolyBoRi import Monomial

sage: BooleSet([Monomial(B)])
{{}}
```

Note: BooleSet prints as {} but are not Python dictionaries.

cartesian_product(rhs)

Return the Cartesian product of this set and the set rhs.

The Cartesian product of two sets X and Y is the set of all possible ordered pairs whose first component is a member of X and whose second component is a member of Y.

\[ X \times Y = \{(x, y) | x \in X \text{ and } y \in Y\}. \]

EXAMPLES:

```python
sage: B = BooleanPolynomialRing(5, 'x')
sage: x0,x1,x2,x3,x4 = B.gens()
sage: f = x1*x2+x2*x3
sage: s = f.set(); s
{{x1,x2}, {x2,x3}}
sage: g = x4 + 1
sage: t = g.set(); t
{{x4}, {}}
sage: s.cartesian_product(t)
{{x1,x2,x4}, {x1,x2}, {x2,x3,x4}, {x2,x3}}
```
**change** *(ind)*

Swaps the presence of $x_i$ in each entry of the set.

**EXAMPLES:**

```python
sage: P.<a,b,c> = BooleanPolynomialRing()
sage: f = a+b
sage: s = f.set(); s
{{a}, {b}}
sage: s.change(0)
{{a,b}, {}}
sage: s.change(1)
{{a,b}, {}}
sage: s.change(2)
{{a,c}, {b,c}}
```

**diff**(rhs)

Return the set theoretic difference of this set and the set rhs.

The difference of two sets $X$ and $Y$ is defined as:

$$X \setminus Y = \{ x | x \in X \text{ and } x \not\in Y \}.$$  

**EXAMPLES:**

```python
sage: B = BooleanPolynomialRing(5, 'x')
sage: x0,x1,x2,x3,x4 = B.gens()
sage: f = x1*x2+x2*x3
sage: s = f.set(); s
{{x1,x2}, {x2,x3}}
sage: g = x2*x3 + 1
sage: t = g.set(); t
{{x2,x3}, {}}
sage: s.diff(t)
{{x1,x2}}
```

**divide**(rhs)

Divide each element of this set by the monomial rhs and return a new set containing the result.

**EXAMPLES:**

```python
sage: B.<a,b,c,d,e,f> = BooleanPolynomialRing(order='lex')
sage: f = b*e + b*c*d + b
sage: s = f.set(); s
{{b,c,d}, {b,e}, {b}}
sage: s.divide(b.lm())
{{c,d}, {e}, {}}
sage: f = b*e + b*c*d + b + c
sage: s = f.set()
sage: s.divide(b.lm())
{{c,d}, {e}, {}}
```

**divisors_of**(m)

Return those members which are divisors of m.

**INPUT:**

```python
```
• $m$ - a boolean monomial

EXAMPLES:

```python
sage: B = BooleanPolynomialRing(5, 'x')
sage: x0, x1, x2, x3, x4 = B.gens()
sage: f = x1*x2 + x2*x3
sage: s = f.set()
sage: s.divisors_of((x1*x2*x4).lead())
{{x1, x2}}
```

**empty()**

Return True if this set is empty.

EXAMPLES:

```python
sage: B.<a,b,c,d> = BooleanPolynomialRing(4)
sage: BS = (a*b + c).set()
sage: BS.empty()
False
sage: BS = B(0).set()
sage: BS.empty()
True
```

**include_divisors()**

Extend this set to include all divisors of the elements already in this set and return the result as a new set.

EXAMPLES:

```python
sage: B.<a,b,c,d,e,f> = BooleanPolynomialRing()
sage: f = a*d*e + a*f + b*d*e + c*d*e + 1
sage: s = f.set(); s
{{a, d, e}, {a, f}, {b, d, e}, {c, d, e}, {}}
sage: s.include_divisors()
{{a, d, e}, {a, d}, {a, e}, {a, f}, {a}, {b, d, e}, {b, d}, {b, e}, {b}, {c, d, e}, {c, d}, {c, e}, {c}, {d, e}, {d}, {e}, {f}, {}}
```

**intersect(other)**

Return the set theoretic intersection of this set and the set rhs.

The union of two sets $X$ and $Y$ is defined as:

$$X \cap Y = \{ x | x \in X \text{ and } x \in Y \}.$$ 

EXAMPLES:

```python
sage: B = BooleanPolynomialRing(5, 'x')
sage: x0, x1, x2, x3, x4 = B.gens()
sage: f = x1*x2 + x2*x3
sage: s = f.set(); s
{{x1, x2}, {x2, x3}}
sage: g = x2*x3 + 1
sage: t = g.set(); t
{{x2, x3}, {}}
```
minimal_elements()

Return a new set containing a divisor of all elements of this set.

EXAMPLES:

```sage
sage: B.<a,b,c,d,e,f> = BooleanPolynomialRing()
sage: f = a*d*e + a*f + a*b*d*e + a*c*d*e + a
sage: s = f.set(); s
{{a,b,d,e}, {a,c,d,e}, {a,d,e}, {a,f}, {a}}
sage: s.minimal_elements()
{{a}}
```

multiples_of(m)

Return those members which are multiples of m.

INPUT:

- m - a boolean monomial

EXAMPLES:

```sage
sage: B = BooleanPolynomialRing(5, 'x')
sage: x0,x1,x2,x3,x4 = B.gens()
sage: f = x1*x2+x2*x3
sage: s = f.set()
sage: s.multiples_of(x1.lm())
{{x1,x2}}
```

n_nodes()

Return the number of nodes in the ZDD.

EXAMPLES:

```sage
sage: B = BooleanPolynomialRing(5, 'x')
sage: x0,x1,x2,x3,x4 = B.gens()
sage: f = x1*x2+x2*x3
sage: s = f.set(); s
{{x1,x2}, {x2,x3}}
sage: s.n_nodes()
4
```

navigation()

Navigators provide an interface to diagram nodes, accessing their index as well as the corresponding then- and else-branches.

You should be very careful and always keep a reference to the original object, when dealing with navigators, as navigators contain only a raw pointer as data. For the same reason, it is necessary to supply the ring as argument, when constructing a set out of a navigator.

EXAMPLES:
sage: from sage.rings.polynomial.pbori.pbori import BooleSet
sage: B = BooleanPolynomialRing(5, 'x')
sage: x0, x1, x2, x3, x4 = B.gens()
sage: f = x1*x2 + x2*x3*x4 + x2*x4 + x3 + x4 + 1
sage: s = f.set(); s
{{x1, x2}, {x2, x3, x4}, {x2, x4}, {x3}, {x4}, {}}}

sage: nav = s.navigation()
sage: BooleSet(nav, s.ring())
{{x1, x2}, {x2, x3, x4}, {x2, x4}, {x3}, {x4}, {}}}

sage: nav.value()
1

sage: nav_else = nav.else_branch()
sage: BooleSet(nav_else, s.ring())
{{x2, x3, x4}, {x2, x4}, {x3}, {x4}, {}}

sage: nav_else.value()
2

ring()
Return the parent ring.

EXAMPLES:

sage: B = BooleanPolynomialRing(5, 'x')
sage: x0, x1, x2, x3, x4 = B.gens()
sage: f = x1*x2 + x2*x3*x4 + x2*x4 + x3 + x4 + 1
sage: f.set().ring() is B
True

set()
Return self.

EXAMPLES:

sage: B.<a,b,c,d> = BooleanPolynomialRing(4)
sage: BS = (a*b + c).set()
sage: BS.set() is BS
True

size_double()
Return the size of this set as a floating point number.

EXAMPLES:

sage: B = BooleanPolynomialRing(5, 'x')
sage: x0, x1, x2, x3, x4 = B.gens()
sage: f = x1*x2 + x2*x3
sage: s = f.set()
sage: s.size_double()
2.0

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**stable_hash()**

A hash value which is stable across processes.

**EXAMPLES:**

```python
sage: B.<x,y> = BooleanPolynomialRing()
sage: x.set() is x.set()
False
sage: x.set().stable_hash() == x.set().stable_hash()
True
```

**Note:** This function is part of the upstream PolyBoRi interface. In Sage all hashes are stable.

**subset0(i)**

Return a set of those elements in this set which do not contain the variable indexed by i.

**INPUT:**

- i - an index

**EXAMPLES:**

```python
sage: BooleanPolynomialRing(5, 'x')
Boolean PolynomialRing in x0, x1, x2, x3, x4
sage: B = BooleanPolynomialRing(5, 'x')
```

**subset1(i)**

Return a set of those elements in this set which do contain the variable indexed by i and evaluate the variable indexed by i to 1.

**INPUT:**

- i - an index

**EXAMPLES:**

```python
sage: BooleanPolynomialRing(5, 'x')
Boolean PolynomialRing in x0, x1, x2, x3, x4
```
union(rhs)

Return the set theoretic union of this set and the set rhs.

The union of two sets \( X \) and \( Y \) is defined as:

\[
X \cup Y = \{ x \mid x \in X \text{ or } x \in Y \}.
\]

EXAMPLES:

```python
sage: B = BooleanPolynomialRing(5, 'x')
sage: x0, x1, x2, x3, x4 = B.gens()
sage: f = x1*x2 + x2*x3
sage: s = f.set(); s
{{x1, x2}, {x2, x3}}
sage: g = x2*x3 + 1
sage: t = g.set(); t
{{x2, x3}, {}}
sage: s.union(t)
{{x1, x2}, {x2, x3}, {}}
```

def vars()

Return the variables in this set as a monomial.

EXAMPLES:

```python
sage: B.<a, b, c, d, e, f> = BooleanPolynomialRing(order='lex')
sage: f = a + b*e + d*f + e + 1
sage: s = f.set()
sage: s
{{a}, {b, e}, {d, f}, {e}, {}}
sage: s.vars()
a*b*d*e*f
```

class sage.rings.polynomial.pbori.pbori.BooleSetIterator

Bases: object

Helper class to iterate over boolean sets.

class sage.rings.polynomial.pbori.pbori.BooleanMonomial

Bases: MonoidElement

Construct a boolean monomial.

INPUT:

- parent - parent monoid this element lives in

EXAMPLES:

```python
sage: from sage.rings.polynomial.pbori.pbori import BooleanMonomialMonoid,
     BooleanPolynomialring
sage: B.<x, y, z> = BooleanPolynomialRing(3)
sage: M = BooleanMonomialMonoid(B)
sage: B = BooleanMonomial(M)
```

7.1. Boolean Polynomials
Note: Use the `BooleanMonomialMonoid.__call__()` method and not this constructor to construct these objects.

**deg()**

Return degree of this monomial.

**EXAMPLES:**

```
sage: from sage.rings.polynomial.pbori.pbori import BooleanMonomialMonoid
sage: P.<x,y,z> = BooleanPolynomialRing(3)
sage: M = BooleanMonomialMonoid(P)
sage: M(x*y).deg()
2
sage: M(x^2*y*z).deg()
3
```

Note: This function is part of the upstream PolyBoRi interface.

**degree(x=None)**

Return the degree of this monomial in `x`, where `x` must be one of the generators of the polynomial ring.

**INPUT:**

- `x` - boolean multivariate polynomial (a generator of the polynomial ring). If `x` is not specified (or is `None`), return the total degree of this monomial.

**EXAMPLES:**

```
sage: from sage.rings.polynomial.pbori.pbori import BooleanMonomialMonoid
sage: P.<x,y,z> = BooleanPolynomialRing(3)
sage: M = BooleanMonomialMonoid(P)
sage: M(x*y).degree()
2
sage: M(x*y).degree(x)
1
sage: M(x*y).degree(z)
0
```

**divisors()**

Return a set of boolean monomials with all divisors of this monomial.

**EXAMPLES:**

```
sage: B.<x,y,z> = BooleanPolynomialRing(3)
sage: f = x*y
sage: m = f.lm()
sage: m.divisors()
{(x, y), {x}, {y}, {}}
```

**gcd(rhs)**

Return the greatest common divisor of this boolean monomial and `rhs`.

**INPUT:**
• rhs - a boolean monomial

EXAMPLES:

```python
sage: B.<a,b,c,d> = BooleanPolynomialRing()
sage: a,b,c,d = a.lm(), b.lm(), c.lm(), d.lm()
sage: (a*b).gcd(b*c)
b
sage: (a*b*c).gcd(d)
1
```

index()

Return the variable index of the first variable in this monomial.

EXAMPLES:

```python
sage: B.<x,y,z> = BooleanPolynomialRing(3)
sage: f = x*y
sage: m = f.lm()
sage: m.index()
0
```

Note: This function is part of the upstream PolyBoRi interface.

iterindex()

Return an iterator over the indices of the variables in self.

EXAMPLES:

```python
sage: from sage.rings.polynomial.pbori.pbori import BooleanMonomialMonoid
sage: P.<x,y,z> = BooleanPolynomialRing(3)
sage: M = BooleanMonomialMonoid(P)
sage: list(M(x*z).iterindex())
[0, 2]
```

multiples(rhs)

Return a set of boolean monomials with all multiples of this monomial up to the bound rhs.

INPUT:

• rhs - a boolean monomial

EXAMPLES:

```python
sage: B.<x,y,z> = BooleanPolynomialRing(3)
sage: f = x
sage: m = f.lm()
sage: g = x*y*z
sage: n = g.lm()
sage: m.multiples(n)
{{x,y,z}, {x,y}, {x,z}, {x}}
sage: n.multiples(m)
{{x,y,z}}
```

7.1. Boolean Polynomials
Note: The returned set always contains `self` even if the bound `rhs` is smaller than `self`.

**navigation()**

Navigators provide an interface to diagram nodes, accessing their index as well as the corresponding then- and else-branches.

You should be very careful and always keep a reference to the original object, when dealing with navigators, as navigators contain only a raw pointer as data. For the same reason, it is necessary to supply the ring as argument, when constructing a set out of a navigator.

**EXAMPLES:**

```python
sage: from sage.rings.polynomial.pbori.pbori import BooleSet
sage: B = BooleanPolynomialRing(5, 'x')
sage: x0,x1,x2,x3,x4 = B.gens()
sage: f = x1*x2+x2*x3*x4+x2*x4+x3+x4+1
sage: m = f.lm(); m
x1*x2
sage: nav = m.navigation()
sage: BooleSet(nav, B)
{{x1, x2}}
sage: nav.value()
1
```

**reducible_by(rhs)**

Return `True` if `self` is reducible by `rhs`.

**INPUT:**

- `rhs` - a boolean monomial

**EXAMPLES:**

```python
sage: B.<x,y,z> = BooleanPolynomialRing(3)
sage: f = x*y
sage: m = f.lm()
sage: m.reducible_by((x*y).lm())
True
sage: m.reducible_by((x*z).lm())
False
```

**ring()**

Return the corresponding boolean ring.

**EXAMPLES:**

```python
sage: B.<a,b,c,d> = BooleanPolynomialRing(4)
sage: a.lm().ring() is B
True
```

**set()**

Return a boolean set of variables in this monomials.

**EXAMPLES:**
```python
sage: B.<x,y,z> = BooleanPolynomialRing(3)
sage: f = x*y
sage: m = f.lm()
sage: m.set()
{{x,y}}
```

**stable_hash()**

A hash value which is stable across processes.

EXAMPLES:

```python
sage: B.<x,y> = BooleanPolynomialRing()
sage: x.lm() is x.lm()
False
sage: x.lm().stable_hash() == x.lm().stable_hash()
True
```

**variables()**

Return a tuple of the variables in this monomial.

EXAMPLES:

```python
sage: from sage.rings.polynomial.pbori.pbori import BooleanMonomialMonoid
sage: P.<x,y,z> = BooleanPolynomialRing(3)
sage: M = BooleanMonomialMonoid(P)
sage: M(x*z).variables() # indirect doctest
(x, z)
```

class sage.rings.polynomial.pbori.pbori.BooleanMonomialIterator

Bases: object

An iterator over the variable indices of a monomial.

class sage.rings.polynomial.pbori.pbori.BooleanMonomialMonoid(polring)

Bases: UniqueRepresentation, Monoid_class

Construct a boolean monomial monoid given a boolean polynomial ring.

This object provides a parent for boolean monomials.

INPUT:

- `polring` - the polynomial ring our monomials lie in

EXAMPLES:

```python
sage: from sage.rings.polynomial.pbori.pbori import BooleanMonomialMonoid
sage: P.<x,y> = BooleanPolynomialRing(2)
sage: M = BooleanMonomialMonoid(P)
sage: M.gens()
```

(continues on next page)
Since GitHub issue #9138, boolean monomial monoids are unique parents and are fit into the category framework:

```
sage: loads(dumps(M)) == M
True
sage: TestSuite(M).run()
```

**gen**(i=0)

Return the i-th generator of self.

INPUT:

- i - an integer

EXAMPLES:

```
sage: from sage.rings.polynomial.pbori.pbori import BooleanMonomialMonoid
sage: P.<x,y,z> = BooleanPolynomialRing(3)
sage: M = BooleanMonomialMonoid(P)
sage: M.gen(0)
x
sage: M.gen(2)
z
sage: P = BooleanPolynomialRing(1000, 'x')
sage: M = BooleanMonomialMonoid(P)
sage: M.gen(50)
x50
```

**gens()**

Return the tuple of generators of this monoid.

EXAMPLES:

```
sage: from sage.rings.polynomial.pbori.pbori import BooleanMonomialMonoid
sage: P.<x,y,z> = BooleanPolynomialRing(3)
sage: M = BooleanMonomialMonoid(P)
sage: M.gens()
(x, y, z)
```

**ngens()**

Return the number of variables in this monoid.

EXAMPLES:

```
sage: from sage.rings.polynomial.pbori.pbori import BooleanMonomialMonoid
sage: P = BooleanPolynomialRing(100, 'x')
sage: M = BooleanMonomialMonoid(P)
sage: M.ngens()
100
```
class sage.rings.polynomial.pbori.pbori.BooleanMonomialVariableIterator
   Bases: object

class sage.rings.polynomial.pbori.pbori.BooleanMulAction
   Bases: Action

class sage.rings.polynomial.pbori.pbori.BooleanPolynomial
   Bases: MPolynomial
   Construct a boolean polynomial object in the given boolean polynomial ring.

   INPUT:
   
   * parent - a boolean polynomial ring

   Note: Do not use this method to construct boolean polynomials, but use the appropriate __call__ method in the parent.

constant()  
Return True if this element is constant.

EXAMPLES:

sage: B.<x,y,z> = BooleanPolynomialRing(3)
sage: x.constant()
False

sage: B(1).constant()
True

Note: This function is part of the upstream PolyBoRi interface.

constant_coefficient()  
Return the constant coefficient of this boolean polynomial.

EXAMPLES:

sage: B.<a,b> = BooleanPolynomialRing()
sage: a.constant_coefficient()
0
sage: (a+1).constant_coefficient()
1

deg()
Return the degree of self. This is usually equivalent to the total degree except for weighted term orderings which are not implemented yet.

EXAMPLES:

sage: P.<x,y> = BooleanPolynomialRing(2)
sage: (x+y).degree()
1
Note: This function is part of the upstream PolyBoRi interface.

degree($x$=None)
Return the maximal degree of this polynomial in $x$, where $x$ must be one of the generators for the parent of this polynomial.

If $x$ is not specified (or is None), return the total degree, which is the maximum degree of any monomial.

EXAMPLES:

```
sage: P.<x,y> = BooleanPolynomialRing(2)
sage: (x+y).degree()
sage: (x*y + x + y + 1).degree()
sage: (x*y + x + y + 1).degree(x)
1
2
1
```

elength()
Return elimination length as used in the SlimGB algorithm.

EXAMPLES:

```
sage: P.<x,y> = BooleanPolynomialRing(2)
sage: x.elength()
sage: f = x*y + 1
sage: f.elength()
1
2
```

REFERENCES:
- Michael Brickenstein; SlimGB: Groebner Bases with Slim Polynomials http://www.mathematik.uni-kl.de/~zca/Reports_on_ca/35/paper_35_full.ps.gz

Note: This function is part of the upstream PolyBoRi interface.

first_term()
Return the first term with respect to the lexicographical term ordering.

EXAMPLES:
sage: B.<a,b,z> = BooleanPolynomialRing(3,order='lex')
sage: f = b*z + a + 1
sage: f.first_term()
a

Note: This function is part of the upstream PolyBoRi interface.

graded_part(deg)
Return graded part of this boolean polynomial of degree deg.

INPUT:
  • deg - a degree

EXAMPLES:

sage: B.<a,b,c,d> = BooleanPolynomialRing(4)
sage: f = a*b*c + c*d + a*b + 1
sage: f.graded_part(2)
a^2*b + c*d
sage: f.graded_part(0)
1

has_constant_part()
Return True if this boolean polynomial has a constant part, i.e. if 1 is a term.

EXAMPLES:

sage: B.<a,b,c,d> = BooleanPolynomialRing(4)
sage: f = a*b*c + c*d + a*b + 1
sage: f.has_constant_part()
True
sage: f = a*b*c + c*d + a*b
sage: f.has_constant_part()
False

is_constant()
Check if self is constant.

EXAMPLES:

sage: P.<x,y> = BooleanPolynomialRing(2)
sage: P(1).is_constant()
True
sage: P(0).is_constant()
True
sage: x.is_constant()
False

(continues on next page)
is_equal(right)

EXAMPLES:

```
sage: B.<a,b,z> = BooleanPolynomialRing(3)
sage: f = a*z + b + 1
sage: g = b + z
sage: f.is_equal(g)
False
sage: f.is_equal((f + 1) - 1)
True
```

Note: This function is part of the upstream PolyBoRi interface.

is_homogeneous()

Return True if this element is a homogeneous polynomial.

EXAMPLES:

```
sage: P.<x, y> = BooleanPolynomialRing()
sage: (x+y).is_homogeneous()
True
sage: P(0).is_homogeneous()
True
sage: (x+1).is_homogeneous()
False
```

is_one()

Check if self is 1.

EXAMPLES:

```
sage: P.<x,y> = BooleanPolynomialRing(2)
sage: P(1).is_one()
True
sage: P.one().is_one()
True
sage: x.is_one()
False
sage: P(0).is_one()
False
```

is_pair()

Check if self has exactly two terms.

EXAMPLES:
\begin{verbatim}
sage: P.<x,y> = BooleanPolynomialRing(2)
sage: P(0).is_pair()
False
sage: x.is_pair()
False
sage: P(1).is_pair()
False
sage: (x*y).is_pair()
False
sage: (x + y).is_pair()
True
sage: (x + 1).is_pair()
True
sage: (x*y + 1).is_pair()
False
sage: (x + y + 1).is_pair()
False
sage: ((x + 1)*(y + 1)).is_pair()
False
\end{verbatim}

**is_singleton()**

Check if self has at most one term.

**EXAMPLES:**

\begin{verbatim}
sage: P.<x,y> = BooleanPolynomialRing(2)
sage: P(0).is_singleton()
True
sage: x.is_singleton()
True
sage: P(1).is_singleton()
True
sage: (x*y).is_singleton()
True
sage: (x + y).is_singleton()
False
sage: (x + 1).is_singleton()
False
sage: (x*y + 1).is_singleton()
False
\end{verbatim}
is_singleton_or_pair()

Check if self has at most two terms.

EXAMPLES:

```
sage: P.<x,y> = BooleanPolynomialRing(2)
sage: P(0).is_singleton_or_pair()
True
sage: x.is_singleton_or_pair()
True
sage: P(1).is_singleton_or_pair()
True
sage: (x*y).is_singleton_or_pair()
True
sage: (x + y).is_singleton_or_pair()
True
sage: (x + 1).is_singleton_or_pair()
True
sage: (x*y + 1).is_singleton_or_pair()
True
sage: (x + y + 1).is_singleton_or_pair()
False
sage: ((x + 1)*(y + 1)).is_singleton_or_pair()
False
```

is_unit()

Check if self is invertible in the parent ring.

Note that this condition is equivalent to being 1 for boolean polynomials.

EXAMPLES:

```
sage: P.<x,y> = BooleanPolynomialRing(2)
sage: P.one().is_unit()
True
sage: x.is_unit()
False
```
**is_univariate()**

Return True if self is a univariate polynomial.

This means that self contains at most one variable.

**EXAMPLES:**

```python
sage: P.<x,y,z> = BooleanPolynomialRing()
sage: f = x + 1
sage: f.is_univariate()
True
sage: f = y*x + 1
sage: f.is_univariate()
False
sage: f = P(0)
sage: f.is_univariate()
True
```

**is_zero()**

Check if self is zero.

**EXAMPLES:**

```python
sage: P.<x,y> = BooleanPolynomialRing(2)
sage: P(0).is_zero()
True
sage: x.is_zero()
False
sage: P(1).is_zero()
False
```

**lead()**

Return the leading monomial of boolean polynomial, with respect to the order of parent ring.

**EXAMPLES:**

```python
sage: P.<x,y,z> = BooleanPolynomialRing(3)
sage: (x+y+y*z).lead()
x

sage: P.<x,y,z> = BooleanPolynomialRing(3, order='deglex')
sage: (x+y+y*z).lead()
y*z
```

**Note:** This function is part of the upstream PolyBoRi interface.

**lead_deg()**

Return the total degree of the leading monomial of self.

**EXAMPLES:**
Polynomials, Release 10.0

```python
sage: P.<x,y,z> = BooleanPolynomialRing(3)
sage: p = x + y*z
sage: p.lead_deg()
1

sage: P.<x,y,z> = BooleanPolynomialRing(3, order='deglex')
sage: p = x + y*z
sage: p.lead_deg()
2

sage: P(0).lead_deg()
0

Note: This function is part of the upstream PolyBoRi interface.
```

### lead_divisors()

Return a BooleSet of all divisors of the leading monomial.

**EXAMPLES:**

```python
sage: B.<a,b,z> = BooleanPolynomialRing(3)
sage: f = a*b + z + 1
sage: f.lead_divisors()
{{a,b}, {a}, {b}, {}}
```

Note: This function is part of the upstream PolyBoRi interface.

### lex_lead()

Return the leading monomial of boolean polynomial, with respect to the lexicographical term ordering.

**EXAMPLES:**

```python
sage: P.<x,y,z> = BooleanPolynomialRing(3)
sage: (x+y+y*z).lex_lead()
x

sage: P.<x,y,z> = BooleanPolynomialRing(3, order='deglex')
sage: (x+y+y*z).lex_lead()
x

sage: P(0).lex_lead()
0
```

Note: This function is part of the upstream PolyBoRi interface.

### lex_lead_deg()

Return degree of leading monomial with respect to the lexicographical ordering.

**EXAMPLES:**
sage: B.<x,y,z> = BooleanPolynomialRing(3,order='lex')
sage: f = x + y*z
sage: f
x + y*z
sage: f.lex_lead_deg()
1

sage: B.<x,y,z> = BooleanPolynomialRing(3,order='deglex')
sage: f = x + y*z
sage: f
y*z + x
sage: f.lex_lead_deg()
1

Note: This function is part of the upstream PolyBoRi interface.

\textbf{lm()}

Return the leading monomial of this boolean polynomial, with respect to the order of parent ring.

EXAMPLES:

sage: P.<x,y,z> = BooleanPolynomialRing(3)
sage: (x+y+y*z).lm()
x
sage: P.<x,y,z> = BooleanPolynomialRing(3, order='deglex')
sage: (x+y+y*z).lm()
y*z
sage: P(0).lm()
0

\textbf{lt()}

Return the leading term of this boolean polynomial, with respect to the order of the parent ring.

Note that for boolean polynomials this is equivalent to returning leading monomials.

EXAMPLES:

sage: P.<x,y,z> = BooleanPolynomialRing(3)
sage: (x+y+y*z).lt()
x
sage: P.<x,y,z> = BooleanPolynomialRing(3, order='deglex')
sage: (x+y+y*z).lt()
y*z

\textbf{map_every_x_to_x_plus_one()}

Map every variable \( x_i \) in this polynomial to \( x_i + 1 \).

EXAMPLES:
monomial_coefficient(m)

Return the coefficient of the monomial m in self, where m must have the same parent as self.

INPUT:

• m - a monomial

EXAMPLES:

```python
sage: P.<x,y> = BooleanPolynomialRing(2)
sage: x.monomial_coefficient(x)
1
sage: x.monomial_coefficient(y)
0
sage: R.<x,y,z,a,b,c>=BooleanPolynomialRing(6)
sage: f=(1-x)*(1+y); f
x*y + x + y + 1
sage: f.monomial_coefficient(1)
1
sage: f.monomial_coefficient(0)
0
```

monomials()

Return a list of monomials appearing in self ordered largest to smallest.

EXAMPLES:

```python
sage: P.<a,b,c> = BooleanPolynomialRing(3,order='lex')
sage: f = a + c*b
sage: f.monomials()
[a, b*c]
sage: P.<a,b,c> = BooleanPolynomialRing(3,order='deglex')
sage: f = a + c*b
sage: f.monomials()
[b*c, a]
sage: P.zero().monomials()
[]
```

n_nodes()

Return the number of nodes in the ZDD implementing this polynomial.

EXAMPLES:
sage: B = BooleanPolynomialRing(5, 'x')
sage: x0, x1, x2, x3, x4 = B.gens()
sage: f = x1*x2 + x2*x3 + 1
sage: f.n_nodes()
4

Note: This function is part of the upstream PolyBoRi interface.

n_vars()

Return the number of variables used to form this boolean polynomial.

EXAMPLES:

sage: B.<a,b,c,d> = BooleanPolynomialRing(4)
sage: f = a*b*c + 1
sage: f.n_vars()
3

Note: This function is part of the upstream PolyBoRi interface.

navigation()

Navigators provide an interface to diagram nodes, accessing their index as well as the corresponding then- and else-branches.

You should be very careful and always keep a reference to the original object, when dealing with navigators, as navigators contain only a raw pointer as data. For the same reason, it is necessary to supply the ring as argument, when constructing a set out of a navigator.

EXAMPLES:

sage: from sage.rings.polynomial.pbori.pbori import BooleSet
sage: B = BooleanPolynomialRing(5, 'x')
sage: x0, x1, x2, x3, x4 = B.gens()
sage: f = x1*x2+x2*x3*x4+x2*x4+x3+x4+1

sage: nav = f.navigation()
sage: BooleSet(nav, B)
{{x1,x2}, {x2,x3,x4}, {x2,x4}, {x3}, {x4}, {}}

sage: nav.value()
1

sage: nav_else = nav.else_branch()

sage: BooleSet(nav_else, B)
{{x2,x3,x4}, {x2,x4}, {x3}, {x4}, {}}

sage: nav_else.value()
2
### nvariables()

Return the number of variables used to form this boolean polynomial.

**EXAMPLES:**
```
sage: B.<a,b,c,d> = BooleanPolynomialRing(4)
sage: f = a*b*c + 1
sage: f.nvariables()
3
```

### reduce(I)

Return the normal form of self w.r.t. I, i.e. return the remainder of self with respect to the polynomials in I. If the polynomial set/list I is not a Groebner basis the result is not canonical.

**INPUT:**
- I - a list/set of polynomials in self.parent(). If I is an ideal, the generators are used.

**EXAMPLES:**
```
sage: B.<x0,x1,x2,x3> = BooleanPolynomialRing(4)
sage: I = B.ideal((x0 + x1 + x2 + x3,
                x0*x1 + x1*x2 + x0*x3 + x2*x3,
                x0*x1*x2 + x0*x1*x3 + x0*x2*x3 + x1*x2*x3,
                x0*x1*x2*x3 + 1))
sage: gb = I.groebner_basis()
sage: f,g,h,i = I.gens()
sage: f.reduce(gb)
0
sage: p = f*g + x0*h + x2*i
sage: p.reduce(gb)
0
sage: p.reduce(I)
x1*x2*x3 + x2
sage: p.reduce([])
x0*x1*x2 + x0*x1*x3 + x0*x2*x3 + x2
```

**Note:** If this function is called repeatedly with the same I then it is advised to use PolyBoRi’s GroebnerStrategy object directly, since that will be faster. See the source code of this function for details.

### reducible_by(rhs)

Return True if this boolean polynomial is reducible by the polynomial rhs.

**INPUT:**
- rhs - a boolean polynomial

**EXAMPLES:**
```python
sage: B.<a,b,c,d> = BooleanPolynomialRing(4,order='deglex')
sage: f = (a*b + 1)*(c + 1)
sage: f.reducible_by(d)
False
sage: f.reducible_by(c)
True
sage: f.reducible_by(c + 1)
True
```

Note: This function is part of the upstream PolyBoRi interface.

**ring()**

Return the parent of this boolean polynomial.

EXAMPLES:

```python
sage: B.<a,b,c,d> = BooleanPolynomialRing(4)
sage: a.ring() is B
True
```

**set()**

Return a BooleSet with all monomials appearing in this polynomial.

EXAMPLES:

```python
sage: B.<a,b,z> = BooleanPolynomialRing(3)
sage: (a*b+z+1).set()
{{a,b}, {z}, {}}
```

**spoly(rhs)**

Return the S-Polynomial of this boolean polynomial and the other boolean polynomial rhs.

EXAMPLES:

```python
sage: B.<a,b,c,d> = BooleanPolynomialRing(4)
sage: f = a*b*c + c*d + a*b + 1
sage: g = c*d + b
sage: f.spoly(g)
a*b + a*c*d + c*d + 1
```

Note: This function is part of the upstream PolyBoRi interface.

**stable_hash()**

A hash value which is stable across processes.

EXAMPLES:

```python
sage: B.<x,y> = BooleanPolynomialRing()
sage: x is B.gen(0)
False
sage: x.stable_hash() == B.gen(0).stable_hash()
True
```
Note: This function is part of the upstream PolyBoRi interface. In Sage all hashes are stable.

subs(in_dict=None, **kwds)

Fixes some given variables in a given boolean polynomial and returns the changed boolean polynomials. The polynomial itself is not affected. The variable, value pairs for fixing are to be provided as dictionary of the form {variable:value} or named parameters (see examples below).

INPUT:

• in_dict - (optional) dict with variable:value pairs

• **kwds - names parameters

EXAMPLES:

```
sage: P.<x,y,z> = BooleanPolynomialRing(3)
sage: f = x*y + z + y*z + 1
sage: f.subs(x=1)
y*z + y + z + 1
sage: f.subs(x=0)
y*z + z + 1
sage: f.subs(x=y)
y*z + y + z + 1
sage: f.subs({x:1},y=1)
0
sage: f.subs(y=1)
x + 1
sage: f.subs(y=1,z=1)
x + 1
sage: f.subs(z=1)
x*y + y
sage: f.subs({'x':1},y=1)
0
```

This method can work fully symbolic:

```
sage: f.subs(x=var('a'),y=var('b'),z=var('c'))
a*b + b*c + c + 1
sage: f.subs({'x':var('a'),'y':var('b'),'z':var('c')})
a*b + b*c + c + 1
```

terms()

Return a list of monomials appearing in self ordered largest to smallest.

EXAMPLES:

```
sage: P.<a,b,c> = BooleanPolynomialRing(3,order='lex')
sage: f = a + c*b
sage: f.terms()
[a, b*c]
sage: P.<a,b,c> = BooleanPolynomialRing(3,order='deglex')
```
sage: f = a + c*b
sage: f.terms()
[b*c, a]

**total_degree()**

Return the total degree of self.

**EXAMPLES:**

```sage
sage: P.<x,y> = BooleanPolynomialRing(2)
sage: (x+y).total_degree()
1
```

```sage
sage: P(1).total_degree()
0
```

```sage
sage: (x*y + x + y + 1).total_degree()
2
```

**univariate_polynomial**(R=\texttt{None})

Return a univariate polynomial associated to this multivariate polynomial.

If this polynomial is not in at most one variable, then a \texttt{ValueError} exception is raised. This is checked using the \texttt{is_univariate()} method. The new Polynomial is over GF(2) and in the variable \texttt{x} if no ring \texttt{R} is provided.

```sage
sage: R.<x, y> = BooleanPolynomialRing()
sage: f = x - y + x*y + 1
sage: f.univariate_polynomial()
Traceback (most recent call last): ...
ValueError: polynomial must involve at most one variable
```

Here’s an example with a constant multivariate polynomial:

```sage
sage: g = R(1)
sage: h = g.univariate_polynomial(); h
1
```

```sage
sage: h.parent()
Univariate Polynomial Ring in x over Finite Field of size 2 (using GF2X)
```

**variable**(i=0)

Return the i-th variable occurring in self. The index i is the index in self.variables()

**EXAMPLES:**

```sage
sage: P.<x,y,z> = BooleanPolynomialRing(3)
sage: f = x*z + z + 1
sage: f.variables()
(x, z)
```

```sage
sage: f.variable(1)
z
```

**variables()**

Return a tuple of all variables appearing in self.

**EXAMPLES:**

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```python
sage: P.<x,y,z> = BooleanPolynomialRing(3)
sage: (x + y).variables()
(x, y)
sage: (x*y + z).variables()
(x, y, z)
sage: P.zero().variables()
()
sage: P.one().variables()
()
```

**vars_as_monomial()**

Return a boolean monomial with all variables appearing in `self`.

**EXAMPLES:**

```python
sage: P.<x,y,z> = BooleanPolynomialRing(3)
sage: (x + y).vars_as_monomial()
x*y
sage: (x*y + z).vars_as_monomial()
x*y*z
sage: P.zero().vars_as_monomial()
1
sage: P.one().vars_as_monomial()
1
```

**Note:** This function is part of the upstream PolyBoRi interface.

**zeros_in(s)**

Return a set containing all elements of `s` where this boolean polynomial evaluates to zero.

If `s` is given as a `BooleSet`, then the return type is also a `BooleSet`. If `s` is a set/list/tuple of tuple this function returns a tuple of tuples.

**INPUT:**

- `s` - candidate points for evaluation to zero

**EXAMPLES:**

```python
sage: B.<a,b,c,d> = BooleanPolynomialRing(4)
sage: f = a*b + c + d + 1

Now we create a set of points:

sage: s = a*b + a*b*c + c*d + 1
sage: s = s.set(); s
{{a,b,c}, {a,b}, {c,d}, {}}
```
This encodes the points (1,1,0), (1,1,0,0), (0,0,1,1) and (0,0,0,0). But of these only (1,1,0,0) evaluates to zero.

```
sage: f.zeros_in(s)
{(a,b)}
```

```
sage: f.zeros_in([(1,1,1,0), (1,1,0,0), (0,0,1,1), (0,0,0,0)])
((1, 1, 0, 0),)
```

**class** sage.rings.polynomial.pbori.pbori.BooleanPolynomialEntry

**Bases:** object

p

**class** sage.rings.polynomial.pbori.pbori.BooleanPolynomialIdeal(ring, gens=[], coerce=True)

**Bases:** MPolynomialIdeal

Construct an ideal in the boolean polynomial ring.

**INPUT:**

- ring - the ring this ideal is defined in
- gens - a list of generators
- coerce - coerce all elements to the ring ring (default: True)

**EXAMPLES:**

```
sage: P.<x0, x1, x2, x3> = BooleanPolynomialRing(4)
sage: I = P.ideal(x0*x1*x2*x3 + x0*x1*x3 + x0*x1 + x0*x2 + x0)
sage: I
Ideal (x0*x1*x2*x3 + x0*x1*x3 + x0*x1 + x0*x2 + x0) of Boolean PolynomialRing in x0, x1, x2, x3
```

```
sage: loads(dumps(I)) == I
True
```

**dimension()**

Return the dimension of self, which is always zero.

**groebner_basis(algorithm='polybori', **kwds)**

Return a Groebner basis of this ideal.

**INPUT:**

- algorithm - either "polybori" (built-in default) or "magma" (requires Magma).
- red_tail - tail reductions in intermediate polynomials, this option affects mainly heuristics. The reducedness of the output polynomials can only be guaranteed by the option redsb (default: True)
- minsb - return a minimal Groebner basis (default: True)
- redsb - return a minimal Groebner basis and all tails are reduced (default: True)
- deg_bound - only compute Groebner basis up to a given degree bound (default: False)
- faugere - turn off or on the linear algebra (default: False)
- linear_algebra_in_last_block - this affects the last block of block orderings and degree orderings. If it is set to True linear algebra takes affect in this block. (default: True)
• **gauss_on_linear** - perform Gaussian elimination on linear polynomials (default: True)

• **selection_size** - maximum number of polynomials for parallel reductions (default: 1000)

• **heuristic** - Turn off heuristic by setting heuristic=False (default: True)

• **lazy** - (default: True)

• **invert** - setting invert=True input and output get a transformation x+1 for each variable x, which should not effect the calculated GB, but the algorithm.

• **other_ordering_first** - possible values are False or an ordering code. In practice, many Boolean examples have very few solutions and a very easy Groebner basis. So, a complex walk algorithm (which cannot be implemented using the data structures) seems unnecessary, as such Groebner bases can be converted quite fast by the normal Buchberger algorithm from one ordering into another ordering. (default: False)

• **prot** - show protocol (default: False)

• **full_prot** - show full protocol (default: False)

EXAMPLES:

```
sage: P.<x0, x1, x2, x3> = BooleanPolynomialRing(4)
sage: I = P.ideal(x0*x1*x2*x3 + x0*x1*x3 + x0*x1 + x0*x2 + x0)
sage: I.groebner_basis()
[x0*x1 + x0*x2 + x0, x0*x2*x3 + x0*x3]
```

Another somewhat bigger example:

```
sage: sr = mq.SR(2,1,1,4,gf2=True, polybori=True)
sage: while True:  # workaround (see :trac:`31891`)
....:     try:
....:         F, s = sr.polynomial_system()
....:         break
....:     except ZeroDivisionError:
....:         pass
sage: I = F.ideal()
```

Polynomial Sequence with 36 Polynomials in 36 Variables

We compute the same example with Magma:

```
sage: sr = mq.SR(2,1,1,4,gf2=True, polybori=True)
sage: while True:  # workaround (see :trac:`31891`)
....:     try:
....:         F, s = sr.polynomial_system()
....:         break
....:     except ZeroDivisionError:
....:         pass
sage: I = F.ideal()
sage: I.groebner_basis(algorithm='magma', prot='sage')  # optional - magma
```


(continues on next page)
Leading term degree: 3. Critical pairs: 101 (all pairs of current degree eliminated by criteria).

Highest degree reached during computation: 3.
Polynomial Sequence with 35 Polynomials in 36 Variables

interreduced_basis()

If this ideal is spanned by \((f_1, \ldots, f_n)\) this method returns \((g_1, \ldots, g_s)\) such that:

- \(<f_1, \ldots, f_n> = <g_1, \ldots, g_s>\)
- \(LT(g_i) \neq LT(g_j)\) for all \(i \neq j\)
- \(LT(g_i)\) does not divide \(m\) for all monomials \(m\) of \(\{g_1, \ldots, g_{i-1}, g_{i+1}, \ldots, g_s\}\)

EXAMPLES:

```python
sage: sr = mq.SR(1, 1, 1, 4, gf2=True, polybori=True)
sage: while True:
    try:
        F, s = sr.polynomial_system()
        break
    except ZeroDivisionError:
        pass
sage: I = F.ideal()
sage: g = I.interreduced_basis()
sage: len(g) == len(set(gi.lt() for gi in g))
True
sage: for i in range(len(g)):
    lt = g[i].lt()
    for j in range(len(g)):
        if i == j:
            continue
        for t in iter(g[j]):
            assert lt not in t.divisors()
```

reduce(f)

Reduce an element modulo the reduced Groebner basis for this ideal. This returns 0 if and only if the element is in this ideal. In any case, this reduction is unique up to monomial orders.

EXAMPLES:

```python
sage: P = PolynomialRing(GF(2),10, 'x')
sage: B = BooleanPolynomialRing(10, 'x')
sage: I = sage.rings.ideal.Cyclic(P)
sage: I = B.ideal([B(f) for f in I.gens()])
sage: gb = I.groebner_basis()
sage: I.reduce(gb[0])
0
sage: I.reduce(gb[0] + 1)
1
sage: I.reduce(gb[0]*gb[1])
0
sage: I.reduce(gb[0]*B.gen(1))
0
```
variety(**kwds)

Return the variety associated to this boolean ideal.

EXAMPLES:

A simple example:

```python
sage: from sage.doctest.fixtures import reproducible_repr
sage: R.<x,y,z> = BooleanPolynomialRing()
```

```python
class sage.rings.polynomial.pbori.pbori.BooleanPolynomialIterator

Bases: object

Iterator over the monomials of a boolean polynomial.
```

```python
class sage.rings.polynomial.pbori.pbori.BooleanPolynomialRing

Bases: BooleanPolynomialRing_base

Construct a boolean polynomial ring with the following parameters:

INPUT:

- `n` - number of variables (an integer > 1)
- `names` - names of ring variables, may be a string or list/tuple
- `order` - term order (default: lex)

EXAMPLES:

```python
sage: R.<x, y, z> = BooleanPolynomialRing()
```

```python
class sage.rings.polynomial.pbori.pbori.BooleanPolynomialRing

Bases: BooleanPolynomialRing_base

Construct a boolean polynomial ring with the following parameters:

INPUT:

- `n` - number of variables (an integer > 1)
- `names` - names of ring variables, may be a string or list/tuple
- `order` - term order (default: lex)

EXAMPLES:

```python
sage: R.<x, y, z> = BooleanPolynomialRing()
```

```python
sage: p = x*y + x*z + y*z
```

```python
sage: x*p
x*y*z + x*y + x*z
```

```python
sage: R.term_order()
Lexicographic term order
```

```python
sage: R = BooleanPolynomialRing(5, 'x', order='deglex(3),deglex(2)')
```

```python
sage: R.term_order()
Block term order with blocks:
(Degree lexicographic term order of length 3,
 Degree lexicographic term order of length 2)
```

```python
sage: R = BooleanPolynomialRing(3, 'x', order='deglex')
```

```python
sage: R.term_order()
Degree lexicographic term order
```

change_ring(base_ring=None, names=None, order=None)

Return a new multivariate polynomial ring with base ring base_ring, variable names set to names, and term ordering given by order.
When `base_ring` is not specified, this function returns a `BooleanPolynomialRing` isomorphic to `self`. Otherwise, this returns a `MPolynomialRing`. Each argument above is optional.

INPUT:

- `base_ring` – a base ring
- `names` – variable names
- `order` – a term order

EXAMPLES:

```
sage: P.<x, y, z> = BooleanPolynomialRing()
sage: P.term_order()
Lexicographic term order
sage: R = P.change_ring(names=('a', 'b', 'c'), order="deglex")
sage: R
Boolean PolynomialRing in a, b, c
sage: R.term_order()
Degree lexicographic term order
sage: T = P.change_ring(base_ring=GF(3))
sage: T
Multivariate Polynomial Ring in x, y, z over Finite Field of size 3
sage: T.term_order()
Lexicographic term order
```

```python
clone(ordering=None, names=[], blocks=[])
```

Shallow copy this boolean polynomial ring, but with different ordering, names or blocks if given.

`ring.clone(ordering=..., names=..., block=...)` generates a shallow copy of `ring`, but with different ordering, names or blocks if given.

EXAMPLES:

```
sage: B.<a,b,c> = BooleanPolynomialRing()
sage: B.clone()
Boolean PolynomialRing in a, b, c

sage: B.<x,y,z> = BooleanPolynomialRing(3,order='deglex')
sage: y*z > x
True

Now we call the clone method and generate a compatible, but 'lex' ordered, ring:

```
sage: C = B.clone(ordering=0)
sage: C(y*z) > C(x)
False
```

Now we change variable names:

```
sage: P.<x0,x1> = BooleanPolynomialRing(2)
sage: P
Boolean PolynomialRing in x0, x1
```
Polynomials, Release 10.0

```
sage: Q = P.clone(names=['t'])
sage: Q
Boolean PolynomialRing in t, x1
```

We can also append blocks to block orderings this way:

```
sage: R.<x1,x2,x3,x4> = BooleanPolynomialRing(order='deglex(1),deglex(3)')
sage: x2 > x3*x4
False
```

Now we call the internal method and change the blocks:

```
sage: S = R.clone(blocks=[3])
sage: S(x2) > S(x3*x4)
True
```

**Note:** This is part of PolyBoRi’s native interface.

---

**construction()**

A boolean polynomial ring is the quotient of a polynomial ring, in a special implementation.

Before github issue #15223, the boolean polynomial rings returned the construction of a polynomial ring, which was of course wrong.

Now, a `QuotientFunctor` is returned that knows about the "pbori" implementation.

**EXAMPLES:**

```
sage: P.<x0, x1, x2, x3> = BooleanPolynomialRing(4,order='degneglex(2),←degneglex(2)')
sage: F,O = P.construction()
sage: O
Multivariate Polynomial Ring in x0, x1, x2, x3 over Finite Field of size 2
sage: F
QuotientFunctor
sage: F(O) is P
True
```

**cover_ring()**

Return $R = \mathbb{F}_2[x_1, x_2, ..., x_n]$ if $x_1, x_2, ..., x_n$ is the ordered list of variable names of this ring. $R$ also has the same term ordering as this ring.

**EXAMPLES:**

```
sage: B.<x,y> = BooleanPolynomialRing(2)
sage: R = B.cover_ring(); R
Multivariate Polynomial Ring in x, y over Finite Field of size 2
sage: B.term_order() == R.term_order()
True
```

The cover ring is cached:
defining_ideal()  
Return $I = \langle x_i^2 + x_i \rangle \subset R$ where $R = \text{self.cover_ring}()$, and $x_i$ any element in the set of variables of this ring.

EXAMPLES:

```sage
sage: B.<x,y> = BooleanPolynomialRing(2)
sage: I = B.defining_ideal(); I
Ideal (x^2 + x, y^2 + y) of Multivariate Polynomial Ring
in x, y over Finite Field of size 2
```

\[ \text{gen}(i=0) \]  
Return the \(i\)-th generator of this boolean polynomial ring.

INPUT:

- \(i\) – an integer or a boolean monomial in one variable

EXAMPLES:

```sage
sage: P.<x,y,z> = BooleanPolynomialRing(3)
sage: P.gen()
x
sage: P.gen(2)
z
sage: m = x.monomials()[0]
sage: P.gen(m)
x
```

gens()  
Return the tuple of variables in this ring.

EXAMPLES:

```sage
sage: P.<x,y,z> = BooleanPolynomialRing(3)
sage: P.gens()
(x, y, z)
```

get_base_order_code()  
EXAMPLES:

```sage
sage: B.<a,b,c,d,e,f> = BooleanPolynomialRing()
sage: B.get_base_order_code()
0
sage: B.<a,b,c,d,e,f> = BooleanPolynomialRing(order='deglex')
sage: B.get_base_order_code()
1
```
(continues on next page)
sage: T = TermOrder('deglex',2) + TermOrder('deglex',2)
sage: B.<a,b,c,d> = BooleanPolynomialRing(4, order=T)
sage: B.get_base_order_code()
1

Note: This function which is part of the PolyBoRi upstream API works with a current global ring. This
notion is avoided in Sage.

get_order_code()
EXAMPLES:

sage: B.<a,b,c,d,e,f> = BooleanPolynomialRing()
sage: B.get_order_code()
0
sage: B.<a,b,c,d,e,f> = BooleanPolynomialRing(order='deglex')
sage: B.get_order_code()
1

Note: This function which is part of the PolyBoRi upstream API works with a current global ring. This
notion is avoided in Sage.

has_degree_order()
Return checks whether the order code corresponds to a degree ordering.

EXAMPLES:

sage: P.<x,y> = BooleanPolynomialRing(2)
sage: P.has_degree_order()
False

id()
Return a unique identifier for this boolean polynomial ring.

EXAMPLES:

sage: P.<x,y> = BooleanPolynomialRing(2)
sage: print("id: {}".format(P.id()))
id: ...
sage: P = BooleanPolynomialRing(10, 'x')
sage: Q = BooleanPolynomialRing(20, 'x')
sage: P.id() != Q.id()
True

ideal(*gens, **kwds)
Create an ideal in this ring.

INPUT:
• gens - list or tuple of generators
• \textit{coerce} - bool (default: True) automatically coerce the given polynomials to this ring to form the ideal

\textbf{EXAMPLES:}

\begin{verbatim}
sage: P.<x,y,z> = BooleanPolynomialRing(3)
sage: P.ideal(x+y)
Ideal (x + y) of Boolean PolynomialRing in x, y, z

sage: P.ideal(x*y, y*z)
Ideal (x*y, y*z) of Boolean PolynomialRing in x, y, z

sage: P.ideal([x+y, z])
Ideal (x + y, z) of Boolean PolynomialRing in x, y, z
\end{verbatim}

\textbf{interpolation_polynomial}(\textit{zeros, ones})

Return the lexicographically minimal boolean polynomial for the given sets of points.

Given two sets of points \textit{zeros} - evaluating to zero - and \textit{ones} - evaluating to one -, compute the lexicographically minimal boolean polynomial satisfying these points.

\textbf{INPUT:}

• \textit{zeros} - the set of interpolation points mapped to zero
• \textit{ones} - the set of interpolation points mapped to one

\textbf{EXAMPLES:}

First we create a random-ish boolean polynomial.

\begin{verbatim}
sage: B.<a,b,c,d,e,f> = BooleanPolynomialRing(6)
sage: f = a*b*c*e + a*d*e + a*f + b + c + e + f + 1
\end{verbatim}

Now we find interpolation points mapping to zero and to one.

\begin{verbatim}
sage: zeros = set([(1, 0, 1, 0, 0, 0), (1, 0, 0, 0, 1, 0),
                (0, 0, 1, 1, 1, 1), (1, 0, 1, 1, 1, 1),
                (0, 0, 0, 0, 1, 0), (0, 1, 1, 1, 1, 0),
                (1, 1, 0, 0, 0, 1), (1, 1, 0, 1, 0, 1)])
sage: ones = set([(0, 0, 0, 0, 0, 0), (1, 0, 1, 0, 1, 0),
              (0, 0, 0, 1, 1, 1), (1, 0, 0, 1, 0, 1),
              (0, 0, 0, 0, 1, 1), (0, 1, 1, 0, 1, 1),
              (0, 1, 1, 1, 1, 1), (1, 1, 1, 0, 1, 0)])
sage: [f(*p) for p in zeros]
[0, 0, 0, 0, 0, 0, 0, 0]
sage: [f(*p) for p in ones]
[1, 1, 1, 1, 1, 1, 1, 1]
\end{verbatim}

Finally, we find the lexicographically smallest interpolation polynomial using PolyBoRi.

\begin{verbatim}
sage: g = B.interpolation_polynomial(zeros, ones); g
b*f + c + d*f + d + e*f + e + 1
sage: [g(*p) for p in zeros]
[0, 0, 0, 0, 0, 0, 0, 0]
sage: [g(*p) for p in ones]
[1, 1, 1, 1, 1, 1, 1, 1]
\end{verbatim}
Alternatively, we can work with PolyBoRi’s native BooleanSet’s. This example is from the PolyBoRi tutorial:

```
sage: B = BooleanPolynomialRing(4,"x0,x1,x2,x3")
sage: x = B.gen
sage: V=(x(0)+x(1)+x(2)+x(3)+1).set(); V
{{x0}, {x1}, {x2}, {x3}, {}}
sage: f=x(0)*x(1)+x(1)+x(2)+1
sage: z = f.zeros_in(V); z
{{x1}, {x2}}
sage: o = V.diff(z); o
{{x0}, {x3}, {}}
sage: B.interpolation_polynomial(z,o)
x1 + x2 + 1
```

ALGORITHM: Calls interpolate_smallest_lex as described in the PolyBoRi tutorial.

**n_variables()**

Return the number of variables in this boolean polynomial ring.

**EXAMPLES:**

```
sage: P.<x0,x1> = BooleanPolynomialRing(2)
sage: P.n_variables()
2
```

```
sage: P = BooleanPolynomialRing(1000, 'x')
sage: P.n_variables()
1000
```

**Note:** This is part of PolyBoRi’s native interface.

**ngens()**

Return the number of variables in this boolean polynomial ring.

**EXAMPLES:**

```
sage: P.<x0,x1> = BooleanPolynomialRing(2)
sage: P.ngens()
2
```

```
sage: P = BooleanPolynomialRing(1000, 'x')
sage: P.ngens()
1000
```

**one()**

**EXAMPLES:**

```
sage: P.<x0,x1> = BooleanPolynomialRing(2)
sage: P.one()
1
```
random_element\[(degree=\text{None}, terms=\text{None}, choose\_degree=\text{False}, vars\_set=\text{None})\]

Return a random boolean polynomial. Generated polynomial has the given number of terms, and at most
given degree.

INPUT:

- **degree** - maximum degree (default: 2 for len(var_set) > 1, 1 otherwise)
- **terms** – number of terms requested (default: 5). If more terms are requested than exist, then this
  parameter is silently reduced to the maximum number of available terms.
- **choose\_degree** - choose degree of monomials randomly first, rather than monomials uniformly ran-
  dom
- **vars\_set** - list of integer indices of generators of self to use in the generated polynomial

EXAMPLES:

\[
\begin{align*}
\text{sage: } & P.<x,y,z> = \text{BooleanPolynomialRing}(3) \\
\text{sage: } & f = P.random\_element(\text{degree}=3, \text{terms}=4) \\
\text{sage: } & f.\text{degree}() \leq 3 \\
& \text{True} \\
\text{sage: } & \text{len}(f.\text{terms}()) \\
& 4 \\
\text{sage: } & f = P.random\_element(\text{degree}=1, \text{terms}=2) \\
\text{sage: } & f.\text{degree}() \leq 1 \\
& \text{True} \\
\text{sage: } & \text{len}(f.\text{terms}()) \\
& 2
\end{align*}
\]

In corner cases this function will return fewer terms by default:

\[
\begin{align*}
\text{sage: } & P = \text{BooleanPolynomialRing}(2, 'y') \\
\text{sage: } & f = P.\text{random\_element}() \\
\text{sage: } & \text{len}(f.\text{terms}()) \\
& 2 \\
\text{sage: } & P = \text{BooleanPolynomialRing}(1, 'y') \\
\text{sage: } & f = P.\text{random\_element}() \\
\text{sage: } & \text{len}(f.\text{terms}()) \\
& 1
\end{align*}
\]

We return uniformly random polynomials up to degree 2:

\[
\begin{align*}
\text{sage: } & \text{from collections import defaultdict} \\
\text{sage: } & B.<a,b,c,d> = \text{BooleanPolynomialRing()} \\
\text{sage: } & \text{counter} = 0.0 \\
\text{sage: } & \text{dic} = \text{defaultdict}(*\text{Integer}) \\
\text{sage: } & \text{def} \text{more\_terms}(): \\
& \quad \text{global} \ \text{counter, dic} \\
& \quad \text{for} \ t \ \text{in} \ B.\text{random\_element}(\text{terms}=\infty).\text{terms}(): \\
& \quad \text{counter} += 1.0 \\
& \quad \text{dic}[t] += 1 \\
\text{sage: } & \text{more\_terms}()
\end{align*}
\]

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```python
sage: while any(abs(dic[t]/counter - 1.0/11) > 0.01 for t in dic):
.....: more_terms()
```

**remove_var**(*order=None, *var*)

Remove a variable or sequence of variables from this ring.

If *order* is not specified, then the subring inherits the term order of the original ring, if possible.

**EXAMPLES:**

```python
sage: R.<x,y,z,w> = BooleanPolynomialRing()
sage: R.remove_var(z)
Boolean PolynomialRing in x, y, w
sage: R.remove_var(z,x)
Boolean PolynomialRing in y, w
sage: R.remove_var(y,z,x)
Boolean PolynomialRing in w
```

Removing all variables results in the base ring:

```python
sage: R.remove_var(y,z,x,w)
Finite Field of size 2
```

If possible, the term order is kept:

```python
sage: R.<x,y,z,w> = BooleanPolynomialRing(order='deglex')
sage: R.remove_var(y).term_order()
Degree lexicographic term order
sage: R.<x,y,z,w> = BooleanPolynomialRing(order='lex')
sage: R.remove_var(y).term_order()
Lexicographic term order
```

Be careful with block orders when removing variables:

```python
sage: R.<x,y,z,u,v> = BooleanPolynomialRing(order='deglex(2),deglex(3)')
sage: R.remove_var(x,y,z)
Traceback (most recent call last):
...
ValueError: impossible to use the original term order (most likely because it was a block order); please specify the term order for the subring
sage: R.remove_var(x,y,z, order='deglex')
Boolean PolynomialRing in u, v
```

**variable**(*i=0*)

Return the *i*-th generator of this boolean polynomial ring.

**INPUT:**

- *i* - an integer or a boolean monomial in one variable

**EXAMPLES:**

```python
sage: P.<x,y,z> = BooleanPolynomialRing(3)
sage: P.variable()
x
sage: P.variable(2)
z
```

(continues on next page)
```python
sage: m = x.monomials()[0]
sage: P.variable(m)

zero()

EXAMPLES:

```python
sage: P.<x0,x1> = BooleanPolynomialRing(2)
sage: P.zero()
```

class sage.rings.polynomial.pbori.pbori.BooleanPolynomialVector

Bases: object

A vector of boolean polynomials.

EXAMPLES:

```python
sage: B.<a,b,c,d,e,f> = BooleanPolynomialRing()
sage: from sage.rings.polynomial.pbori.pbori import BooleanPolynomialVector
sage: l = [B.random_element() for _ in range(3)]
sage: v = BooleanPolynomialVector(l)
3
sage: all(vi.parent() is B for vi in v)
True
```

append(elt)

Append the element elt to this vector.

EXAMPLES:

```python
sage: B.<a,b,c,d,e,f> = BooleanPolynomialRing()
sage: from sage.rings.polynomial.pbori.pbori import BooleanPolynomialVector
sage: v = BooleanPolynomialVector()

```

class sage.rings.polynomial.pbori.pbori.BooleanPolynomialVectorIterator

Bases: object

class sage.rings.polynomial.pbori.pbori.CCuddNavigator

Bases: object

constant()

else_branch()

terminal_one()

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then_branch()

class sage.rings.polynomial.pbori.pbori.FGLMStrategy

Bases: object

Strategy object for the FGLM algorithm to translate from one Groebner basis with respect to a term ordering A to another Groebner basis with respect to a term ordering B.

main()

Execute the FGLM algorithm.

EXAMPLES:

```python
sage: from sage.rings.polynomial.pbori.pbori import *
sage: B.<x,y,z> = BooleanPolynomialRing()
sage: ideal = BooleanPolynomialVector([x+z, y+z])
sage: list(ideal)
[x + z, y + z]
sage: old_ring = B
sage: new_ring = B.clone(ordering=dp_asc)
sage: list(FGLMStrategy(old_ring, new_ring, ideal).main())
y + x, z + x
```

class sage.rings.polynomial.pbori.pbori.GroebnerStrategy

Bases: object

A Groebner strategy is the main object to control the strategy for computing Groebner bases.

Note: This class is mainly used internally.

add_as_you_wish(p)

Add a new generator but let the strategy object decide whether to perform immediate interreduction.

INPUT:

• p - a polynomial

EXAMPLES:

```python
sage: from sage.rings.polynomial.pbori.pbori import *
sage: B.<a,b,c,d,e,f> = BooleanPolynomialRing()
sage: gbs = GroebnerStrategy(B)
sage: gbs.add_as_you_wish(a + b)
sage: list(gbs)
[a + b]
sage: gbs.add_as_you_wish(a + c)
sage: list(gbs)
a + b
```

Note that nothing happened immediately but that the generator was indeed added:

```python
sage: list(gbs)
[a + b]
sage: gbs.symmGB_F2()
sage: list(gbs)
a + c, b + c
```

Chapter 7. Boolean Polynomials
**add_generator**($p$)

Add a new generator.

**INPUT:**

- $p$ - a polynomial

**EXAMPLES:**

```sage
from sage.rings.polynomial.pbori.pbori import *
sage: B.<a,b,c,d,e,f> = BooleanPolynomialRing()
sage: gbs = GroebnerStrategy(B)
sage: gbs.add_generator(a + b)
sage: list(gbs)
[a + b]
sage: gbs.add_generator(a + c)
Traceback (most recent call last):
  ... ValueError: strategy already contains a polynomial with same lead
```

**add_generatorDelayed**($p$)

Add a new generator but do not perform interreduction immediately.

**INPUT:**

- $p$ - a polynomial

**EXAMPLES:**

```sage
from sage.rings.polynomial.pbori.pbori import *
sage: B.<a,b,c,d,e,f> = BooleanPolynomialRing()
sage: gbs = GroebnerStrategy(B)
sage: gbs.add_generator(a + b)
sage: list(gbs)
[a + b]
sage: gbs.add_generatorDelayed(a + c)
sage: list(gbs)
[a + b]
sage: list(gbs.all_generators())
[a + b, a + c]
```

**all_generators**()

**EXAMPLES:**

```sage
from sage.rings.polynomial.pbori.pbori import *
sage: B.<a,b,c,d,e,f> = BooleanPolynomialRing()
sage: gbs = GroebnerStrategy(B)
sage: gbs.add_as_you_wish(a + b)
sage: list(gbs)
[a + b]
sage: gbs.add_as_you_wish(a + c)

sage: list(gbs)
[a + b]
```

(continues on next page)
sage: list(gbs.all_generators())
[a + b, a + c]

all_spols_in_next_degree()

clean_top_by_chain_criterion()

contains_one()

    Return True if 1 is in the generating system.

    EXAMPLES:

    We construct an example which contains 1 in the ideal spanned by the generators but not in the set of generators:

sage: B.<a,b,c,d,e,f> = BooleanPolynomialRing()
sage: from sage.rings.polynomial.pbori.pbori import GroebnerStrategy
sage: gb = GroebnerStrategy(B)
sage: gb.add_generator(a*c + a*f + d*f + d + f)
sage: gb.add_generator(b*c + b*e + c + d + 1)
sage: gb.add_generator(a*f + a + c + d + 1)
sage: gb.add_generator(a*d + a*e + b*e + c + f)
sage: gb.add_generator(b*d + c + d*f + e + f)
sage: gb.add_generator(a*b + b + c*e + e + 1)
sage: gb.add_generator(a + b + c*d + c*e + 1)
sage: gb.contains_one()
False

Still, we have that:

sage: from sage.rings.polynomial.pbori.pbori import groebner_basis
sage: groebner_basis(gb)
[1]

faugere_step_dense(v)

    Reduces a vector of polynomials using linear algebra.

    INPUT:

    • v - a boolean polynomial vector

    EXAMPLES:

sage: B.<a,b,c,d,e,f> = BooleanPolynomialRing()
sage: from sage.rings.polynomial.pbori.pbori import GroebnerStrategy
sage: gb = GroebnerStrategy(B)
sage: gb.add_generator(a*c + a*f + d*f + d + f)
sage: gb.add_generator(b*c + b*e + c + d + 1)
sage: gb.add_generator(a*f + a + c + d + 1)
sage: gb.add_generator(a*d + a*e + b*e + c + f)
sage: gb.add_generator(b*d + c + d*f + e + f)
sage: gb.add_generator(a*b + b + c*e + e + 1)
sage: gb.add_generator(a + b + c*d + c*e + 1)
sage: from sage.rings.polynomial.pbori.pbori import BooleanPolynomialVector
implications(i)
    Compute "useful" implied polynomials of i-th generator, and add them to the strategy, if it finds any.
    INPUT:
        • i - an index

ll_reduce_all()
    Use the built-in ll-encoded BooleSet of polynomials with linear lexicographical leading term, which coincides with leading term in current ordering, to reduce the tails of all polynomials in the strategy.

minimalize()
    Return a vector of all polynomials with minimal leading terms.

    Note: Use this function if strat contains a GB.

minimalize_and_tail_reduce()
    Return a vector of all polynomials with minimal leading terms and do tail reductions.

    Note: Use that if strat contains a GB and you want a reduced GB.

definitions
    next_spoly()
    nf(p)
    Compute the normal form of p with respect to the generating set.
    INPUT:
        • p - a boolean polynomial

    EXAMPLES:

        sage: P = PolynomialRing(GF(2),10,'x')
        sage: B = BooleanPolynomialRing(10,'x')
        sage: I = sage.rings.ideal.Cyclic(P)
        sage: I = B.ideal([B(f) for f in I.gens()])
        sage: gb = I.groebner_basis()
        sage: from sage.rings.polynomial.pbori.pbori import GroebnerStrategy
        sage: G = GroebnerStrategy(B)
        sage: _ = [G.add_generator(f) for f in gb]
        sage: G.nf(gb[0])
        0
        sage: G.nf(gb[0] + 1)
        1
        sage: G.nf(gb[0]*gb[1])
        0

(continues on next page)
Note: The result is only canonical if the generating set is a Groebner basis.

**nnpairs()**

**reduction_strategy**

**select(m)**

Return the index of the generator which can reduce the monomial m.

**INPUT:**

- m - a BooleanMonomial

**EXAMPLES:**

```
sage: B.<a,b,c,d,e> = BooleanPolynomialRing()
sage: f = B.random_element()
sage: g = B.random_element()
sage: while g.lt() == f.lt():
    ....:     g = B.random_element()
sage: from sage.rings.polynomial.pbori.pbori import GroebnerStrategy
sage: strat = GroebnerStrategy(B)
sage: strat.add_generator(f)
sage: strat.add_generator(g)
sage: strat.select(f.lm())
0
sage: strat.select(g.lm())
1
sage: strat.select(e.lm())
-1
```

**small_spolys_in_next_degree(f, n)**

**some_spolys_in_next_degree(n)**

**suggest_plugin_variable()**

**symmGB_F2()**

Compute a Groebner basis for the generating system.

**Note:** This implementation is out of date, but it will revived at some point in time. Use the groebner_basis() function instead.

**top_sugar()**

**variable_has_value(v)**

Computes, whether there exists some polynomial of the form \( v + c \) in the Strategy – where c is a constant – in the list of generators.

**INPUT:**
• \( v \) - the index of a variable

EXAMPLES:

```
sage: B.<a,b,c,d,e,f> = BooleanPolynomialRing()
sage: from sage.rings.polynomial.pbori.pbori import GroebnerStrategy
goog: gb = GroebnerStrategy(B)
goog: gb.add_generator(a*c + a*f + d*f + d + f)
goog: gb.add_generator(b*c + b*e + c + d + 1)
goog: gb.add_generator(a*f + a + c + d + 1)
goog: gb.add_generator(a*d + a*e + b*e + c + f)
goog: gb.add_generator(b*d + c + d*f + e + f)
goog: gb.add_generator(a*b + b + c*e + e + 1)
goog: gb.variable_has_value(0)
False
```

```
sage: from sage.rings.polynomial.pbori import groebner_basis
sage: g = groebner_basis(gb)
sage: list(g)
[a, b + 1, c + 1, d, e + 1, f]
```

```
sage: gb = GroebnerStrategy(B)
sage: _ = [gb.add_generator(f) for f in g]
sage: gb.variable_has_value(0)
True
```

**class** sage.rings.polynomial.pbori.pbori.MonomialConstruct

Bases: object

Implements PolyBoRi's Monomial() constructor.

**class** sage.rings.polynomial.pbori.pbori.MonomialFactory

Bases: object

Implements PolyBoRi's Monomial() constructor. If a ring is given is can be used as a Monomial factory for the given ring.

EXAMPLES:

```
sage: from sage.rings.polynomial.pbori.pbori import *
sage: B.<a,b,c> = BooleanPolynomialRing()
sage: fac = MonomialFactory()
sage: fac = MonomialFactory(B)
```

**class** sage.rings.polynomial.pbori.pbori.PolynomialConstruct

Bases: object

Implements PolyBoRi’s Polynomial() constructor.

lead(\( x \))

Return the leading monomial of boolean polynomial \( x \), with respect to the order of parent ring.

EXAMPLES:

```
sage: from sage.rings.polynomial.pbori.pbori import *
sage: B.<a,b,c> = BooleanPolynomialRing()
```

(continues on next page)
class sage.rings.polynomial.pbori.pbori.PolynomialFactory

Bases: object

Implements PolyBoRi’s Polynomial() constructor and a polynomial factory for given rings.

lead(x)

Return the leading monomial of boolean polynomial x, with respect to the order of parent ring.

EXAMPLES:

```sage
from sage.rings.polynomial.pbori.pbori import *
B.<a,b,c> = BooleanPolynomialRing()
P = PolynomialFactory().lead(a)
a
```

class sage.rings.polynomial.pbori.pbori.ReductionStrategy

Bases: object

Functions and options for boolean polynomial reduction.

add_generator(p)

Add the new generator p to this strategy.

INPUT:

* p - a boolean polynomial.

EXAMPLES:

```sage
from sage.rings.polynomial.pbori.pbori import *
B.<x,y,z> = BooleanPolynomialRing()
red = ReductionStrategy(B)
red.add_generator(x)
[f.p for f in red]
[x]
```

can_rewrite(p)

Return True if p can be reduced by the generators of this strategy.

EXAMPLES:

```sage
from sage.rings.polynomial.pbori.pbori import *
B.<a,b,c,d> = BooleanPolynomialRing()
red = ReductionStrategy(B)
red.add_generator(a*b + c + 1)
red.add_generator(b*c + d + 1)
red.can_rewrite(a*b + a)
True
red.can_rewrite(b + c)
False
red.can_rewrite(a*d + b*c + d + 1)
True
```
cheap_reductions(p)

Perform ‘cheap’ reductions on p.

INPUT:

- p - a boolean polynomial

EXAMPLES:

```
sage: from sage.rings.polynomial.pbori.pbori import *
sage: B.<a,b,c,d> = BooleanPolynomialRing()
sage: red = ReductionStrategy(B)
sage: red.add_generator(a*b + c + 1)
sage: red.add_generator(b*c + d + 1)
sage: red.add_generator(a)
sage: red.cheap_reductions(a*b + a)
0
sage: red.cheap_reductions(b + c)
b + c
sage: red.cheap_reductions(a*d + b*c + d + 1)
b*c + d + 1
```

head_normal_form(p)

Compute the normal form of p with respect to the generators of this strategy but do not perform tail any reductions.

INPUT:

- p – a polynomial

EXAMPLES:

```
sage: from sage.rings.polynomial.pbori.pbori import *
sage: B.<x,y,z> = BooleanPolynomialRing()
sage: red = ReductionStrategy(B)
sage: red.opt_red_tail = True
sage: red.add_generator(x + y + 1)
sage: red.add_generator(y*z + z)
```

```
sage: red.head_normal_form(x + y*z)
y + z + 1
sage: red.nf(x + y*z)
y + z + 1
```

nf(p)

Compute the normal form of p w.r.t. to the generators of this reduction strategy object.

EXAMPLES:

```
sage: from sage.rings.polynomial.pbori.pbori import *
sage: B.<x,y,z> = BooleanPolynomialRing()
sage: red = ReductionStrategy(B)
sage: red.add_generator(x + y + 1)
sage: red.add_generator(y*z + z)
sage: red.nf(x)
y + 1
```

(continues on next page)


```
sage: red.nf(y*z + x)
y + z + 1
```

**reduced_normal_form**(*p*)

Compute the normal form of *p* with respect to the generators of this strategy and perform tail reductions.

**INPUT:**

- *p* - a polynomial

**EXAMPLES:**

```
sage: from sage.rings.polynomial.pbori.pbori import *
sage: B.<x,y,z> = BooleanPolynomialRing()
sage: red = ReductionStrategy(B)
sage: red.add_generator(x + y + 1)
sage: red.add_generator(y*z + z)
sage: red.reduced_normal_form(x)
y + 1
sage: red.reduced_normal_form(y*z + x)
y + z + 1
```

```
sage.rings.polynomial.pbori.pbori.TermOrder_from_pb_order(n, order, blocks)
```

```
class sage.rings.polynomial.pbori.pbori.VariableBlock
    Bases: object
class sage.rings.polynomial.pbori.pbori.VariableConstruct
    Bases: object
    Implements PolyBoRi’s Variable() constructor.
class sage.rings.polynomial.pbori.pbori.VariableFactory
    Bases: object
    Implements PolyBoRi’s Variable() constructor and a variable factory for given ring
```

```
sage.rings.polynomial.pbori.pbori.add_up_polynomials(v, init)
    Add up all entries in the vector v.
    **INPUT:**
    - *v* - a vector of boolean polynomials
    **EXAMPLES:**
    
    ```
sage: from sage.rings.polynomial.pbori.pbori import *
sage: B.<a,b,c,d> = BooleanPolynomialRing()
sage: v = BooleanPolynomialVector()
sage: l = [B.random_element() for _ in range(5)]
sage: _ = [v.append(e) for e in l]
sage: add_up_polynomials(v, B.zero()) == sum(l)
    True
    ```
```

```
sage.rings.polynomial.pbori.pbori.contained_vars(m)
```
sage.rings.polynomial.pbori.pbori.easy_linear_factors(p)

sage.rings.polynomial.pbori.pbori.gauss_on_polys(inp)

Perform Gaussian elimination on the input list of polynomials.

**INPUT:**

- inp – an iterable

**EXAMPLES:**

```python
sage: B.<a,b,c,d,e,f> = BooleanPolynomialRing()
sage: from sage.rings.polynomial.pbori.pbori import *
sage: l = [B.random_element() for _ in range(B.ngens())]
sage: A, v = Sequence(l, B).coefficient_matrix()
sage: e = gauss_on_polys(l)
sage: E, v = Sequence(e, B).coefficient_matrix()
sage: E == A.echelon_form()
```

True

sage.rings.polynomial.pbori.pbori.get_var_mapping(ring, other)

Return a variable mapping between variables of other and ring. When other is a parent object, the mapping defines images for all variables of other. If it is an element, only variables occurring in other are mapped.

Raises NameError if no such mapping is possible.

**EXAMPLES:**

```python
sage: P.<x,y,z> = BooleanPolynomialRing(3)
sage: R.<z,y> = QQ[]
sage: sage.rings.polynomial.pbori.pbori.get_var_mapping(P,R)
[z, y]
sage: sage.rings.polynomial.pbori.pbori.get_var_mapping(P, z^2)
[z, None]
sage: R.<z,x> = BooleanPolynomialRing(2)
sage: sage.rings.polynomial.pbori.pbori.get_var_mapping(P,R)
[z, x]
sage: sage.rings.polynomial.pbori.pbori.get_var_mapping(P, x^2)
[None, x]
```

sage.rings.polynomial.pbori.pbori.if_then_else(root, a, b)

The opposite of navigating down a ZDD using navigators is to construct new ZDDs in the same way, namely giving their else- and then-branch as well as the index value of the new node.

**INPUT:**

- root - a variable
- a - the if branch, a BooleSet or a BoolePolynomial
- b - the else branch, a BooleSet or a BoolePolynomial

**EXAMPLES:**

```python
sage: from sage.rings.polynomial.pbori.pbori import if_then_else
sage: B = BooleanPolynomialRing(6,'x')
```
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sage: x0,x1,x2,x3,x4,x5 = B.gens()
sage: f0 = x2*x3+x3
sage: f1 = x4
sage: if_then_else(x1, f0, f1)
{{x1,x2,x3}, {x1,x3}, {x4}}

sage: if_then_else(x1.lm().index(),f0,f1)
{{x1,x2,x3}, {x1,x3}, {x4}}

sage: if_then_else(x5, f0, f1)
Traceback (most recent call last):
...  
IndexError: index of root must be less than the values of roots of the branches

sage.rings.polynomial.pbori.pbori.interpolate(zero, one)

Interpolate a polynomial evaluating to zero on zero and to one on ones.

INPUT:

- zero - the set of zero
- one - the set of ones

EXAMPLES:

sage: B = BooleanPolynomialRing(4,"x0,x1,x2,x3")
sage: x = B.gen
sage: from sage.rings.polynomial.pbori.pbori.interpolate import *

sage: V=(x(0)+x(1)+x(2)+x(3)+1).set()

sage: V
{{x0}, {x1}, {x2}, {x3}, {}}

sage: f=x(0)*x(1)+x(1)+x(2)+1
sage: nf_lex_points(f, V)
x1 + x2 + 1

sage: z=f.zeros_in(V)

sage: z
{{x1}, {x2}}

sage: o=V.diff(z)

sage: o
{{x0}, {x3}, {}}

sage: interpolate(z,o)
x0*x1*x2 + x0*x1 + x0*x2 + x1*x2 + x1 + x2 + 1

sage.rings.polynomial.pbori.pbori.interpolate_smallest_lex(zero, one)

Interpolate the lexicographical smallest polynomial evaluating to zero on zero and to one on ones.

INPUT:

- zero - the set of zeros
• one - the set of ones

EXAMPLES:

Let V be a set of points in $\mathbb{F}_2^n$ and f a Boolean polynomial. V can be encoded as a BooleSet. Then we are interested in the normal form of f against the vanishing ideal of V: $I(V)$.

It turns out, that the computation of the normal form can be done by the computation of a minimal interpolation polynomial, which takes the same values as f on V:

```sage
sage: B = BooleanPolynomialRing(4,"x0,x1,x2,x3")
sage: x = B.gen
sage: from sage.rings.polynomial.pbori.interpolate import *
sage: V=(x(0)+x(1)+x(2)+x(3)+1).set()
```

We take $V = \{e_0,e_1,e_2,e_3,0\}$, where $e_i$ describes the i-th unit vector. For our considerations it does not play any role, if we suppose V to be embedded in $\mathbb{F}_2^4$ or a vector space of higher dimension:

```sage
sage: V
{{x0}, {x1}, {x2}, {x3}, {}}
sage: f=x(0)*x(1)+x(1)+x(2)+1
sage: nf_lex_points(f, V)
x1 + x2 + 1
```

In this case, the normal form of f w.r.t. the vanishing ideal of V consists of all terms of f with degree smaller or equal to 1.

It can be easily seen, that this polynomial forms the same function on V as f. In fact, our computation is equivalent to the direct call of the interpolation function `interpolate_smallest_lex`, which has two arguments: the set of interpolation points mapped to zero and the set of interpolation points mapped to one:

```sage
sage: z=f.zeros_in(V)
sage: z
{{x1}, {x2}}
sage: o=V.diff(z)
sage: o
{{x0}, {x3}, {}}
sage: interpolate_smallest_lex(z,o)
x1 + x2 + 1
```

`sage.rings.polynomial.pbori.pbori.ll_red_nf_noredsb(p, reductors)`

Reduce the polynomial p by the set of reductors with linear leading terms.

INPUT:

• p - a boolean polynomial

• reductors - a boolean set encoding a Groebner basis with linear leading terms.

EXAMPLES:
Redude the polynomial \( p \) by the set of reductors with linear leading terms.

**INPUT:**
- \( p \) - a boolean polynomial
- \( \text{reductors} \) - a boolean set encoding a Groebner basis with linear leading terms.

**EXAMPLES:**

```python
sage: from sage.rings.polynomial.pbori.pbori import ll_red_nf_redsb
sage: B.<a,b,c,d> = BooleanPolynomialRing()
```

```python
sage: p = a*b + c + d + 1
sage: f,g = a + c + 1, b + d + 1
sage: reductors = f.set().union( g.set() )
```

```python
sage: ll_red_nf_redsb(p, reductors)
b*c + b*d + c + d + 1
```

Redude the polynomial \( p \) by the set of reductors with linear leading terms. It is assumed that the set \( \text{reductors} \) is a reduced Groebner basis.

**INPUT:**
- \( p \) - a boolean polynomial
- \( \text{reductors} \) - a boolean set encoding a reduced Groebner basis with linear leading terms.

**EXAMPLES:**

```python
sage: from sage.rings.polynomial.pbori.pbori import ll_red_nf_redsb
```

```python
sage: B.<a,b,c,d> = BooleanPolynomialRing()
```

```python
sage: p = a*b + c + d + 1
sage: f,g = a + c + 1, b + d + 1
sage: reductors = f.set().union( g.set() )
```

```python
sage: ll_red_nf_redsb(p, reductors)
b*c + b*d + c + d + 1
```

Map every variable \( x_i \) in this polynomial to \( x_i + 1 \).

**EXAMPLES:**

```python
sage: B.<a,b,z> = BooleanPolynomialRing(3)
```

```python
sage: f = a*b + z + 1; f
```

```python
a*b + z + 1
```

```python
sage: from sage.rings.polynomial.pbori.pbori import map_every_x_to_x_plus_one
```

```python
(continues on next page)```
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(continued from previous page)

```python
sage: map_every_x_to_x_plus_one(f)
a*b + a + b + z + 1
sage: f(a+1,b+1,z+1)
a*b + a + b + z + 1
```

```
sage.rings.polynomial.pbori.pbori.mod_mon_set(a_s, v_s)
sage.rings.polynomial.pbori.pbori.mod_var_set(a, v)
sage.rings.polynomial.pbori.pbori.mult_fact_sim_C(v, ring)
sage.rings.polynomial.pbori.pbori.nf3(s, p, m)
sage.rings.polynomial.pbori.pbori.parallel_reduce(input, strat, average_steps, delay_f)
sage.rings.polynomial.pbori.pbori.random_set(variables, length)
```

Return a random set of monomials with `length` elements with each element in the variables `variables`.

**EXAMPLES:**

```python
sage: from sage.rings.polynomial.pbori.pbori import random_set, set_random_seed
sage: B.<a,b,c,d,e> = BooleanPolynomialRing()
sage: (a*b*c*d).lm()
a*b*c*d
sage: set_random_seed(1337)
sage: random_set((a*b*c*d).lm(),10)
{{a,b,c,d}, {a,b}, {a,c,d}, {a,c}, {b,c,d}, {b,d}, {b}, {c,d}, {c}, {d}}
```

```
sage.rings.polynomial.pbori.pbori.recursively_insert(n, ind, m)
sage.rings.polynomial.pbori.pbori.red_tail(s, p)
```

Perform tail reduction on `p` using the generators of `s`.

**INPUT:**

- `s` - a reduction strategy
- `p` - a polynomial

**EXAMPLES:**

```python
sage: from sage.rings.polynomial.pbori.pbori import *
sage: B.<x,y,z> = BooleanPolynomialRing()
sage: red = ReductionStrategy(B)
sage: red.add_generator(x + y + 1)
sage: red.add_generator(y*z + z)
sage: red_tail(red,x)
x
sage: red_tail(red,x*y + x)
x*y + y + 1
```

```
sage.rings.polynomial.pbori.pbori.set_random_seed(seed)
```

Set the PolyBoRi random seed to `seed`.

**EXAMPLES:**

7.1. Boolean Polynomials
sage: from sage.rings.polynomial.pbori.pbori import random_set, set_random_seed
sage: B.<a,b,c,d,e> = BooleanPolynomialRing()

sage: (a*b*c*d).lm()
\texttt{a*b*c*d}

sage: set_random_seed(1337)

sage: random_set((a*b*c*d).lm(),2)
\{\{b\}, \{c\}\}

sage: random_set((a*b*c*d).lm(),2)
\{\{a,c,d\}, \{c\}\}

sage: set_random_seed(1337)

sage: random_set((a*b*c*d).lm(),2)
\{\{b\}, \{c\}\}

sage: random_set((a*b*c*d).lm(),2)
\{\{a,c,d\}, \{c\}\}

sage.rings.polynomial.pbori.pbori.
\texttt{substitute}\_\texttt{variables} (parent, vec, poly)

\texttt{var(i) is replaced by vec[i] in poly.}

\textbf{EXAMPLES:}

sage: B.<a,b,c> = BooleanPolynomialRing()

sage: f = a*b + c + 1

sage: from sage.rings.polynomial.pbori.pbori import substitute_variables

sage: substitute_variables(B, [a,b,c],f)
a*b + c + 1

sage: substitute_variables(B, [a+1,b,c],f)
a*b + b + c + 1

sage: substitute_variables(B, [a+1,b+1,c],f)
a*b + a + b + c

sage: substitute_variables(B, [a+1,b+1,B(0)],f)
a*b + a + b

Substitution is also allowed with different rings:

sage: B.<a,b,c> = BooleanPolynomialRing()

sage: f = a*b + c + 1

sage: B.<w,x,y,z> = BooleanPolynomialRing(order='deglex')

sage: from sage.rings.polynomial.pbori.pbori import substitute_variables

sage: substitute_variables(B, [x,y,z], f) * w
w*x*y + w*z + w

sage.rings.polynomial.pbori.pbori.\texttt{top}\_\texttt{index}(s)

\texttt{Return the highest index in the parameter s.}

\textbf{INPUT:}

\begin{itemize}
  \item s - BooleSet, BooleMonomial, BoolePolynomial
\end{itemize}

\textbf{EXAMPLES:}

sage: B.<x,y,z> = BooleanPolynomialRing(3)

sage: from sage.rings.polynomial.pbori.pbori import top_index
sage: top_index(x.lm())
Polynomials, Release 10.0

sage: top_index(y*z)
1
sage: top_index(x + 1)
0

sage.rings.polynomial.pbori.pbori.unpickle_BooleanPolynomial\(\text{\texttt{unpickl}}} \text{\texttt{e Polyno}} \text{\texttt{mial}} \text{\texttt{a}}\(\text{\texttt{ring, string}}\)
Unpickle boolean polynomials

EXAMPLES:

```python
sage: T = TermOrder('deglex',2)+TermOrder('deglex',2)
sage: P.<a,b,c,d> = BooleanPolynomialRing(4,order=T)
sage: loads(dumps(a+b)) == a+b  # indirect doctest
True
```

sage.rings.polynomial.pbori.pbori.unpickle_BooleanPolynomial0\(\text{\texttt{unpickl}}} \text{\texttt{e Polyno}} \text{\texttt{mial}} \text{\texttt{a}}\(\text{\texttt{ring, l}}\)
Unpickle boolean polynomials.

EXAMPLES:

```python
sage: T = TermOrder('deglex',2)+TermOrder('deglex',2)
sage: P.<a,b,c,d> = BooleanPolynomialRing(4,order=T)
sage: loads(dumps(a+b)) == a+b  # indirect doctest
True
```

sage.rings.polynomial.pbori.pbori.unpickle_BooleanPolynomialRing\(\text{\texttt{unpickl}}} \text{\texttt{e Polyno}} \text{\texttt{mial}} \text{\texttt{Ring}}\(\text{\texttt{a, names, order}}\)
Unpickle boolean polynomial rings.

EXAMPLES:

```python
sage: T = TermOrder('deglex',2)+TermOrder('deglex',2)
sage: P.<a,b,c,d> = BooleanPolynomialRing(4,order=T)
sage: loads(dumps(P)) == P  # indirect doctest
True
```

sage.rings.polynomial.pbori.pbori.zeros\(\text{\texttt{pol, s}}\)
Return a BooleSet encoding on which points from s the polynomial pol evaluates to zero.

INPUT:

- pol - a boolean polynomial
- s - a set of points encoded as a BooleSet

EXAMPLES:

```python
sage: B.<a,b,c,d> = BooleanPolynomialRing(4)
sage: f = a*b + a*c + d + b

Now we create a set of points:

```python
sage: s = a*b + a*b*c + c*d + b*c
sage: s = s.set(); s
{{a,b,c}, {a,b}, {b,c}, {c,d}}
```

7.1. Boolean Polynomials
This encodes the points (1,1,1,0), (1,1,0,0), (0,0,1,1) and (0,1,1,0). But of these only (1,1,0,0) evaluates to zero:

```python
sage: from sage.rings.polynomial.pbori.pbori import zeros
sage: zeros(f, s)
{{a,b}}
```

For comparison we work with tuples:

```python
sage: f.zeros_in([(1,1,1,0), (1,1,0,0), (0,0,1,1), (0,1,1,0)])
((1, 1, 0, 0),)
```
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